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GLACIAL FEATURES AROUND THE KEEWATIN ICE DIVIDE: DISTRICTS OF MACKENZIE AND KEEWATIN

J.M. Aylsworth
W.W. Shilts

1989

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View along crest of esker in northern District of Keewatin (approximately 65°45'N, 99°00'W). GSC 203541-M

Critical Reader

R.J. Fulton

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GLACIAL FEATURES AROUND THE KEEWATIN ICE DIVIDE: DISTRICTS OF MACKENZIE AND KEEWATIN

Abstract

Four zones that are roughly concentric about the Keewatin Ice Divide are defined by landform/sediment assemblages. Zone 1, including the Keewatin Ice Divide, is characterized by a lack of eskers or oriented landforms and includes significant areas of low relief hummocky moraine. Zone 2 is delimited by the distribution of ribbed (rogen) moraine, but also includes extensive drumlin fields and well developed esker systems. Zone 3 is characterized by a fairly continuous, commonly drumlinized, drift cover, that thins outward; Zone 4 comprises large tracts of bedrock outcrop with minimal drift cover.

The types or associations of landforms, the presence or absence of landforms, and the configurations of the zones themselves are controlled by a complex interplay of ice dynamics and bedrock geology. Zones 3 and 4 are more influenced by the quantity of debris available for construction and hence bedrock geology. Zones 1 and 2 are more influenced by ice dynamics, in particular stagnation of a thin ice sheet during deglaciation. Yet even within Zone 2, bedrock geology, which determines the physical properties of the entrained debris, influences the manner of ice deformation and thus the type of landform produced. In general, less deformable sediments form ribbed moraine while more deformable occur in drumlins. Unlike drumlins, ribbed moraine, the morphology of which seems to be a relict of englacial structure, may be preserved only where associated sediment is released from stagnant ice. Hence, the outer edge of Zone 2 may mark the limit of widespread stagnation of the ice sheet.

The integrated system of trunk and tributary eskers, formed in conduits at the base of the ice by meltwater plunging downward from the surface, probably mirrors the pattern of movement of meltwater on the surface of the ice sheet. This suggests virtual stagnation of the ice sheet while it still covered a large area.

Résumé

Quatre zones à peu près concentriques par rapport à la ligne de partage glaciaire de Keewatin sont définies par des assemblages de formes sédimentaires. La Zone 1, comprenant la ligne de partage glaciaire de Keewatin, est caractérisée par un manque d'eskers ou de formes de relief orientées et comprend des zones importantes de moraines mamelonnées à faible relief. La Zone 2 est non seulement délimitée par la répartition des moraines côtelées (de Rogen), mais comprend également de vastes champs de drumlins et des systèmes d'eskers bien développés. La Zone 3 est caractérisée par une couverture de matériaux de transport glaciaires relativement continue et généralement drumlinisée qui s'amincit vers l'extérieur; la Zone 4 comprend de larges bandes d'affleurements rocheux et une couverture minimale de matériaux de transport glaciaires.

Les types ou associations de formes de relief, la présence ou l'absence de formes de relief et la configuration des zones elles-mêmes sont conditionnés par les effets réciproques complexes de la dynamique glaciaire et de la géologie du socle. Les zones 3 et 4 sont surtout caractérisées par la quantité de matériaux disponibles pour la construction et subissent donc, de ce fait, l'influence de la géologie du socle. Les zones 1 et 2 sont davantage régies par la dynamique glaciaire, en particulier par la stagnation d'un mince inlandsis pendant la déglaciation. Pourtant même dans la Zone 2, la géologie du socle qui détermine les propriétés physiques des débris entraînés influe sur la façon dont la glace se déforme, par conséquent sur le type de forme de relief produite. En général, les sédiments moins déformables forment des moraines côtelées tandis que les sédiments plus déformables se retrouvent dans des drumlins. Contrairement aux drumlins, les moraines côtelées, dont la morphologie semble correspondre aux vestiges d'une structure intraglaciaire, n'ont peut-être été conservées que là où des sédiments connexes ont été libérés de la glace stagnante. C'est pourquoi la bordure extérieure de la Zone 2 pourrait délimiter la pleine étendue de la stagnation de l'inlandsis.

Les systèmes intégrés d'eskers tronqués et tributaires, dont l'accumulation dans des conduits à la base de la glace est due aux eaux de fonte plongeant vers le bas à partir de la surface, reflètent probablement la configuration d'écoulement des eaux de fonte à la surface de l'inlandsis. Cela semble indiquer de fait la stagnation de l'inlandsis pendant qu'il recouvrait encore une grande superficie.

INTRODUCTION

Map 24-1987, which accompanies this report shows six major landform/sediment associations around the Keewatin Ice Divide, northwestern Canadian Shield: 1) eskers and associated glaciofluvial deposits, 2) drumlins and other glacially streamlined features, 3) ribbed (rogen) moraine, 4) low relief hummocky moraine, 5) major end moraine ridges, and 6) major drift-free or drift-poor areas. The area covered is underlain by Precambrian bedrock and extends from 60N to 68N and from Hudson Bay to just beyond the western limit of the Canadian Shield—an area of approximately 1 190 000 km^2 (113 NTS 1:250 000 sheets; Fig. 1). To put this size in perspective, the area is roughly equal to that of the Fennoscandian Peninsula (Finland, Sweden, Norway), is larger than the entire area of continental glaciation in the United States, and is slightly larger than Ontario but slightly smaller than Quebec.

Two major projects undertaken by Geological Survey of Canada personnel provided the impetus for this compilation of glacial features. The first was a discussion of the glacial geomorphology of the Canadian Shield—a geomorphological system dominated by the last continental glaciation (Shilts, et al., 1987). The other was the compilation of data for a surficial materials map of Canada at 1:5 000 000 scale (R.J. Fulton, in preparation).

Although much of the District of Keewatin has been mapped in great detail, in some cases based on literally thousands of ground observations and samples, other vast areas of the northwestern Canadian Shield have been mapped only at the broadest reconnaissance level during the helicopter surveys of the late 1950s and early 1960s (Blake, 1963; Craig, 1960, 1961, 1964, 1965; Fyles, 1955). Indeed, some regions have been mapped only at the scale (1:5 000 000) of the Glacial Map of Canada (Prest et al., 1968). Wherever possible,

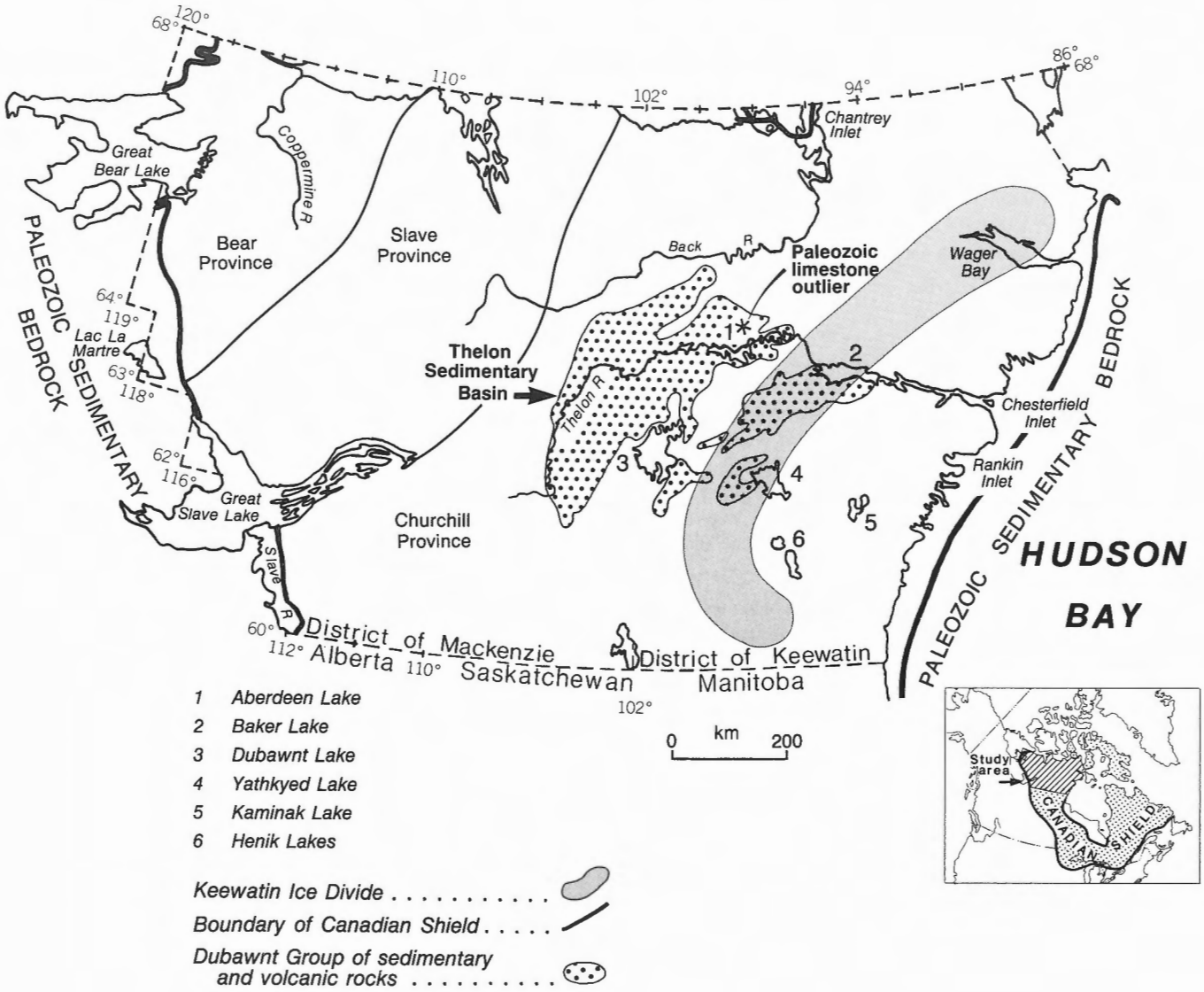


Figure 1. Location map.

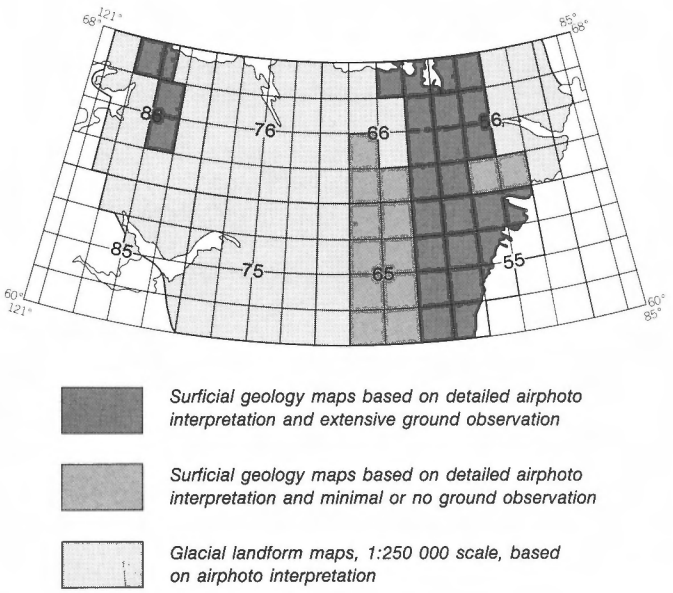


Figure 2. Compilation sources (see Map 24-1987 for complete references).

the present compilation was derived from published maps or from authors' manuscript maps at 1:250 000 or larger scale (Fig. 2). Approximately 30% of the area was compiled from detailed surficial materials maps based on interpretation of 1:60 000 scale airphotos and on extensive ground checking (most of District of Keewatin and Coppermine River area). A further 10% was compiled from surficial materials maps with minimal or no ground checking beyond the archival field notes of earlier geologists (southwestern Keewatin). The remaining 60% of the region was compiled at 1:250 000 scale from interpretation of 1:60 000 scale airphotos. The latter maps, although incomplete in terms of full coverage of the surficial geology, are both complete and detailed for the six specific glacial features. Deposits on much of this part of the Canadian Shield are unobscured by tree cover and are texturally distinguishable by associated permafrost patterns; therefore, airphoto interpretation allows a detail of mapping that is unattainable in more southerly locales where forest cover obscures both landforms and sediments.

BEDROCK GEOLOGY

The Canadian Shield is a geologically complex terrain in which rocks were deposited, formed, and deformed over a time span encompassing more than three-quarters of the known geological history of the Earth. Most of the region is characterized by vast tracts of massive granitoid gneiss, the earlier lithologies and structures of which have been obliterated by metamorphism and granitization (Fig. 3). The granitoid gneiss is interrupted in places by plutonic bodies, particularly in Slave Province, and by curving belts of sedimentary rock, gneisses derived from sedimentary rock, and volcanic strata.

Upper Proterozoic unmetamorphosed sediments outcrop northeast of Great Bear Lake and in the Thelon basin near the centre of the region. The latter basin is underlain by Dubawnt Group, comprising unmetamorphosed, flat-lying sedimentary and volcanogenic rocks (Fig. 3, inset). The western edge of the region and the area west of Chantry Inlet are underlain by relatively soft Paleozoic rocks.

Before discussing the glacial geomorphology of the Canadian Shield, it is appropriate to make some general observations of the bedrock geological factors that have influenced the nature and distribution of glacial landforms and sediments. The widespread recrystallization related to metamorphism has produced rocks that are physically hard. Therefore, the glaciers that passed over most of the Canadian Shield traversed a hard substrate that yielded relatively little debris through glacial erosion. Notwithstanding the above generalization, some areas of the Canadian Shield yielded abundant glacial debris and probably played major roles in influencing the dynamic behavior of the ice sheet. In the centre of the region, the Thelon sedimentary basin, filled with Upper Proterozoic, unmetamorphosed, flat-lying sedimentary and volcanogenic rocks of the Dubawnt Group, was the source of large volumes of clastic sediment produced through glacial erosion of the generally poorly consolidated outcrops (Fig. 3). These sediments were dispersed widely over adjacent crystalline terrane. The significance of this major source of sediment as well as that of another region underlain by relatively unmetamorphosed sedimentary rock northeast of Great Bear Lake (Fig. 3) will become apparent later in this discussion.

GLACIAL LANDFORM ASSEMBLAGES

The most striking feature of the distribution of glacial landforms on the northwestern Canadian Shield is the apparent arrangement of these landforms in roughly concentric zones about the Keewatin Ice Divide.

The Keewatin Ice Divide (Lee et al., 1957; Lee, 1959) was the highest area on the western part of the Laurentide Ice Sheet. It was a roughly north-south oriented region from which ice flowed in all directions. The Keewatin Ice Divide bisects a broad elongate area with distinctive glacial morphology. It stretches from near the Manitoba-Keewatin border to the vicinity of Wager Bay–a distance of about 700 km. It originally was recognized as an ice divide because oriented features showed it to be the region on the west side of Hudson Bay toward which the western sector of the Laurentide Ice Sheet shrank. In addition, from dispersal patterns of distinctive rock types, striations, and the general pattern of glacial landforms, this region can be seen to have served also as a long-lived dispersal centre for Keewatin Ice. Although the dispersal centre migrated eastward and southward during its existence, and undoubtedly had many more offshoots and irregularities than apparent in its final form, it probably migrated no more than 100 km, and its final location is a reasonable approximation of its general position throughout the last glaciation. This assumption is based on the general patterns of dispersal of rocks from the Thelon sedimentary

basin and on the complete lack of any evidence of southward transport of distinctive limestone erratics from a small outlier of Paleozoic bedrock that lies just north of Aberdeen Lake (Fig. 3, 4).

Characteristic suites of glacial landforms radiate outward to form four landform/sediment zones, roughly concentric about the Keewatin Ice Divide (Fig. 5). Each of these zones and their characteristic landforms will be fully discussed in following sections. Briefly summarized, the innermost zone (Zone 1) includes the Keewatin Ice Divide. It is characterized by featureless—that is, lacking prominent landform characteristics—till plains or low hummocky moraine and an absence of eskers. Zone 2 is characterized by the presence of well developed linear trains of ribbed moraine, which radiate from the divide like spokes of a wheel and alternate laterally with long trains of streamlined features. Zone 3 is characterized by a fairly continuous cover of drift, commonly till, which thins to a discontinuous veneer in the outer portion of the zone; drumlin fields are common in the inner half of this zone. The outermost zone (Zone 4) comprises extensive areas of massive crystalline bedrock outcrop that are nearly devoid of drift.

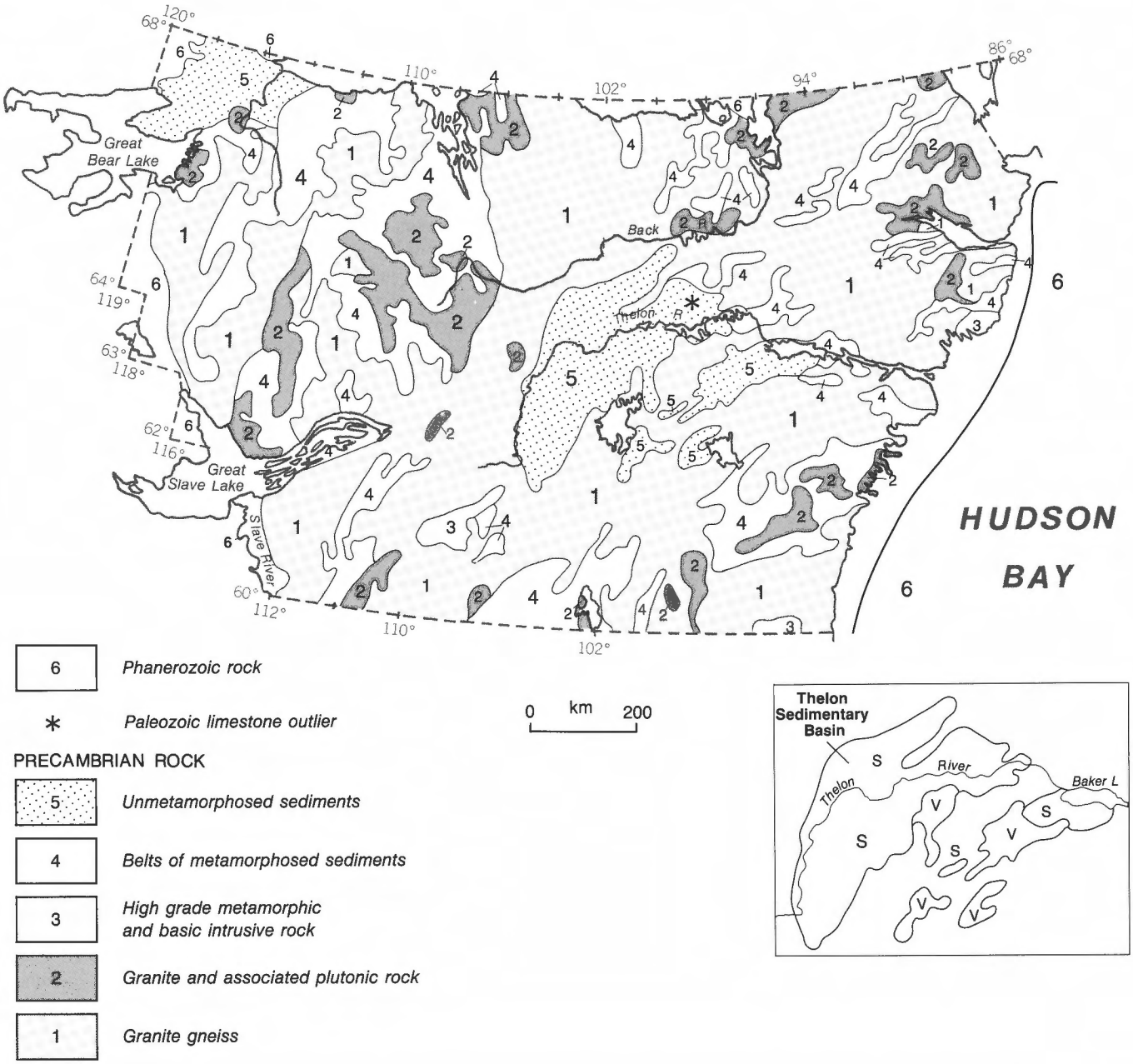


Figure 3. Generalized bedrock geology of the area around the Keewatin Ice Divide (modified from Douglas, 1968). The mainly crystalline bedrock of this region was generally resistant to glacial erosion. Note location of Dubawnt Group of unmetamorphosed sedimentary (s) and volcanic (v) rocks (inset). The sedimentary lithologies were particularily susceptible to glacial erosion.

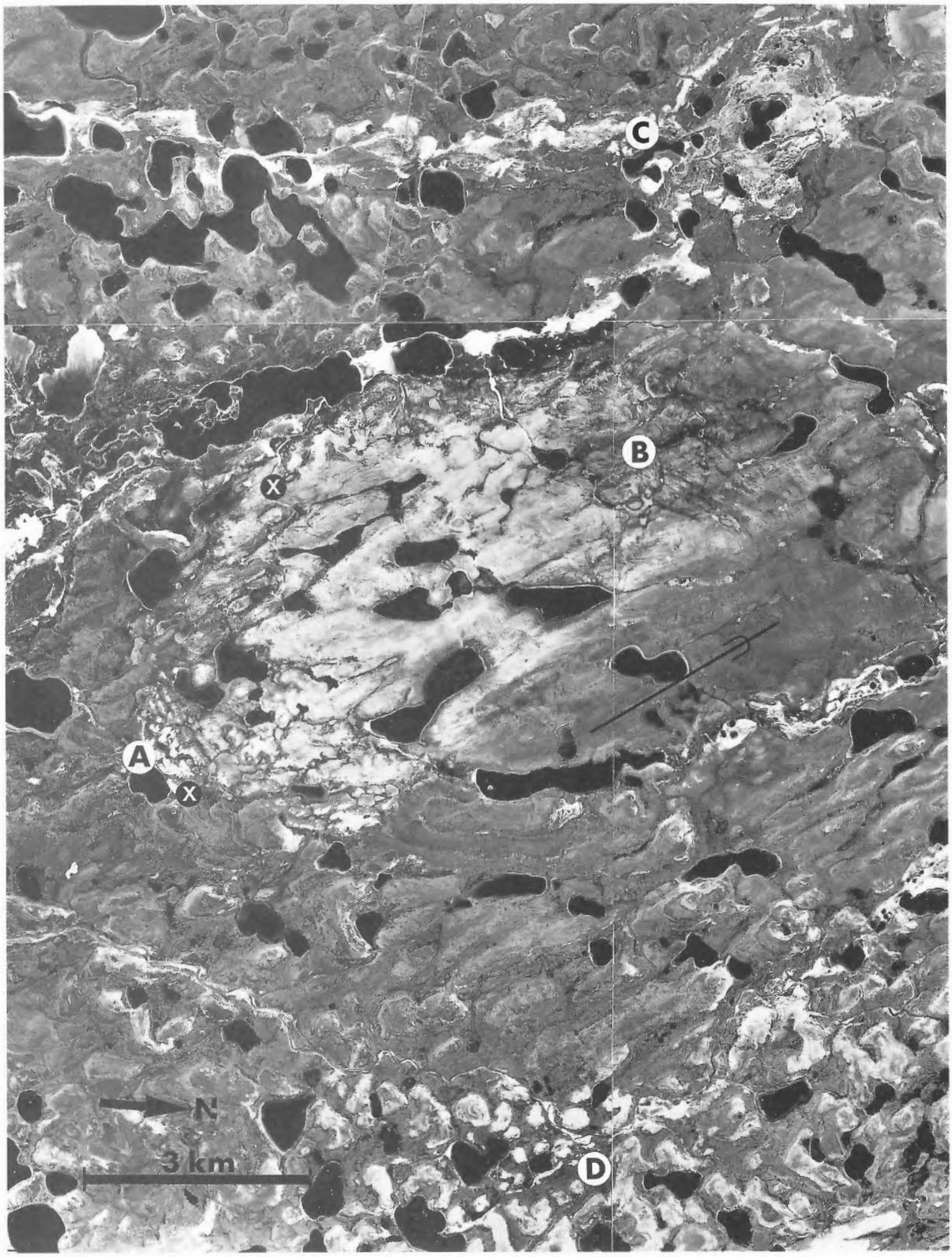


Figure 4. Lack of vegetation on an isolated outlier of Paleozoic limestone with associated carbonate-rich till causes the light-toned area in the centre of the figure. The only two known carbonate outcrops are marked "X". Carbonate erratics are absent immediately south (at A, up ice) of this outlier implying that ice flow was northward. The carbonate-rich till is rapidly diluted northward, although at B carbonate erratics are still abundant. Similar vegetation-poor areas in the large esker complex (C) and on ribbed moraine (D) are caused by the lack of nutrients in gravel and till almost wholly composed of orthoquartzitic debris from the Thelon sedimentary basin to the south. No carbonate erratics were observed on the esker. NAPL A15329-82,83,126,127

Some zones seem to relate to the dynamics of the ice sheet and the style of deglaciation whereas other zones seem to relate at least partially to the geology of the glacier bed. The pattern of drift cover appears at first glance to be a function of changing ice dynamics away from the ice divide. However, this may be only an apparent relationship because a large area of very easily erodible bedrock (Fig. 3) occupies the Thelon sedimentary basin near the centre of the ice sheet. Here as elsewhere, distribution of glacial landforms and sediment is closely related to geology. Because of this interplay between ice dynamics and bedrock geology it is most useful to begin the discussion at the outermost zone and progress inward towards the ice divide.

Zone 4: the drift-poor zone

The outermost zone comprises extensive areas of massive, crystalline bedrock outcrop that are nearly devoid of drift (Fig. 6, 7). Even eskers, which are well developed on either side of this zone, gradually disappear westward from Zone 3 over this sediment-poor area. The lack of drift in Zone 4 is probably related to the relative resistance to glacial erosion and consequent lack of sediment production of the underlying crystalline bedrock. Debris dispersed from the less resistant rocks lying closer to the centre of the ice sheet apparently had been largely removed from the base of the glacier by the time it reached this area. Although similar glacial dynamic processes may have occurred here as occurred elsewhere, no depositional record could be left because of the lack of debris in the ice. The projections of relatively continuous drift cover that extend northwestward along lowlands through the drift-poor zone may represent trains of debris eroded from the poorly consolidated sedimentary rocks of the Thelon sedimentary basin and transported preferentially along the lower elements of the landscape. West of Zone 4, in the area underlain by "softer" Paleozoic bedrock, glacial deposits are continuous and varied again.

Zone 3: the outer drift zone

Zone 3 is characterized by an intricate dendritic pattern of eskers and a drift cover, commonly till, which thickens from a discontinuous veneer in its outer portion to a fairly continuous mantle of drift over the rest of the zone. Extensive fields of drumlins and other streamlined forms occur, particularily in the inner part of the zone (Fig. 8).

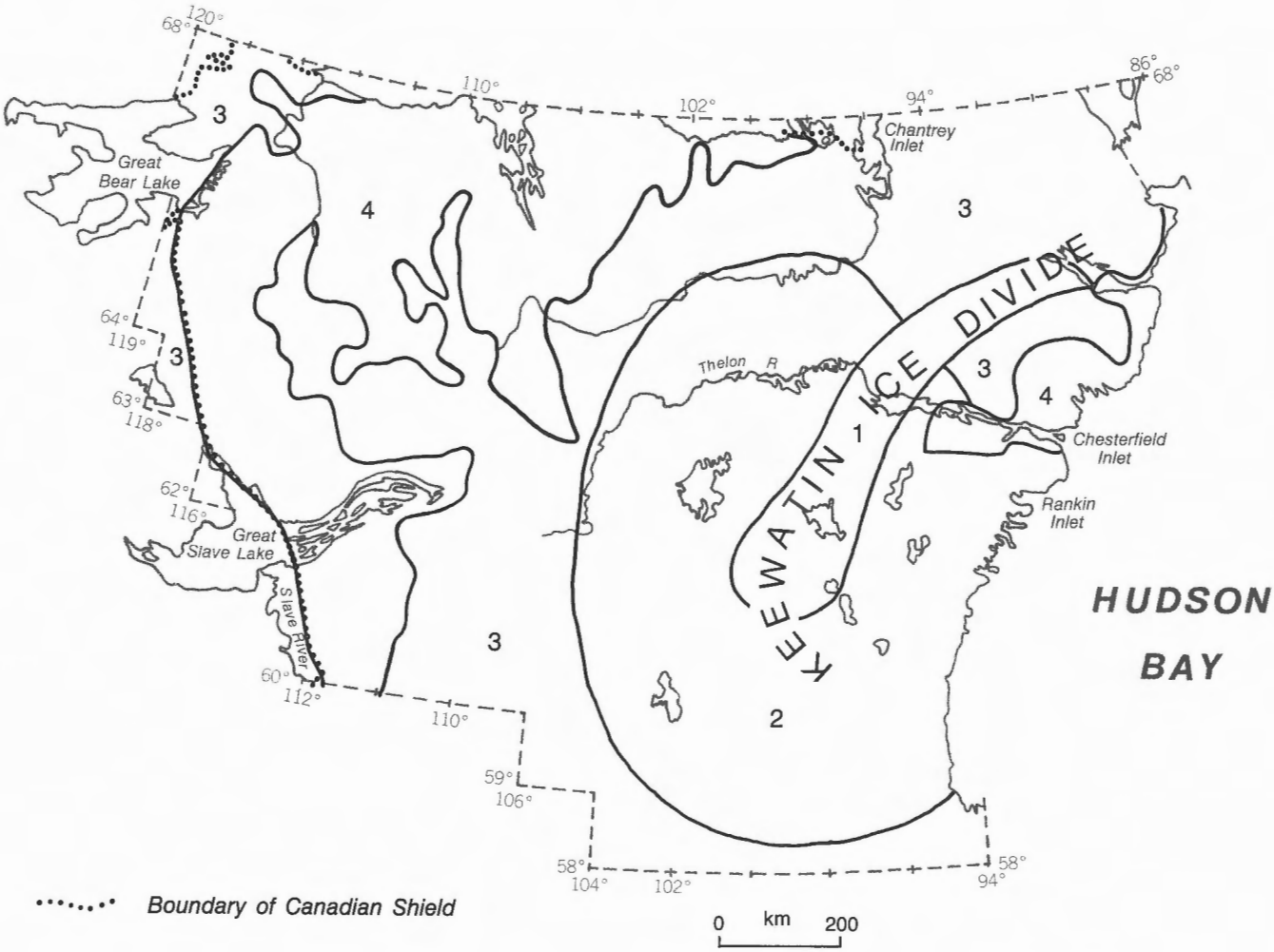


Figure 5. Glacial landform assemblages define four zones that are concentric about the Keewatin Ice Divide (modified from Shilts et al., 1987). The map is extended to the south to show southern limit of Zone 2.

The drumlin form is typically much more elongate than the classical shape described in textbooks. Individual drumlins or flute ridges can attain lengths of more than 1 km, but are rarely more than 100 m wide. North of Dubawnt Lake individual flutes are up to 20 km long and less than 250 m wide (Fig. 9). Drumlins and other streamlined features usually occur in fields, and the fields themselves are noticeably elongated in the direction of ice flow. Fields may curve, following regional ice flow patterns and, in rare cases where the converging flow was particularily intense, individual drumlins may be noticeably "bent".

The most spectacular fields of streamlined features on the Canadian Shield are developed within and down-ice from the Thelon sedimentary basin, where intense glacial erosion of poorly consolidated, unmetamorphosed clastic sedimentary rocks produced large quantities of glacial sediment (Fig. 8, 9). Drumlin fields also extend from lake basins, which for a variety of geological reasons were easily eroded, providing abundant debris that was formed into drumlins down-ice from the basin.

The concentricity of this zone about the Keewatin Ice Divide may reflect as much the presence of easily eroded outcrops between it and the divide as it reflects regular change of glaciodynamic conditions away from the divide. Terrane similar to Zone 3 occurs northwest of Zone 4 on the unmetamorphosed Proterozoic sedimentary rocks located northeast of Great Bear Lake and also on the Paleozoic rocks west of the Paleozoic-Precambrian contact. The similarity of sediment/landform associations in those areas to those in Zone 3 suggests that the high production of glacial debris is more important in forming bed characteristics than dynamic conditions within or under the ice. Similar glacial landform assemblages in the geologically similar Proterozoic Athabaska sedimentary basin have been interpreted by Shaw (1983) and Shaw and Kvill (1984) to be evidence of the action of sub-ice meltwater floods. We believe that there is no evidence in the Northwest Territories to warrant this conclusion. The intricate esker patterns and the scarcity of ribbed moraine within Zone 3 do suggest, however, that this zone differs in some dynamic way from adjacent Zone 2. Esker systems (discussed below) reach their maximum development of dendritic drainage systems within this zone.

Zone 2: The zone of ribbed moraine

Zone 2, a 200-250 km wide, U-shaped belt that wraps around the southern end of the Keewatin Ice Divide, is characterized by well developed, linear trains of ribbed (rogen) moraine which radiate from near the vicinity of the Keewatin Ice Divide and extend along former flow lines. The abrupt up-ice and less abrupt down-ice ends of the trains of ribbed moraine define the limits of Zone 2 (Fig. 10). The zone is also characterized by radiating esker-outwash systems and linear drumlin fields. Both of these latter features commence near the inner margin of Zone 2 but extend well beyond this zone.

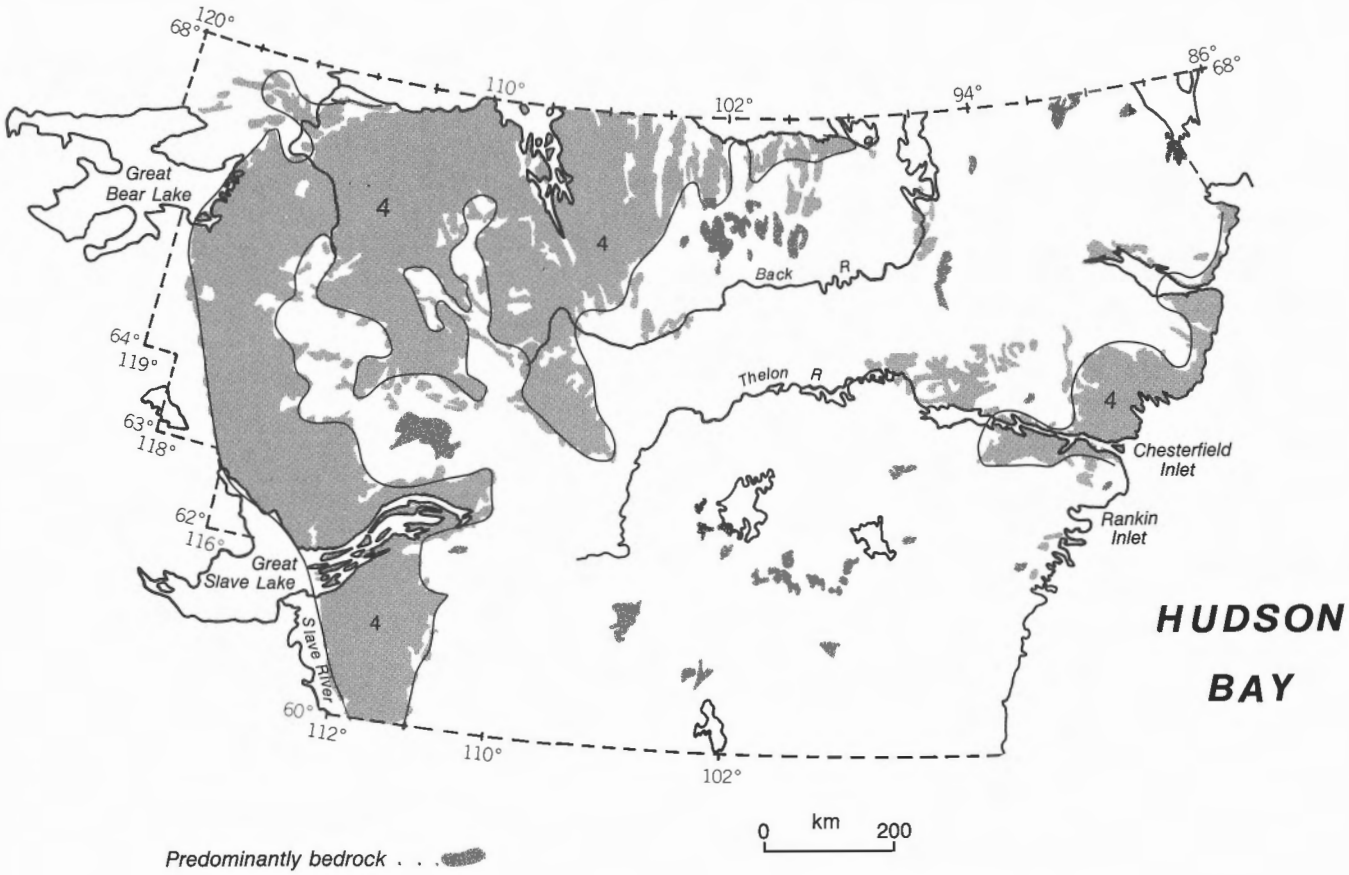


Figure 6. The drift-poor area of Zone 4 and other predominantly bedrock areas.

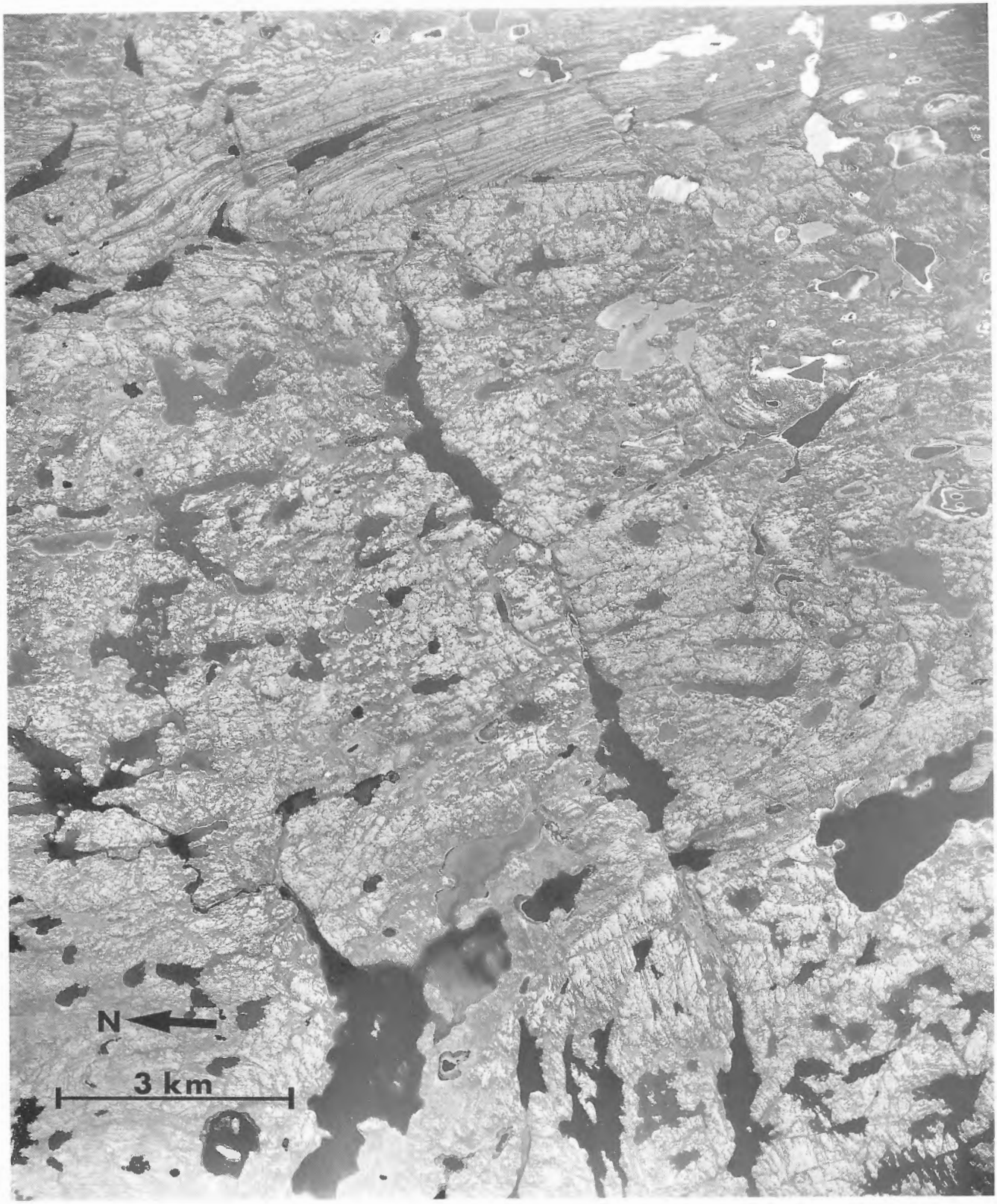


Figure 7. A typical area within Zone 4 of crystalline rock outcrop with discontinuous thin patches of drift. In this example, north of Great Slave Lake, the bare rock surface consists of highly deformed greywacke (east) intruded by granodiorite (west). Drift is restricted to small hollows and is commonly covered by peat. NAPL A13781-102

Classic ribbed moraine, also known as rogen moraine, comprises nested series of short, sinuous ridges, which, individually, trend roughly perpendicular to ice flow (Hughes, 1964; Cowan, 1968; Elson, 1969; Lundqvist, 1969; Shilts, 1977; Shaw, 1979; Bouchard, 1980). The ridges are generally less than 2 km long and less than 10 m high with an irregular crest height. They are in some places asymmetric in cross-section, having a steeper down-ice side. These classic forms are closely associated with less well defined ridges or irregularly shaped hummocks of similar composition and relief which we consider to be simply poorly developed or "broken" ribbed moraine.

Ribbed moraine is commonly formed of till associated with dense concentrations of boulders, which may mantle the till or be intermixed with it. Less commonly the moraines may be formed of reworked sand and gravel derived from overridden proglacial outwash, such as is thought to be the case for the eastward-trending train south of South Henik Lake, District of Keewatin. Prominent trains of ribbed moraine are also formed of sediment almost entirely composed of disaggregated debris from the friable sandstones and conglomerates of the Thelon sedimentary basin. There is so little foreign debris in these ridges that they are composed almost exclusively of orthoquartzite clasts, quartz sand, and kaolin, with so few nutrients that vegetation does not grow on many of them (Fig. 4).

Almost all of the ribbed moraine on the northwestern Canadian Shield occurs within Zone 2 where it forms linear trains radiating from the Keewatin Ice Divide like the spokes of a wheel. Similar belts also can be distinguished in the vicinity of the Labrador and Scandinavian ice divides (Shilts et al., 1987; Lundqvist, 1969). In Keewatin the commencement of the fields of ribbed moraine is abrupt, with virtually no transition from the featureless terrain near the ice divide. Where best developed, ribbed moraine distribution is little influenced by topography, occurring in some places on tops of isolated hills. Where the trains become separated, ribbed moraine occurs preferentially in shallow depressions with featureless or drumlinized till plains between the trains. In general, the down-ice limit of the zone of ribbed moraine is abrupt, although isolated, small, linear trains occur locally farther down-ice.

A close spatial relationship has been observed between ribbed moraine and drumlins or similar streamlined features. Although trains of ribbed moraine and trains of drumlins may

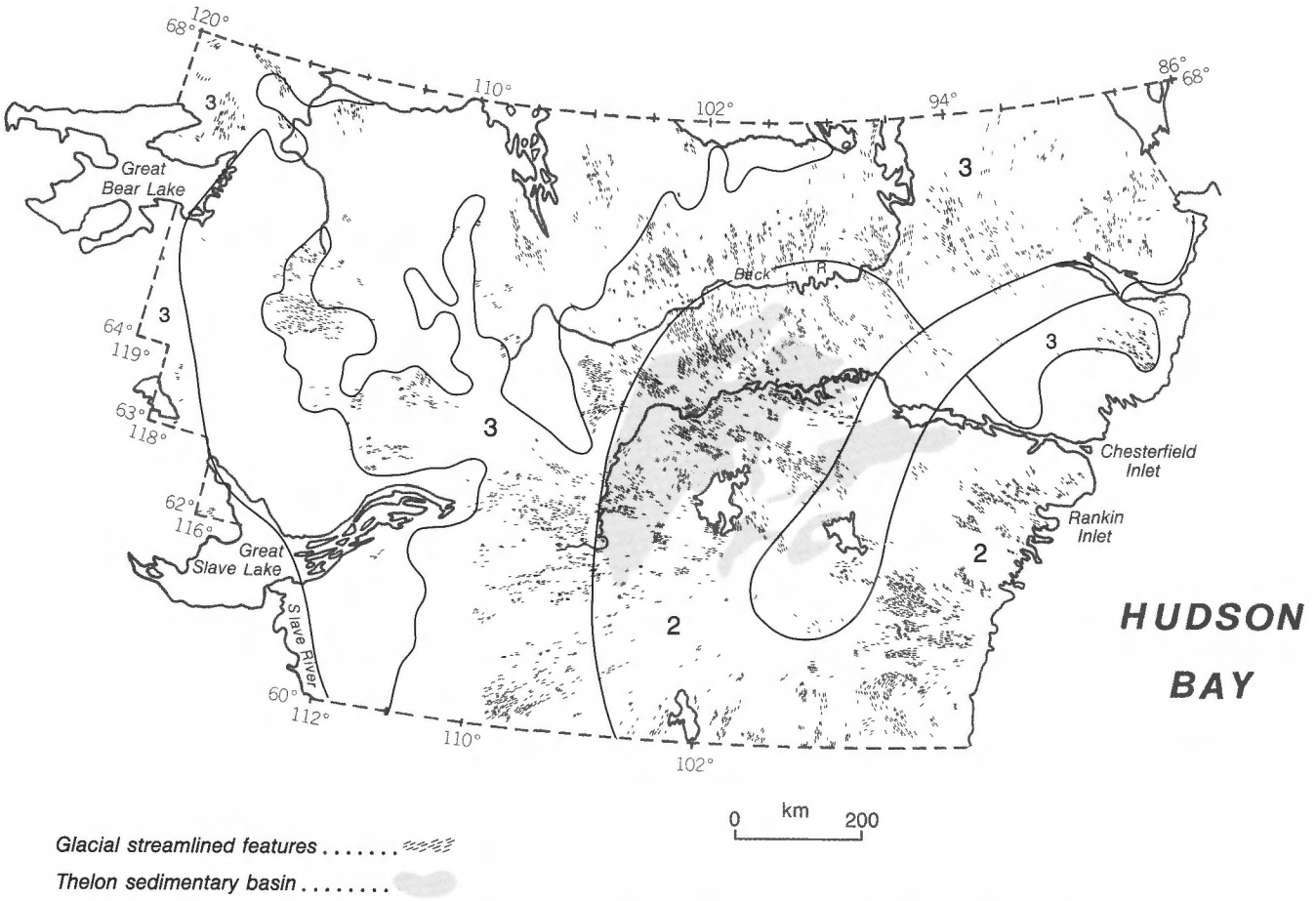


Figure 8. Drumlins and other streamlined features are generally restricted to Zones 2 and 3 (modified from Shilts et al., 1987). Note the location of the Dubawnt Group sedimentary rocks of the Thelon sedimentary basin, an easily erodable source of clastic sediment.

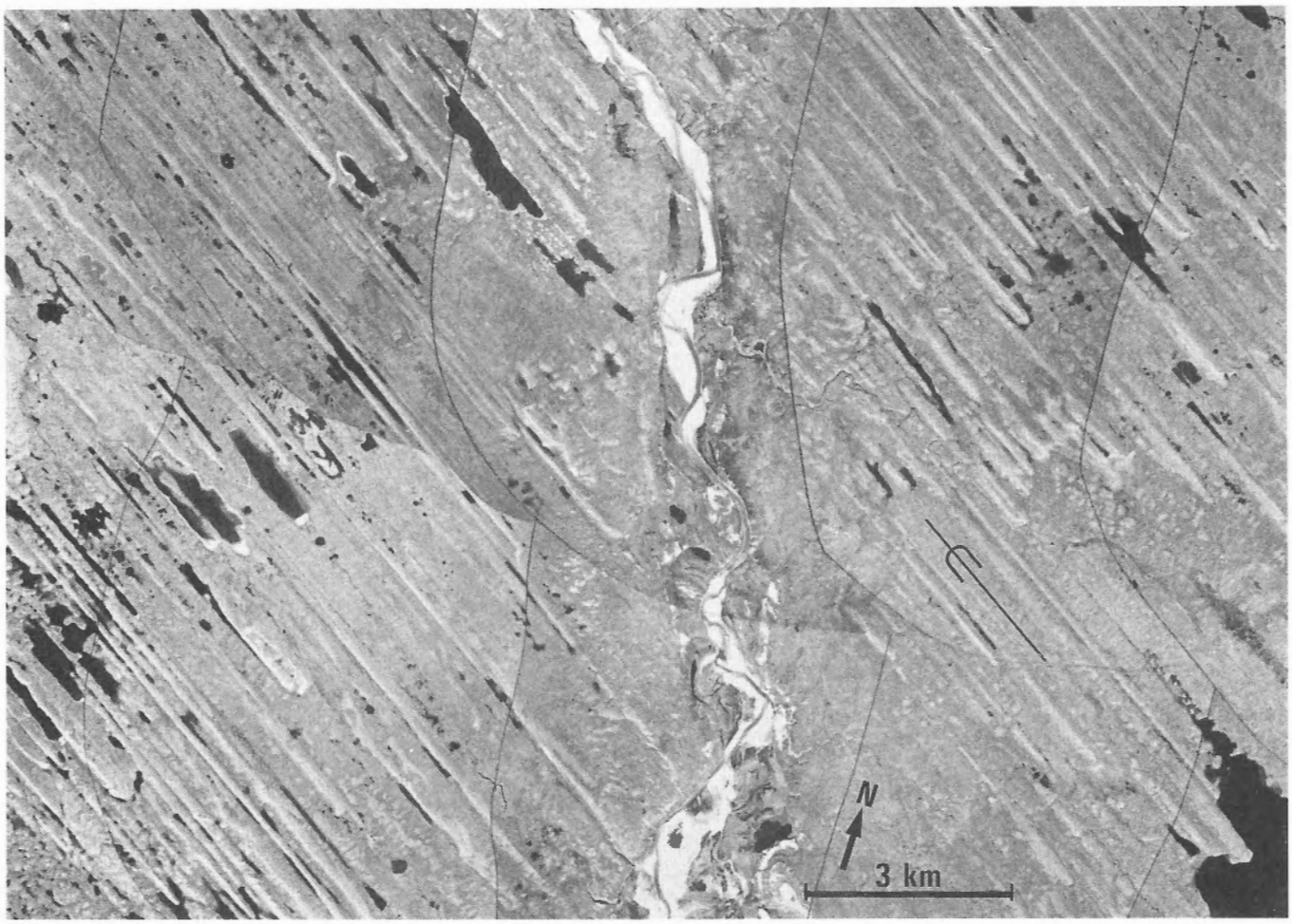


Figure 9. Spectacular fluting, northwest of Dubawnt Lake, developed on the friable sandstones of the Thelon sedimentary basin. NAPL RE 11662-5 N1/2

pass down-ice one into the other, as is suggested in the Scandinavian literature (Lundqvist, 1969), the common overall pattern for the northwestern Shield—indeed the entire Canadian Shield (Shilts et al., 1987)—is lateral contact between alternating parallel trains of features, both radiating from the divide. This lateral juxtaposition may be either abrupt or transitional (Fig. 11). Where a transition zone exists, individual ribs are fluted or individual drumlins/flutings are broken up into rib-like ridges (Fig. 12, 13). Less commonly, isolated drumlins may occur within ribbed moraine and, even less so, ribbed moraine may occur between parallel flutings. In the latter case, individual ribs may stretch from flank to flank of the flutings.

Just as trains of drumlins extend from specific source areas, trains of ribbed moraine also extend from specific bedrock sources. For example, the large trains of ribbed moraine west of Rankin Inlet extend down-ice, southeastward, from outcrops of postglacially frost-shattered granite (Fig. 14). Large quantities of felsenmeer must have existed on these outcrops prior to the last glaciation and may have provided the dense boulder cover of similar lithology that mantles the trains of ribbed moraine (Fig. 15). In the boulder-free areas between the trains of ribbed moraine till has been formed into drumlins. This tendency for ribbed moraine to be associated with heavy concentrations of boulders and for drumlins to be relatively boulder-free has been observed throughout southern Keewatin.

Any theory about the origin of ribbed moraine must explain the implications of the relationship between ribbed moraine and proximity to the Keewatin Ice Divide, the close spatial relationship between drumlins and ribbed moraine within Zone 2, and the disparate compositional nature of the two groups of landforms.

The association with the ice divide implies some glaciodynamic control. Certainly the morphology of the ribbed moraine suggests formation under conditions of compressive flow. Although the cross-sectional asymmetry is not obvious everywhere, where it is developed the ridges have the aspect of inclined plates of sediment thrust one on top of another (Fig. 16). They are similar in composition and aspect to those described by Klassen (1982) at the snouts of modern glaciers on Bylot Island. This seems to suggest that they are a relict of englacial structure–debris transported along thrust zones in the ice. Such a form may be preserved only by slow

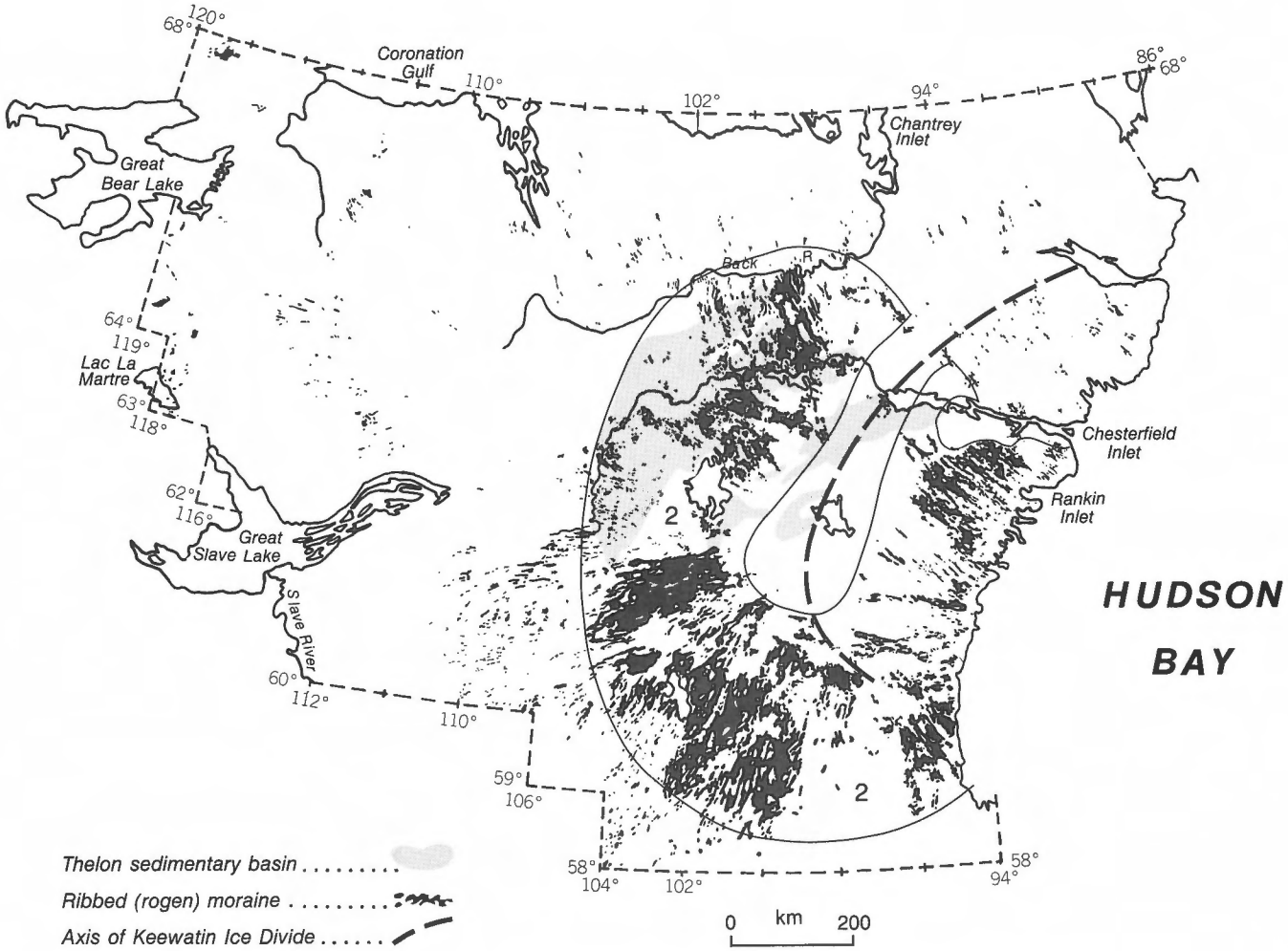


Figure 10. Ribbed moraine occurs predominantly in Zone 2; the map is extended to the south to show southern limit of ribbed moraine (modified from Shilts et al., 1987; Manitoba area adapted from Dredge et al., 1985 and Dredge and Nixon, 1986).

basal meltout from an ice mass with little or no internal movement and, as such, may be an indication of widespread stagnation.

Because of their close spatial relationship in Zone 2 and because both groups of landforms contain elements that reflect regional flow patterns of active ice, ribbed moraine and drumlins probably formed under similar glaciodynamic conditions at the base of the ice. Although basal stress conditions have been cited as responsible for formation of one or the other type of feature in Scandinavia (Lundqvist, 1969; Sugden and John, 1976)–ribbed moraine reflecting compressive ice flow and drumlins reflecting extensive ice flow–these arguments are insufficient to explain the close spatial relationship between the features, their association with specific source areas, and the paucity of ribbed moraine outside of Zone 2. It is our opinion that, although basal stress conditions are important, whether one landform or the other was developed was not so much a function of compressive or extensive ice flow as it was a function of the physical character of the debris the ice was carrying. More deformable sediment–in the absence of heavy boulder concentrations–formed drumlins or flutes, less deformable–gravel, crushed bedrock, bouldery debris from outcrops covered by felsenmeer–formed ribbed moraine. Thus, the critical dynamic basal conditions may have been controlled by the abundance and physical properties of the entrained debris, aspects which are themselves controlled by the nature of the source area. Whatever their origin, some model must be sought that explains not only the morphology of the features, but also the close spatial relationship between ribbed moraine and drumlins within Zone 2. The existence of drumlins beyond Zone 2 implies that drumlinized or fluted terrain is formed beneath the ice and is preserved regardless of the conditions of deglaciation, whereas ribbed moraine, whose morphology seems to be a relict of englacial structure, may be destroyed under all but those conditions associated with melting of largely stagnant ice. If this is the case, massive stagnation may have extended for considerable distances from the Keewatin Ice Divide just prior to final collapse of the Keewatin ice mass.

In essence, the outer margin of Zone 2 may represent the limit of massive stagnation of the Keewatin sector of the Laurentide Ice Sheet. Additional evidence of stagnation is

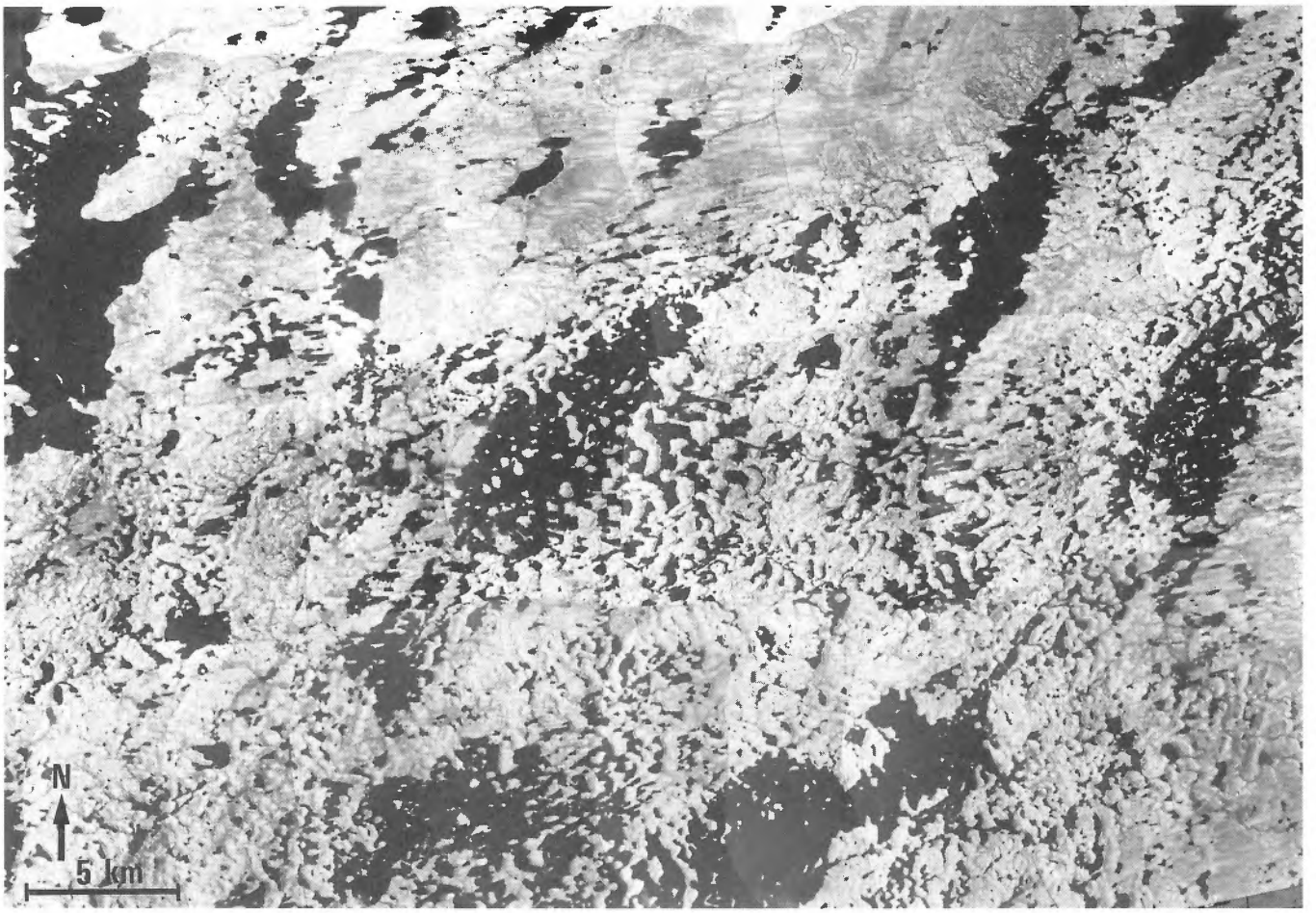


Figure 11. Abrupt contact between drumlinized till plain (to north) and large train of classical ribbed moraine southwest of Dubawnt Lake. NAPL RE 11662-6, east

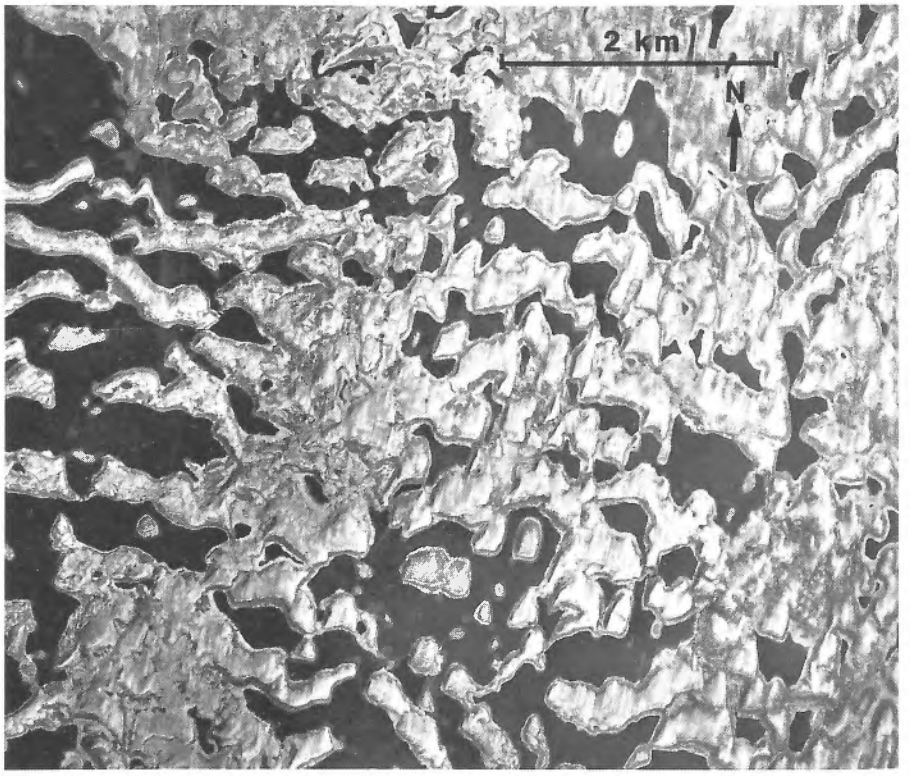


Figure 12. Fluted or drumlinized ribbed moraine deposited by ice flowing southward, southwestern District of Keewatin. NAPL A17180-106

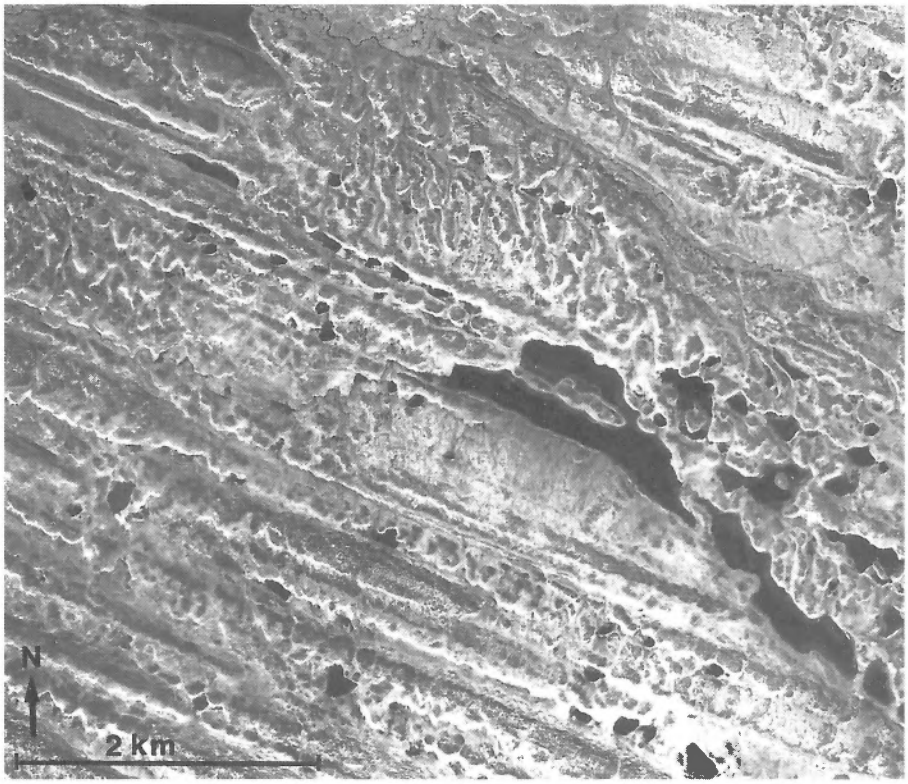


Figure 13. Drumlins or flutings partially broken up into ribbed moraine north of Dubawnt Lake. NAPL A15050-153

provided by the esker patterns. Briefly stated, eskers commonly cut obliquely across drumlin fields which were formed originally under active ice, and esker tributaries commonly join trunk eskers at right angles, implying that ice flow was sluggish or non-existent.

Within Zone 2 there are areas, interspersed with drumlin and ribbed moraine trains, where no organized glacial constructional landforms occur. These areas may reflect a sediment-poor part of the glacier bed, with the lack of sediment reflecting either the natural resistance of underlying or up ice lithologies to erosion or some dynamic condition at the base of the glacier which precluded significant glacial erosion. Alternatively, some may be satellite ice flow centres, the featureless terrain being similar to that which flanks the main ice divide.

Zone 1: The Keewatin Ice Divide and hummocky moraine

The innermost zone, which includes the Keewatin Ice Divide, is characterized by areas of low hummocky moraine and featureless plains, which in places are but a discontinuous veneer of till over bedrock. Within Zone 1, there is an absence of eskers and ribbed moraine and a paucity of streamlined features.

Small, low, rounded hummocks of till, less than 5 m high and 100 m across, cover much of the plain in the vicinity of the southern end of the Keewatin Ice Divide (Fig. 17, 18). They generally seem to be underlain by till similar in composition to material that is formed into drumlins in nearby areas and do not have the dense surface cover of boulders typical of ribbed moraine.

Although hummocky moraine is best developed in Zone 1 it is not restricted to that area. Similar, but less extensive, clusters of low hummocks occur west of Dubawnt Lake (Fig. 17). Small areas of hummocky moraine have been noted in places immediately adjacent to and within areas of ribbed moraine. The latter hummocks may have the boulder cover typical of ribbed moraine.

Hummocky moraine probably consists of debris released from the basal portions of a glacier that was almost totally stagnant. In the vicinity of the ice divide, flow velocities would have been low so little erosion and entrainment of debris would be expected. Before the divide migrated southeastward to this area, however, ice flow velocities would have been higher here, and, therefore, sediment would have been effectively eroded and entrained. The low flow velocities that existed in this area after the outflow centre migrated to it may have prevented the entrained sediments from being formed into the streamlined landforms that are typical of lithologically similar deposits down-ice.

Eskers and other glaciofluvial deposits

Most of the northwestern Canadian Shield is covered by an integrated pattern of eskers radiating outward from the area of the Keewatin Ice Divide (Fig. 19). A typical esker system begins as a series of hummocks or short, flat-topped segments which pass downstream into relatively continuous, large esker ridges or (rarely) beaded eskers; where they are discontinuous, esker segments are connected by areas of outwash, meltwater channels, or belts of bedrock stripped free of drift. The largest of the systems can be traced, with gaps, as far as 700 km, and unbroken lengths of individual esker ridges can be traced for up to 75 km.

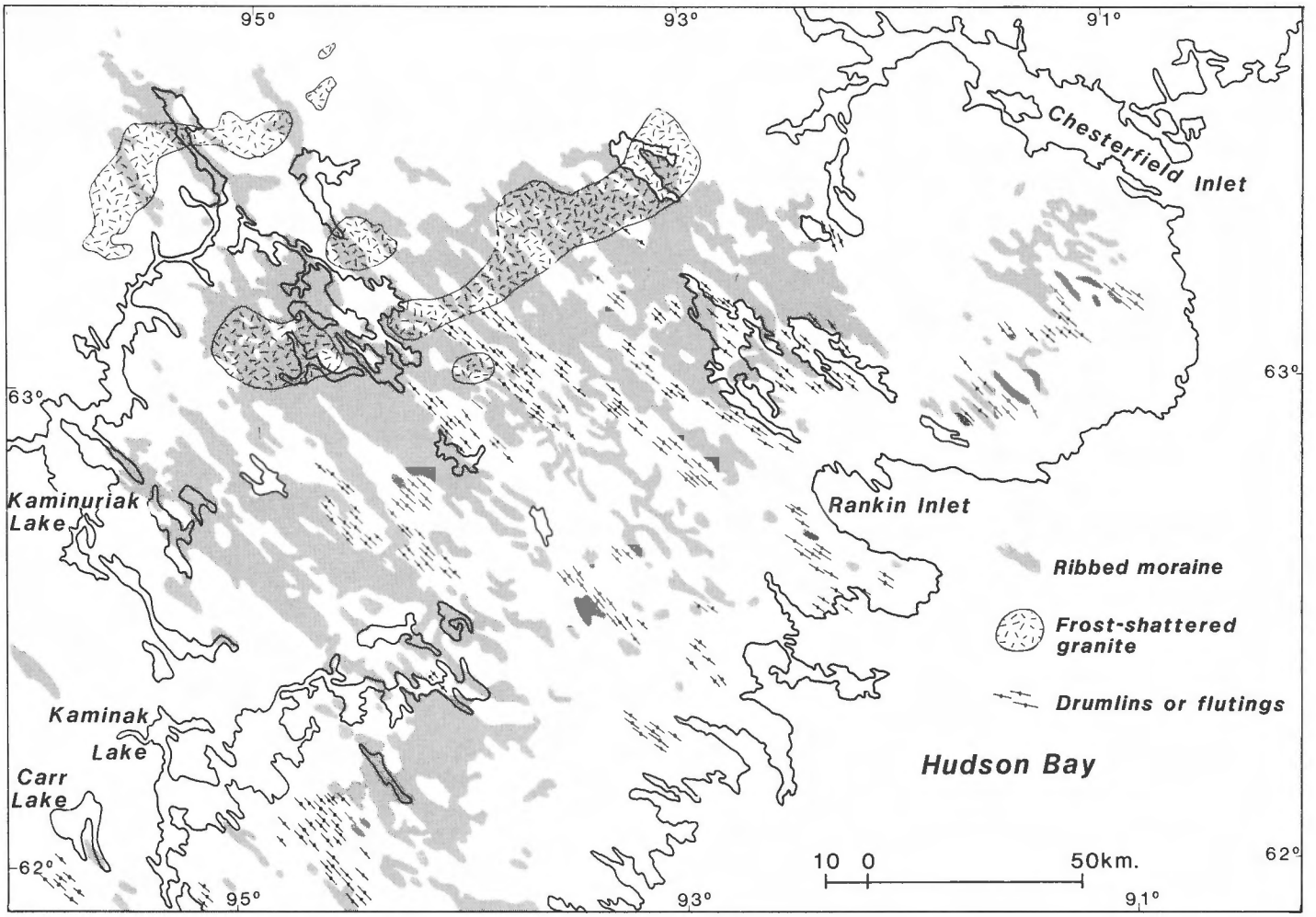


Figure 14. Trains of ribbed moraine extend from outcrops of granite particularly susceptible to frost-shattering (after Shilts et al., 1987). Surface of ribbed moraine is covered with granite boulders. Intervening boulder-free areas have drumlin fields. Note drumlin train extending from Kaminak Lake.

Throughout most of the area, eskers are sharp ridged and up to 40 m high, with conical knobs projecting here and there well above the average elevation of the esker crest. Along their length they may be interrupted in places by bulges where the single ridge splits into multiple ridges which coalesce downstream (Fig. 20). These bulges may be the result of greatly increased sedimentation in the esker tunnel, perhaps due to increased basal debris in that part of the ice sheet, to topographic irregularities of the glacier bed, or to slowing retreat of the ice front due to climatic deterioration. Whatever the cause, when the tunnel became blocked by sediment, a bypass tunnel formed. This process may have occurred repeatedly until the ice front retreated upstream, past the area of blockage.

Above marine limit and outside of areas inundated by proglacial lakes, eskers are commonly flanked by glaciofluvial outwash terraces that are scarred by channels and disrupted by kettle lakes (Fig. 20). In many areas, these terraces occur around basins presently occupied by lakes, presenting an apparent paradox: how can evidence of free flow be juxtaposed with obvious manifestation of blocked drainage? To

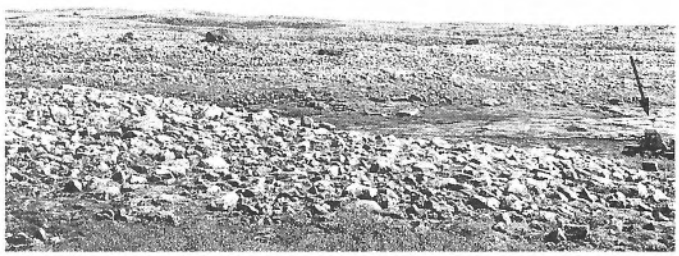


Figure 15. Ribbed moraine with extensive cover of granite boulders derived from outcrops west of Rankin Inlet (see Fig. 13). Note helicopter, indicated by an arrow, for scale. Photo by C.M. Cunningham, 1977, 77CC-4-1

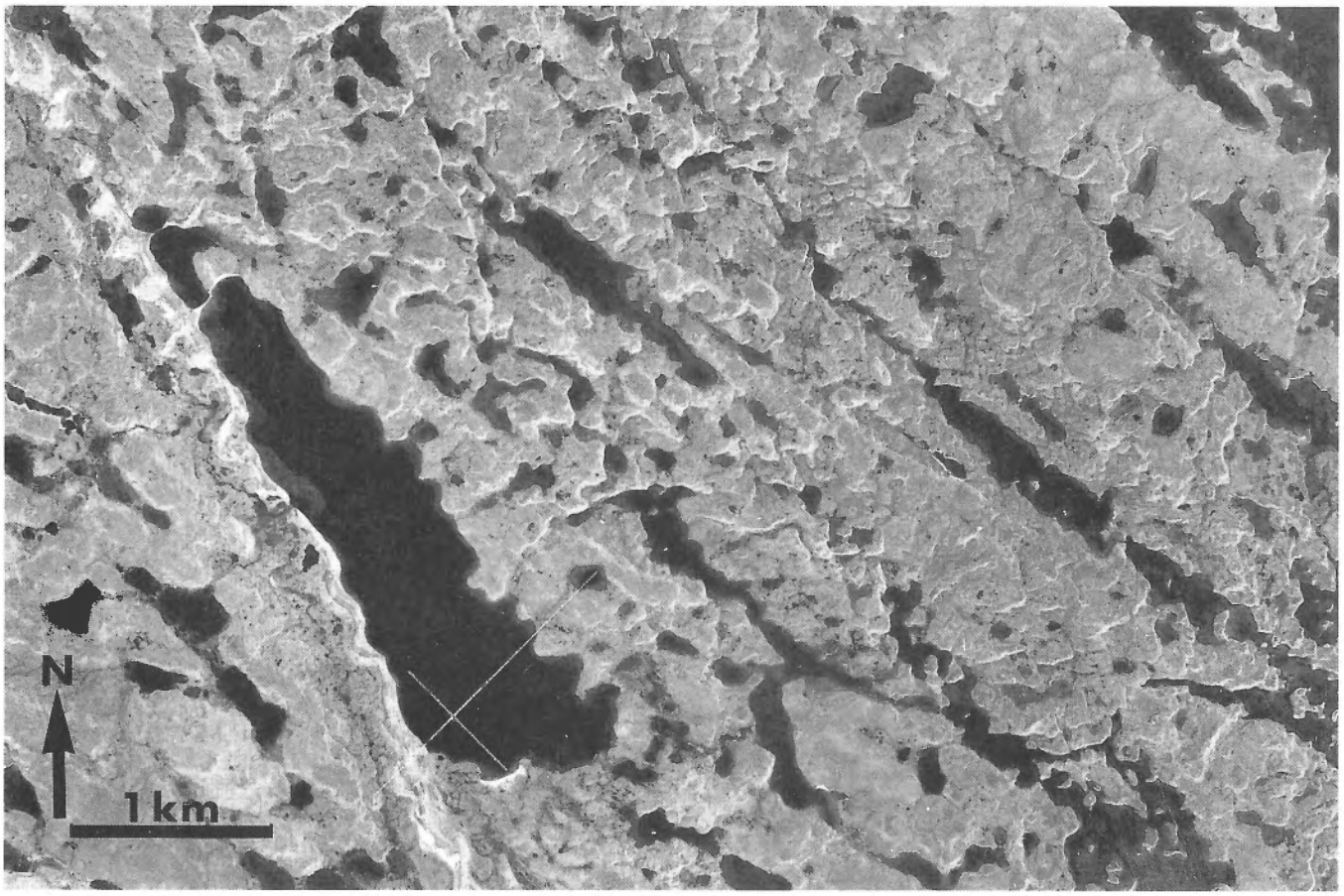


Figure 16. Asymmetric ribbed moraine deposited by ice moving from northwest to southeast, west of Rankin Inlet. Ridges have aspect of plates of boulder-covered till thrust one on the back of another, steep plate edges facing down ice. NAPL A14887-2

resolve the paradox, we have suggested that a thin (<25 m) mass of ice was left behind in depressions as the ice front retreated, probably due to the insulating effects of basal debris melting out of the surface of downwasting, largely stagnant ice (Shilts, 1984; Shilts et al., 1987). The terraces are remnants of outwash that was deposited, on the inactive esker ridge, "fossilized" in the thin ice, or against valley sides, by braided meltwater streams issuing from the esker tunnel mouth and flowing across a temporary ice floor (Shilts, 1984). Gradients of these surfaces were continually changing due to melting of remnant ice downstream and each terrace is truncated at the point where its upstream expansion in front of the retreating ice front was interrupted by abrupt downcutting related to this gradient adjustment. Where the "fossil" esker ridge projected through remnant ice, it was planed off or terraced by fluvial erosion or deposition to the level of the terrace or ice floor, leaving terrace-like benches or remarkably flat-topped esker segments in places (Fig. 21). Terrace fragments remain only where deposited on solid rock or drift on the valley sides or on the eskers themselves.

Below marine limit, eskers commonly were reworked by wave action during the offlap phase of the Tyrrell Sea. This has had the effect of subduing their relief to the extent that they rarely project more than 10 m above the adjacent terrain. Although sedimentation occurred adjacent to these submarine eskers, the well developed lateral terraces typical of those exposed in the subaerial environment are generally lacking and, where present, consist of thick, fine grained sediment deposited in deep water.

Many of the individual esker systems consist of a long trunk esker joined by simple, short tributaries at irregular intervals along its length. Just as commonly, individual esker systems reflect a well developed dendritic drainage pattern with both trunk and tributaries bifurcating upstream until they disappear near the ice divide. In these systems the major tributaries commonly roughly parallel the main trunk, only changing direction near the junction, to approach the main esker at a right angle. Thus, the overall pattern is of elongate, subparallel dendritic systems which radiate outward from the area of the Keewatin Ice Divide (Fig. 19).

Evidence of eskers cutting at an angle across other landforms which were created by actively flowing ice, and the common pattern of esker tributaries changing direction to approach the trunk esker at right angles, demonstrates that the ice sheet was at least locally stagnant at the time of esker deposition. Because of their lack of deformation and association with subglacial meltwater channels, it is evident that the eskers were deposited subglacially. However, it is improbable that an intricate network of tributary tunnels, in many cases independent of the influence of local topography, could

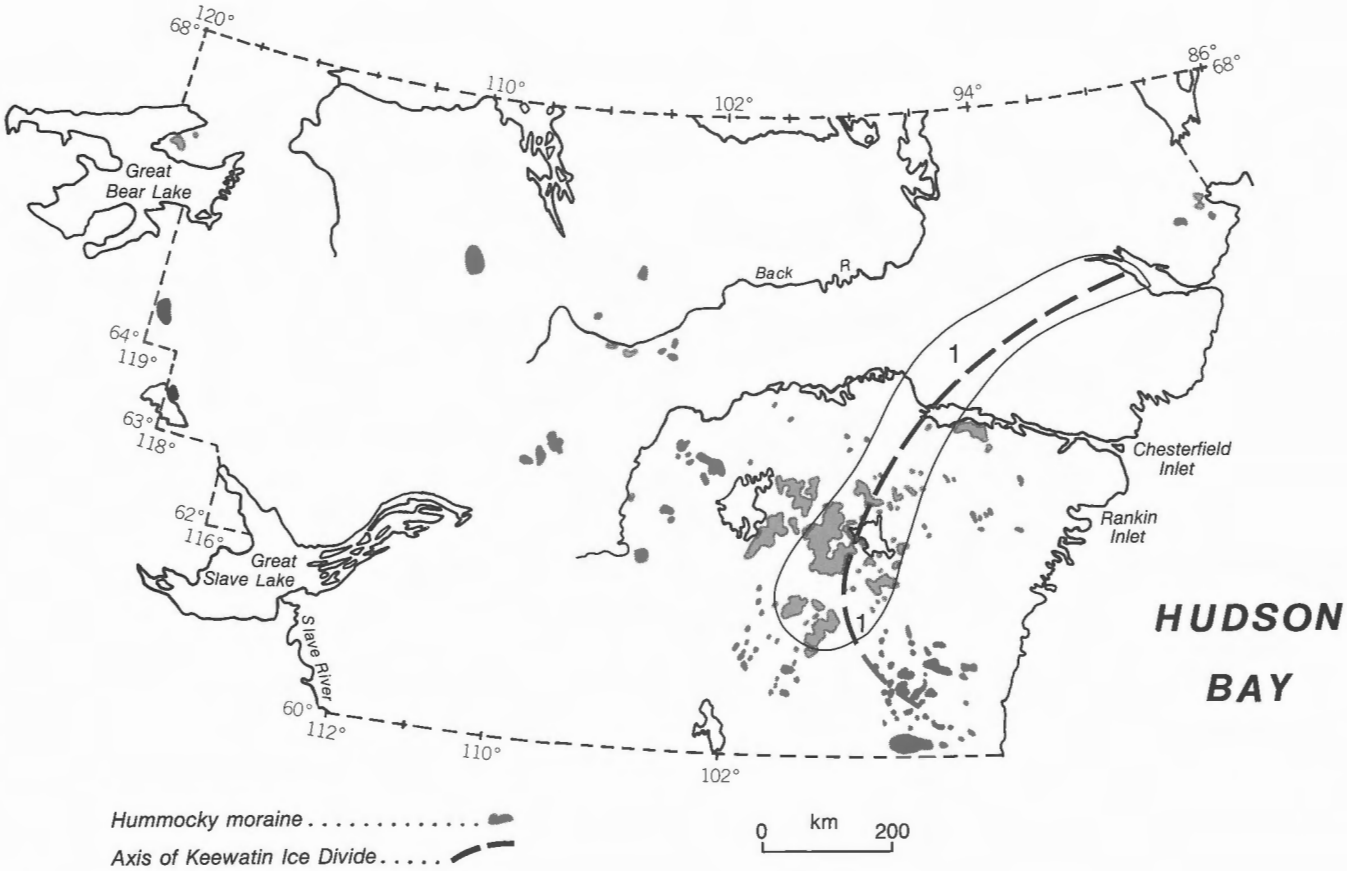
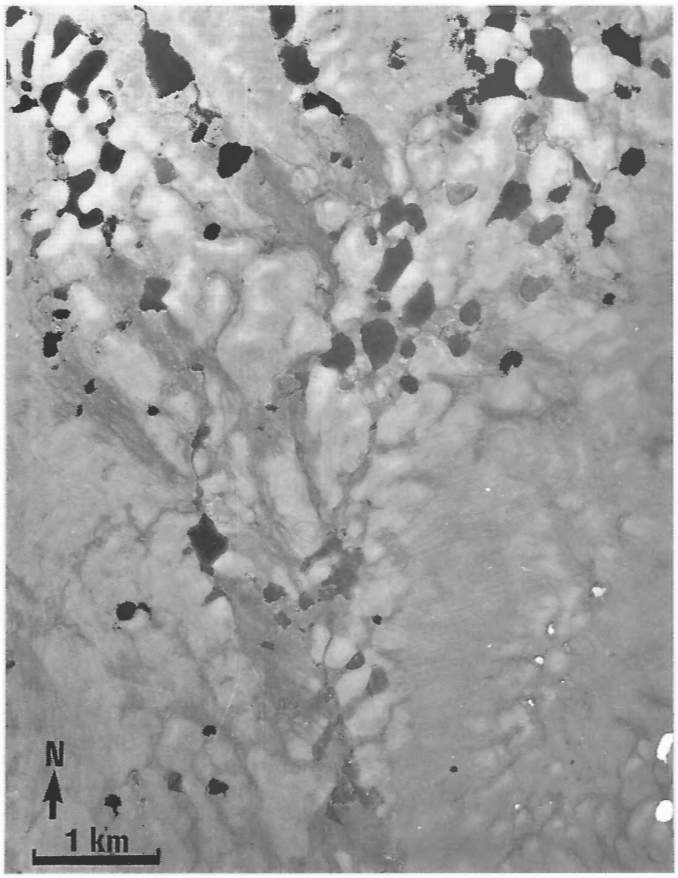


Figure 17. Distribution of hummocky moraine; it is best developed in Zone 1.



have been developed totally subglacially. Likewise, it is unlikely that such a system could have maintained open tunnels through the more plastic, thicker ice nearer the ice sheet's centre. It is more likely that the eskers were deposited in short meltwater tunnels, a few kilometres in length, by meltwater which only left the surface to plunge down to the glacier base near the brittle margin of the ice (Shilts, 1984; St-Onge, 1984). The tunnels would have migrated headward as the ice retreated, following the traces of surface drainage, thus accounting for regular bifurcation upstream and the general lack of control of subglacial topography (Shilts, 1984). A dendritic system is the natural pattern for the movement of water over a nearly level featureless plain such as the surface of a large ice sheet. The esker deposits themselves may mimic such a surface drainage pattern.

Although the pattern is by no means universal, there is a tendency for tributary eskers to join main eskers preferentially from the left, that is, from the north for those eskers deposited by eastward-flowing meltwater streams east of the Keewatin Ice Divide and from the south for those eskers deposited by westward-flowing meltwater west of the divide.

Figure 18. Low hummocky moraine, west of Yathkyed Lake, characteristic of terrain in vicinity of Keewatin Ice Divide. NAPL A14378-132

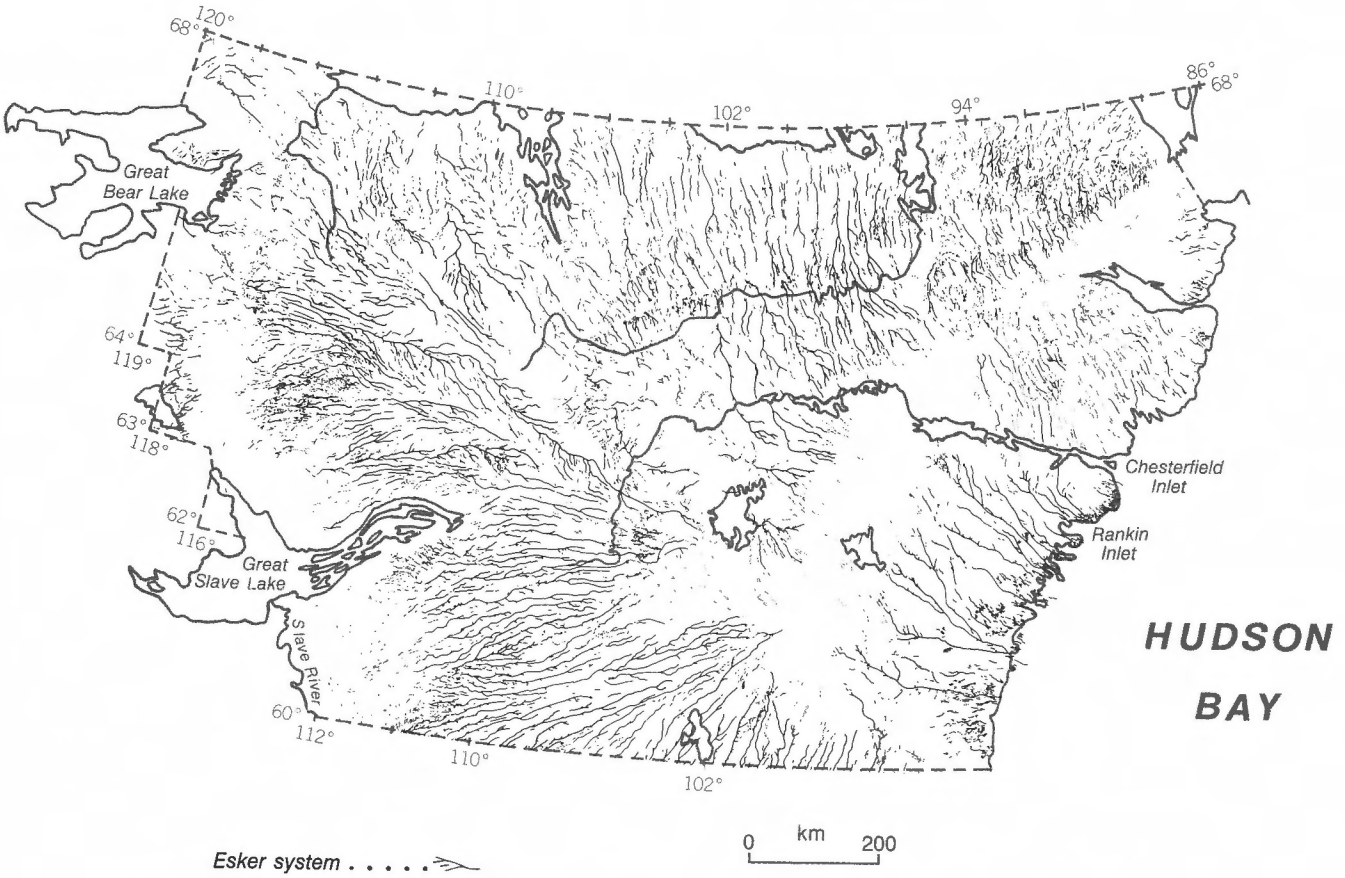


Figure 19. Distribution of eskers; in order to display better the pattern of features, esker segments have been joined where separated by meltwater channels (after Shilts et al., 1987).

The reason for the preferred direction of approach of tributaries (from the left) is unknown. Perhaps it reflects the influence of coriolis force on the movement of water on a large featureless plain—the surface of the ice sheet.

The lack of eskers in the westernmost part of the study area undoubtedly reflects a sediment-poor part of the ice sheet, due in all probability to hard, massive crystalline bedrock and diminished amounts of long-travelled debris. The esker systems are well developed again down ice from this resistant bedrock, on the more easily eroded Paleozoic sediments that flank the Shield to the west.

North of Back River, two prominent ice recessional positions are marked by belts, transverse to ice flow, of glaciofluvial deposits, formed by coalescing ice contact deltas or fans, outwash trains, and closely spaced short esker segments with distributaries (Fig. 22). In the vicinity of these features, short esker segments abound between the major systems, and major outwash trains parallel the inferred ice front. In other locations, unassociated with major glaciofluvial aprons, clusters of short, subparallel esker ridges occur between trunk eskers in 1 to 10 km wide bands that trend at right angles to general esker direction. In these bands trunk eskers may be interrupted by major subaqueous fans or deltas or short distributary ridges may fan out from them. Several clusters and sedimentary bulges occur along the Hudson Bay coast from Chesterfield Inlet southward to Eskimo Point. The eastern clusters may mark the ice front during a halt or slowdown in retreat and thus may correlate with the clusters of esker segments and outwash features that mark retreat positions northwest of the Keewatin Ice Divide.

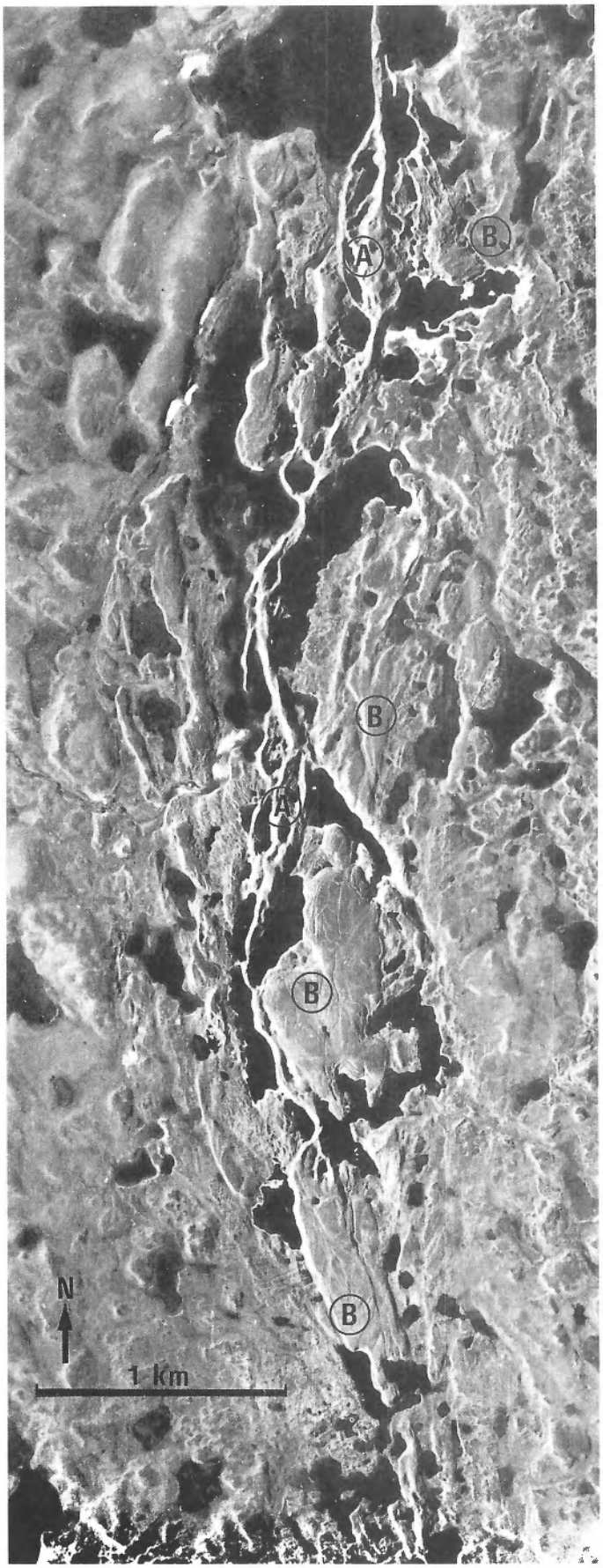
Major moraine ridges

End moraines as distinct ridges, rather than as glaciofluvial aprons, are not common on the northwestern Canadian Shield, although some occur in the northern and northwestern parts of the area (Fig. 22).

The largest end moraine system–the MacAlpine Moraine (Blake, 1963; Falconer et al., 1965)–comprises a complex of end moraine ridges in intimate association with aprons of coalescing glaciofluvial fans and deltas and clusters of eskers. Taken together, these ice marginal features mark a major recessional position. Deposits and landforms of the Chantrey Moraine System are similar to those of the MacAlpine system (Falconer et al., 1965; Dyke, 1984).

Although short in length, Twin Jugs Moraine (Blake, 1963) is a prominent feature of the landscape. It is associated with an extensive area of hummocky moraine and a few large eskers intersect it.

Moraines near the western margin of the Canadian Shield are less prominent. Except for their orientation parallel to



presumed ice front trends, they are indistinguishable from eskers on the basis of airphoto interpretation alone. A ridge north of Great Bear Lake and another east of Lac La Martre were first mapped by Craig (1960, 1965). Forcier Moraine, east of Great Bear Lake was identified by St-Onge et al. (1981). During the present project, another moraine, which we propose naming Rebesca Moraine for a nearby lake, was distinguished on the basis of its continuity transverse to ice flow direction and its orientation transverse to the few eskers which meet it. It is possible that Rebesca Moraine formed concurrently with Forcier Moraine.

Because of the similarity of form, both from airphoto interpretation and on the ground, it is possible that other short end moraines may have been improperly identified as esker tributaries. Much more ground checking is needed to identify properly the presence of ice marginal complexes and to decipher the depositional environments associated with such complexes. The relative rarity of end moraines is probably a function both of the largely passive nature of the shrinking Keewatin ice mass and, at least in the westernmost parts of the map area, the paucity of debris available for landform construction.

SUMMARY

Map 24-1987, at 1:1 000 000 scale and based on airphoto interpretation and existing maps, portrays glacial features on the northwestern Canadian Shield. Six major types of glacial terrain occur around the Keewatin Ice Divide: 1) hummocky moraine, 2) ribbed (rogen) moraine, 3) drumlinized or fluted terrain; 4) sculpted bedrock surfaces in drift-poor terrain; 5) subglacial drainage corridors with or without eskers and associated glaciofluvial, glaciomarine, or glaciolacustrine deposits; and 6) end moraines and associated deposits. Some of these features (eskers, drumlins, ribbed moraine) occur in trains or corridors that radiate outward from the Keewatin Ice Divide and all occur in one or more of four zones that are roughly concentric about the divide. The innermost zone (1), which is bisected by the Keewatin Ice Divide, is characterized by discontinuous, thin till cover and by extensive areas of low-relief hummocky moraine. Eskers and oriented landforms are rare in this zone. Zone 2 is delimited by the distribution of ribbed moraine, but also includes extensive drumlin fields which typically pass laterally into parallel trains of ribbed moraine. Both types of landforms extend from specific source areas. Ribbed moraine is commonly formed of till with a heavy boulder cover. In the intervening areas between trains of moraines, where the boulder cover is missing, drumlins are found. A well developed esker system generally parallels but may cut across the trains of oriented landforms. In Zone 3 a well developed dendritic esker system passes across a till-covered terrain which is commonly drumlinized, but includes only rare occurrences of ribbed moraine. Drift cover and both size and frequency of eskers diminish outward. Zone 4 comprises extensive areas of nearly drift-free,

Figure 20. Bifurcating esker ridges forming nodes (A) and outwash terrace remnants (B) superimposed on esker and valley sides. Note meander scars on surface of terraces. NAPL A15390-33

ice-moulded bedrock with virtually no esker development. Its outer edge in the western part of the map area is the contact of the Canadian Shield with unmetamorphosed Paleozoic sedimentary rock. Down-ice from and starting abruptly at this contact the Paleozoic rocks are covered by a drift/landform assemblage similar to that in Zone 3.

The distribution of glacial landforms in roughly concentric zones around the Keewatin Ice Divide reflects a complex and as yet imperfectly understood interplay between dynamic conditions within the ice sheet and the geology of the bed across which it flowed. Configuration of Zones 3 and 4 is probably partially related to geological characteristics of the glacier bed, in particular the radial dispersal (and eventual depletion) of a heavy sediment load eroded from the poorly consolidated outcrops coincidentally located near the dispersal centre of the ice sheet. The sediment-poor ice that traversed Zone 4 was apparently unable to erode local, hard, crystalline bedrock effectively; thus the lack of landforms in this zone reflects a lack of sediment necessary for their construction. The inner two zones are probably more influenced by ice dynamics. Sediment/landform assemblages

Figure 21. Flat-topped knob contrasts with generally sharp crest of esker. The knob was flattened by later meltwater erosion by streams flowing on stagnant ice into which esker was frozen. Lateral terraces are still younger deposits (arrows). Photo by B.C. McDonald, GSC 10-27-68

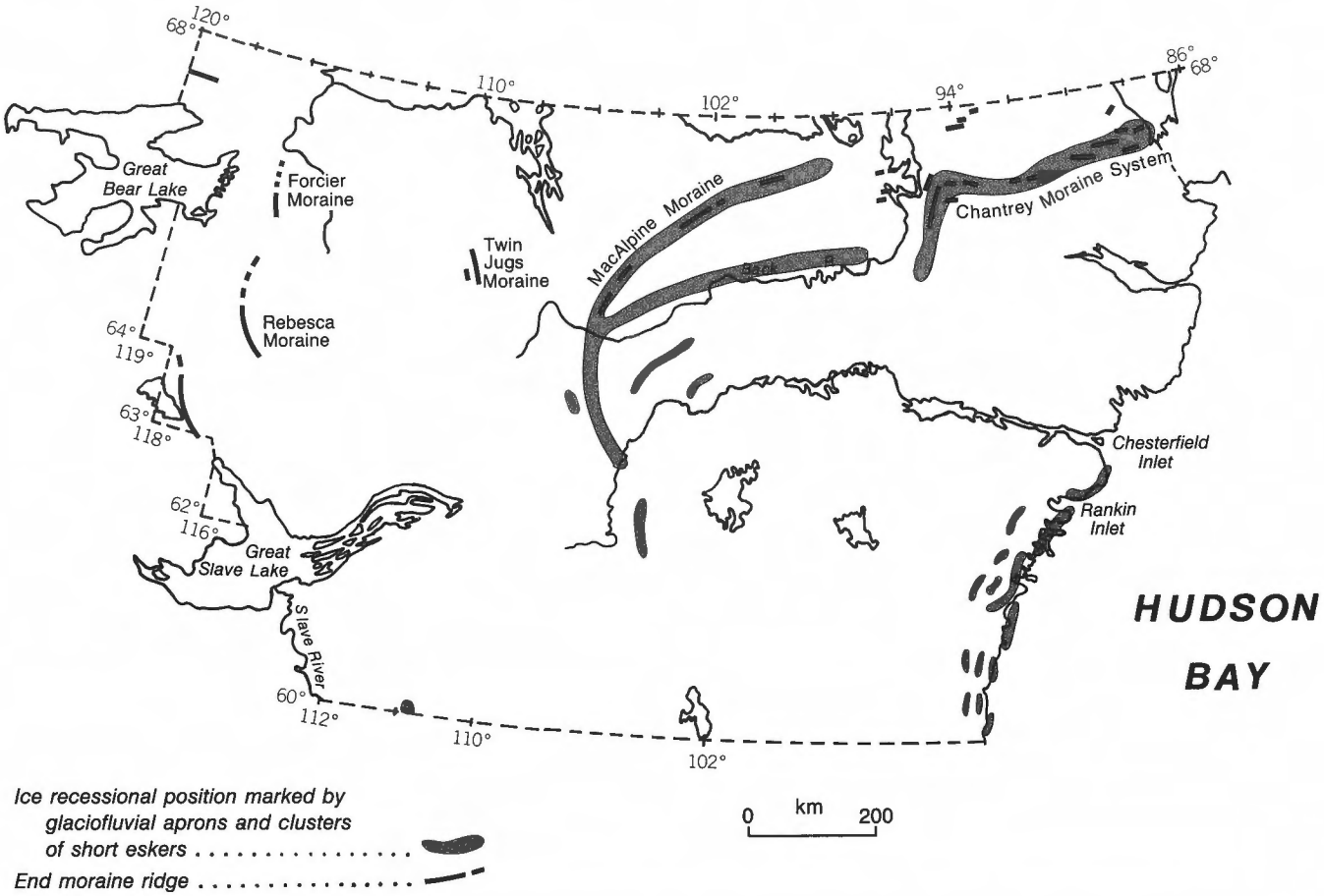


Figure 22. Ice marginal positions indicated by clusters of short parallel eskers, eskers with distributaries, coalescing aprons of ice contact fans and deltas, and major moraine ridges.

in Zone 1 reflect stagnation of a thin ice sheet during deglaciation and low flow velocities just prior to deglaciation. Within Zone 2 the association of ribbed moraine with the ice divide implies some glaciodynamic control. Certainly the morphology of the ribbed moraine suggests formation under conditions of compressive flow. Although the cross-sectional asymmetry is not obvious everywhere, where it is developed the ridges have the aspect of inclined plates of sediment thrust one on top of another. This suggests that they are a relict of englacial structure–debris transported along thrust zones in the ice. Such a form may be preserved only by slow basal meltout from an ice mass with little or no internal movement and, as such, may be an indication of widespread stagnation. Yet, even within Zone 2, the outer edge of which we have speculated may mark the limit of widespread stagnation, the presence or absence of one form or another often can be related to the geology of the terrain at the up-ice end of particular trains of landforms. For example, because of their close spatial relationship in Zone 2 and because both groups of landforms contain elements that reflect regional flow patterns of active ice, ribbed moraine and drumlins probably formed under similar glaciodynamic conditions at the base of the ice. However, basal stress conditions alone are insufficient to explain the close spatial relationship between the features, their association with specific source areas, and the paucity of ribbed moraine outside of Zone 2. We believe that whether one landform or the other was developed was not so much a function of compressive or extensive ice flow as it was a function of the physical character of the debris the ice was carrying. More deformable sediment–in the absence of heavy boulder concentrations–formed drumlins or flutes; less deformable material–gravel, crushed bedrock, bouldery debris from outcrops covered by felsenmeer–formed ribbed moraine. Thus, the critical dynamic basal conditions may have been controlled by the abundance and physical properties of debris entrained in or lying below the sole of the glacier. These physical properties determined whether the debris permitted the basal ice and its substrate to deform plastically or brittly. The nature and quantity of this debris are in turn closely related to the "geology" of the source and dispersal areas, including the structure and degree of frost shattering of the source outcrops, their lithology, and the topography of source outcrops and dispersal area. Because debris was entrained and dispersed in the form of linear glacial trains, the landforms themselves occur in trains, extending from specific outcrops or source areas.

The existence of drumlins beyond Zone 2 implies that drumlinized or fluted terrain is formed beneath the ice and is preserved regardless of the conditions of deglaciation, whereas ribbed moraine, the morphology of which seems to be a relict of englacial structure, may be destroyed under all but those conditions associated with melting of largely stagnant ice. Additional evidence of stagnation is provided by the esker patterns. Briefly stated, eskers commonly cut obliquely across drumlin fields which were formed originally under active ice, and esker tributaries commonly join trunk eskers at right angles, implying that ice flow was, at least sluggish or non-existent. The integrated system of trunk and tributary eskers, formed in short conduits at the base of the ice by meltwater plunging downward from the surface, near the brittle margin, probably mirrors the pattern of movement of meltwater on the surface of the ice sheet. The distribution of eskers and ribbed moraine suggests virtual stagnation of the ice sheet while it still covered a large area.

From a practical point of view, scientists or prospectors carrying out mineral exploration or other activities relating to drift composition in these terrains should be cognizant of the compositional biases that may be present in landform trains. In the case of glaciofluvial corridors, the depositional models discussed here and elsewhere are essential to understand in evaluating geochemical anomalies or occurrences of mineralized float.

ACKNOWLEDGMENTS

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