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GLACIAL EROSION BY THE LAURENTIDE ICE SHEET

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Abstract. The aim of the paper is to analyse landscapes of glacial erosion associated with the Laurentide ice sheet at its maximum and to relate them to the three main variables affecting glacial erosion, namely former basal thermal regime of the ice sheet, the topography of the bed, and the geology of the bed. The key to the analysis is the comparison of the distribution of landscape types with the simulated pattern of the basal thermal regime of the former ice sheet.

Landscapes of *areal scouring* are found to be associated with zones of basal melting and occur beneath much of the former ice-sheet centre and in those places where the topography favoured converging ice flow. The landscape type may also have formed beneath cold-based ice when it was carrying debris inherited from an up-stream zone of regelation. Areas with *little or no sign of glacial erosion* occur primarily in the north in the Queen Elizabeth Islands but they also occur on uplands associated with diverging ice flow; they coincide with areas calculated to have been covered by cold-based ice devoid of debris. Landscapes of *selective linear erosion* are common on uplands near the eastern periphery of the ice sheet. In these situations, pre-existing valleys channelled ice flow and created a situation where there was warm-based ice over the valleys and cold-based protective ice over the intervening plateaux. Variations in the permeability of the bedrock base have modified the landscape pattern, mainly in those areas where there was a change from one basal thermal regime to another. In general, permeable rocks tend to have experienced less erosion than impermeable rocks.

Using lake-basin density as an indication of the intensity of glacial erosion, a zone of maximum erosion is identified and this forms a ring between the centre of the former ice sheet and its periphery. This ring coincides with a zone where melt water from the ice-sheet centre is calculated to have frozen on to the bottom of the ice sheet. This regelation incorporated basal debris into the ice, forming a basal layer 20–50 m thick and afforded an efficient means of debris evacuation.

A conceptual model is developed and hangs round the following postulates:

(1) Landscapes of glacial erosion are related primarily to the basal thermal regime of the ice sheet.
(2) Landscapes of glacial erosion are equilibrium forms related to maximum glacial conditions. This implies that at some stage in the Pleistocene the Laurentide ice sheet was in a stable maximum condition for a long period of time.
(3) Mechanisms allowing evacuation of debris rather than those of abrasion or fracture may be the most important in influencing the amount of erosion achieved by an ice sheet.
(4) Cold-based ice may accomplish erosion if it contains debris.

Résumé. *Érosion glaciaire par la calotte de glacier Laurentide.* Le but de cet article est d'analyser les paysages dus à l'érosion glaciaire au maximum de la glaciation Laurentide et de les rattacher aux trois principales variables agissant sur l'érosion glaciaire: le régime thermique qui régnait autrefois à la base de la calotte, la topographie du lit et la géologie du lit. La clé pour une telle analyse est la comparaison entre la distribution des types de paysages et le comportement simulé du régime thermique à la base de l'ancienne calotte.

Le décapage en nappe est associé à des zones de fusion à la base sous la majeure partie du centre de l'ancienne calotte et ces zones se situent aux endroits où la topographie favorise la convergence des courants de glace. Ce type de paysage peut également se former sous un glacier froid à la base lorsqu'il charrie des débris morainiques hérités d'une zone de regel à l'amont. Les zones *présentant peu ou pas de traces d'érosion glaciaire* se trouvent au nord des Queen Elizabeth Islands, mais se rencontrent également sur les hautes terres liées à une divergence des courants de glace; elles coïncident avec des surfaces que les calculs montrent avoir été couvertes par de la glace froide dépourvue de débris morainiques. Les paysages *d'érosion linéaire sélective* sont communs sur les hauts plateaux au voisinage de la périphérie orientale de la calotte. Dans ces sites, des vallées préexistantes ont canalisé le courant de glace et une glace froide protectrice s'est installée sur les plateaux intermédiaires. Des variations dans la perméabilité de la base du bedrock peuvent modifier le type de paysage sur une échelle locale surtout dans les secteurs de transition entre un régime thermique et un autre. En général, les roches perméables tendent à avoir connu moins d'érosion que les roches imperméables.

En utilisant l'abondance des lacs comme un indice de l'intensité de l'érosion glaciaire, on peut repérer une zone d'érosion maximale qui forme un anneau entre le centre de l'ancienne calotte et sa périphérie. Cet anneau coïncide avec une zone où l'eau de fusion issue du centre de la calotte regelait sur ses bords. Ce regel incorporait des débris morainiques dans la glace formant un niveau de base de 20 à 50 m d'épaisseur et fournissait un moyen efficace d'évacuation des matériaux.

Un modèle théorique est imaginé qui repose sur les hypothèses suivantes:

(1) Les paysages d'érosion glaciaire sont liés au premier chef au régime thermique à la base de la calotte glaciaire.
(2) Les paysages d'érosion glaciaire sont des formes d'équilibre surtout au maximum de la glaciation. Cette dernière conclusion implique qu'à un certain stade du Pleistocène, la calotte glaciaire Laurentide a été dans des conditions de maximum stable pendant une longue période.

(3) Une érosion en nappe intense suppose des mécanismes efficaces d'évacuation des matériaux produits tout autant que des mécanismes d'érosion ou de fracture.
(4) Les glaciers froids à la base peuvent être des agents d'érosion s'ils contiennent des débris morainiques.

Zusammenfassung. *Glaziale Erosion durch den Laurentinischen Eisschild.* Ziel dieser Arbeit ist es, Landschaften glazialer Erosion aus dem Höchststand des Laurentinischen Eisschildes zu analysieren und sie mit den drei Hauptparametern in Beziehung zu setzen, von der glaziale Erosion abhängt, nämlich dem früheren Wärmeumsatz am Untergrund des Eisschildes, der Topographie und der Geologie des Untergrundes. Der Schlüssel zur Analyse ist der Vergleich zwischen der Verteilung von Landschaftstypen und dem simulierten Modell des basalen Wärmeumsatzes im früheren Eisschild.

Für Landschaften mit flächenhafter Abschürfung lässt sich eine Verbindung zu Zonen mit Abschmelzvorgängen feststellen; sie treten unter einem Grossteil des Zentrums des früheren Eisschildes und zwar an solchen Stellen, wo die Topographie konvergierenden Eisfluss begünstigte. Derselbe Formtyp kann sich aber auch unter kaltem Eis gebildet haben, wenn dieses Schutt aus einer weiter oben gelegenen Zone der Regelation enthielt. Gebiete mit *geringen oder gar keinen Anzeichen von glazialer Erosion* kommen vor allem im Norden der Queen Elizabeth Islands vor, aber auch auf Hochflächen, wo der Eisfluss divergierte; sie decken sich mit jenen Gebieten, die rechnerisch mit kaltem, schuttfreiem Eis bedeckt waren. Landschaften *selektiver Erosion* sind auf Hochflächen nahe dem Ostrand des Eisschildes häufig. In diesen Lagen wurde der Eisstrom durch vorgegebene Täler gelenkt; dadurch ergab sich eine Situation, in der temperiertes Eis über den Tälern und kaltes, schützendes Eis über den dazwischen angeordneten Plateaus lag. Unterschiede in der Durchlässigkeit des Felsuntergrundes können zu lokalen Veränderungen des Formenmusters führen, vor allem in solchen Gebieten, wo die thermischen Verhältnisse am Untergrund von einem zum andern Typ wechseln. Allgemein ist durchlässiger Fels weniger erosionsanfällig als undurchlässiger.

Zieht man die Dichte der Seenbecken als Kriterium für die Intensität der glazialen Erosion heran, so lässt sich eine Zone maximaler Erosion feststellen, die ringförmig zwischen dem Zentrum des früheren Eisschildes und seiner Peripherie liegt. Dieser Ring fällt mit jener Zone zusammen, wo Schmelzwasser aus dem Zentrum des Eisschildes auf den Untergrund des Eisschildes auffror. Durch diese Regelation wurde basaler Schutt in das Eis aufgenommen; in einer Schicht von 20–50 m Mächtigkeit fand so ein sehr wirkungsvoller Abransport von Schutt statt.

Die entwickelte Modellvorstellung beruht auf folgenden Postulaten:

(1) Für die Bildung von Landschaften mit glazialer Erosion sind vor allem die thermischen Verhältnissen am Untergrund des Eisschildes ausschlaggebend.
(2) Landschaften mit glazialer Erosion sind Gleichgewichtsformen, die zu einem glazialen Höchststand gehören. Dies bedeutet zugleich, dass in einem bestimmten Stadium des Pleistozäns der Laurentinische Eisschild sich für lange Zeit auf einem stationären Höchststand befand.
(3) Mechanismen, bei denen der Schuttransport die Abrasion oder den Bruch überwiegt, dürften bestimmend für den Grad der Erosion durch einen Eisschild sein.
(4) Kaltes Untergrundeis kann Erosion bewirken, wenn es Schutt enthält.

Introduction

The most abundant evidence of glacial erosion by ice sheets exists in those areas formerly covered by the Laurentide and Scandinavian ice sheets. Although modified by post-glacial weathering, the beds of these former ice sheets are accessible and offer a potentially rewarding field of study whereby the glacial landforms on the ground may be examined and related to former glaciological processes. At present too little is known about the landform patterns to be able to relate them to glaciological processes and as a result there is something of a gulf between the progress of theoretical studies of processes occurring at the bottom of ice sheets and the field evidence which is required to constrain and further develop such theory. It is the purpose of this paper to analyse landscapes of glacial erosion in Canada and to offer some perspectives on the relative importance of the main variables believed to affect glacial erosion, namely (1) thermal characteristics of the basal ice, (2) topography of the glacier bed, and (3) geology of the bed.

The methodology employed is to compare spatial variations in landscapes of glacial erosion with the spatial variations in the three main variables affecting erosion. The landscape map was derived from a combination of field work and remote-sensing techniques while the topographic and geological information was derived from existing maps. The distribution of different basal thermal regimes was calculated by simulating the characteristics of the former Laurentide ice sheet at its maximum. Such maximum conditions may reflect one or several Cenozoic glaciations, all of which pre-date Wisconsin time.

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The landscape evidence

Classification

The mapping of the landscapes of glacial erosion employs a simple morphological classification used by the writer in Greenland and elsewhere (Sugden, 1974; Sugden and John, 1976). The main characteristics of the classification are described below.

A landscape of *areal scouring* comprises an irregular rock surface which has everywhere been dominantly shaped by the action of ice (Fig. 1). This landscape type has been described by Linton (1963) as knock-and-lochan topography. A good example of the landscape type occurs around the head of Frobisher Bay (Fig. 2). Here the most obvious feature is the widespread occurrence of glacially abraded rock surfaces, occasionally with striations and crescentic gouges still preserved. At a scale of hundreds or thousands of metres, these rock surfaces form part of smooth and elongated hills streamlined in the direction of ice flow. In between the hills are structurally controlled depressions which often contain irregular lakes. Sample measurements reveal a 1 000 m long hill to be commonly 60 m high and a 200 m

Fig. 1. Vertical air photograph of a landscape of areal scouring, near Nettilling Lake, Baffin Island.

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long hill to be 10–15 m high. At this scale the profile of the hills is not broken up by irregularities induced by plucked or other lee-side effects. At a scale of 10–100 m the streamlined hills can be seen to comprise a series of individual rock knobs and depressions. Typically, the knobs are *roches moutonnées* with ice-moulded up-stream flanks and plucked and craggy lee sides. Boulders bounded by clear joint faces are common and include some which are still in place as well as those which have been moved horizontally some tens of metres from their original starting place.

A landscape of *selective linear erosion* consists of glacially excavated troughs separated by upland plateaux with little or no sign of glacial erosion (Fig. 3). An example of this landscape type in the Coronation Fiord area of Baffin Island was examined in detail in the field. The

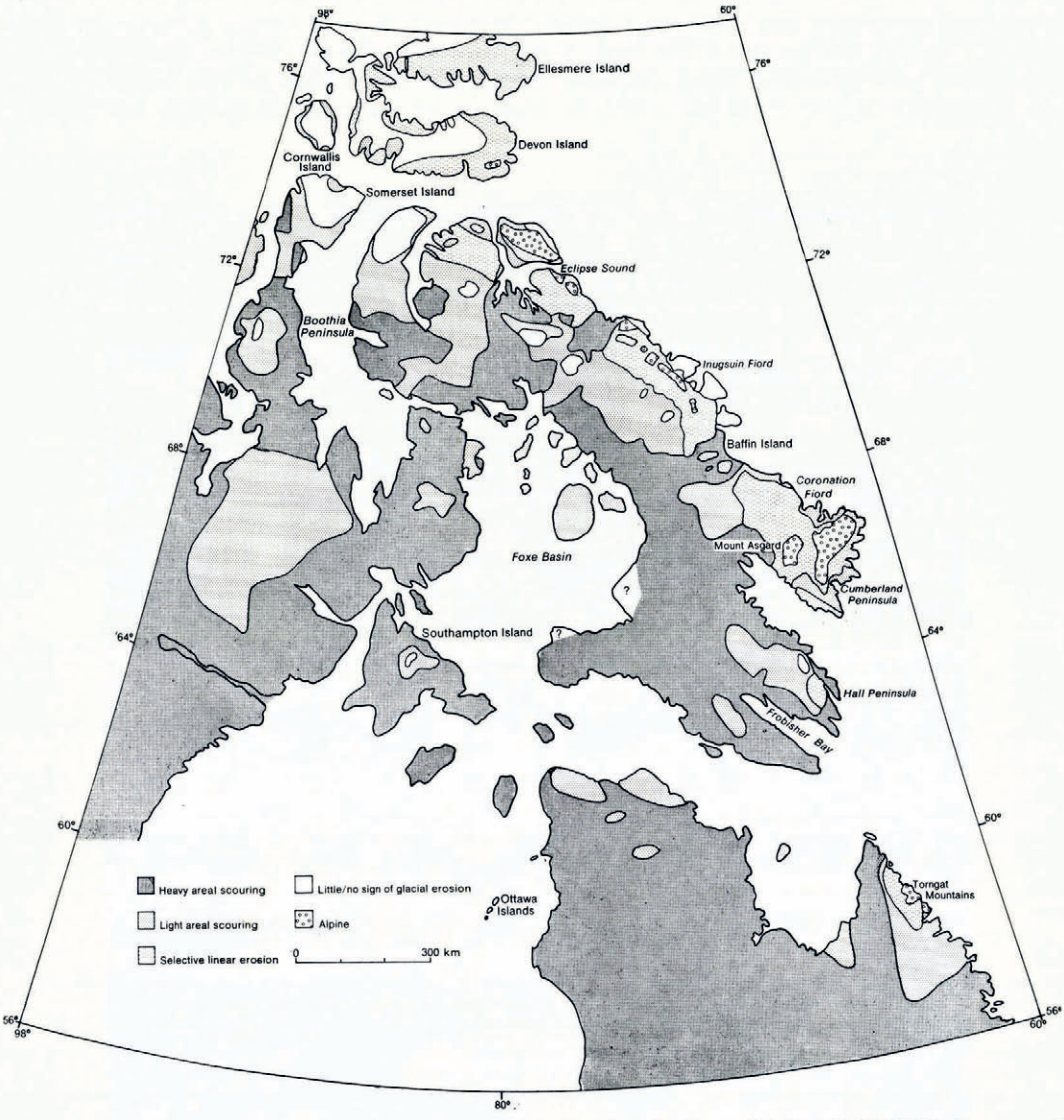

Fig. 2. Distribution of landscapes of glacial erosion in the eastern Canadian Arctic, compiled from LANDSAT-1 imagery and conventional air photographs, backed up by field work in selected sites.

fjords are troughs with steep cliffs rising precipitously above the fjord water to altitudes in excess of 950 m. The upland areas on either side of the troughs are gently sloping and marked by broad and open river valleys. The surface supports regolith derived in the main by weathering from the underlying bedrock but also from till containing distinctive glacial erratics. For example, at an altitude of 910 m on the plateau just north of Coronation Fiord glacially faceted boulders of grey fine-grained gneiss and red coarse-grained pegmatite occur on bedrock consisting of coarse-grained garnetiferous biotite-gneiss. Bedrock tors are characteristic of the upper surfaces and may be surrounded by erratics. One of the most striking features of this landscape type is the clarity of the break between the cliff top of the glacial trough and the gentle upper slopes. Other examples of this landscape type with seemingly identical characteristics have been described in the Torngat Mountains of Labrador and the Inugsuin Fiord area of eastern Baffin Island by Ives (1957, 1975).

A landscape of *little or no sign of glacial erosion* consists of an extensive area where the dominant landforms are river valleys and where long gentle slopes are swathed in regolith derived in the main from the underlying bedrock. Often tors occur on interfluves. Such

Fig. 3. A landscape of selective linear erosion in the vicinity of Saglek Fiord, Labrador. (Photograph by J. D. Ives.)

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landscapes are common in the northern Canadian Arctic and are easily distinguished on air photographs. The landscape type is characteristic of much of Somerset Island and has been described in detail by Dyke (1976) (Fig. 4). Although there is no obvious sign of glacial erosion, a former ice cover is frequently indicated by the occurrence of glacial erratics, for example, on Somerset Island (Dyke, 1976) and elsewhere in the Arctic Archipelago (Blake, 1964, 1975).

It has been suggested by a referee that the lack of evidence of glacial erosion associated with the latter landscape type and the plateau areas of landscapes of selective linear erosion could represent areas where mass wasting has masked any landforms of glacial erosion since deglaciation. Whereas this may have occurred in a few localized places, the possibility of it explaining the basic classification given above can be excluded for two main reasons. In the first place, the amount of mass wasting in Arctic Canada since deglaciation appears inadequate

Fig. 4. Photograph from approximately 50 m above the ground of a landscape of little or no sign of erosion in Somerset Island. Erratics occur around the tors. (Photograph by A. S. Dyke; GSC-203014-D.)

to obliterate relief features associated with glacial scouring, at least on hard rocks. Whereas the glacial landforms have a characteristic amplitude of several tens of metres, the effect of mass wasting is measured in metres or less. This can be illustrated from Broughton Island, Baffin Island, by the preservation of such delicate features as lateral moraines 2–10 m high, which have been dated as being at least *c.* 50 000 years old and possibly more than 120 000 years old (England and Andrews, 1973). Also, the preservation of glacial erratics on hill crests and in the vicinity of tors on hill summits, for example on Broughton Island (Sugden and Watts, in press), implies relatively little mass wasting since deglaciation; if there had been significant landscape modification by mass wasting, erratics would tend to have been swept down into valleys or other depressions. In the second place, areas of little or no erosion represent relict surfaces bearing old regolith. One example of this in Baffin Island is illustrated by the discovery of thin Tertiary deposits on such a surface just north-west of the Barnes Ice

Cap (Andrews and others, 1972). Furthermore, studies of weathering pits and clay-mineral assemblages associated with the regolith of the upland component of a landscape of selective linear erosion near Coronation Fiord point to subaerial weathering over long time periods, probably measured in hundreds of thousands of years (Boyer and Pheasant, 1974; Isherwood, unpublished). Field work in the same area revealed glacial erratics in the regolith fresh enough to retain their glacial polish (Sugden and Watts, in press) and thus it seems clear that the formation of the regolith must pre-date at least the last full glaciation of the area. In such a case, the hypothesis of glacial protection implied by the classification given above seems fully compatible with the field evidence.

The final landscape type is an *alpine landscape* which consists of massifs shaped essentially by the action of local valley glaciers constrained in their flow by the topography of each individual mountain block. A coarsely dendritic trough pattern, horns and arêtes are characteristic. A spectacular example of the landscape type, much in demand for the making of Canadian whisky advertisements and Secret Service movies, occurs in the Mount Asgard area of Cumberland Peninsula, Baffin Island!

Distribution of the landscape types

The mapping of erosional landscapes relied heavily on the interpretation of LANDSAT-1 images, backed up by the scrutiny of several thousand oblique and vertical air photographs as well as field work in selected locations on Baffin Island. In practice it was found that LANDSAT images (especially bands 5 and 6) were easily interpreted in terms of the classification given above. Landscapes of areal scouring can be picked out by the irregular lake pattern, presence of clear structural lineations revealing the outcropping of bedrock at the surface and the absence of dendritic river patterns (Fig. 5). Areas of little or no sign of erosion are characterized by regular dendritic river patterns, the absence of structurally controlled lakes and a texture indicating the presence of regolith. An intermediate category (light areal scouring) was introduced to cover those areas where the river pattern is clearly preserved but where there are also a few lakes and some structural lineations. Landscapes of selective linear erosion are distinguished by troughs with clearly marked edges and intervening plateau areas covered in regolith and devoid of lakes. In those cases where the intervening upland is ice scoured, the whole landscape type was classified as one of areal scouring. Alpine landscapes are marked by a complex, coarsely dendritic trough pattern and the presence of pointed peaks.

Figure 6 depicts the broad distribution of main landscape types for the whole of the area covered by the Laurentide ice sheet at its maximum. In addition to the erosional categories discussed above, a depositional zone is included and describes those areas where bedrock is largely obscured by drift. The map, covering as it does such a large area, is obviously highly generalized and is intended to be no more than a guide to the broad pattern of landscape variation. The main feature is a broad area of areal scouring extending over the central area of the former ice sheet. Along the south-eastern maritime margin, the zone extends at least as far as the coast, while along the southern and western land margins the zone gives way to a peripheral zone of deposition. In the north the areal scouring gives way to landscapes with little or no sign of glacial erosion. This transition takes place mainly beneath the waters of Viscount Melville Sound but in several places the transition is abrupt and takes place on land. For example, on Somerset Island, Netterville and others (1976) have described the change between the characteristic ice-scoured depressions and rock knobs south of the boundary and the fluvial topography, regolith and tors of the area immediately to the north. Landscapes with little or no sign of glacial erosion include most low-lying islands in the Queen Elizabeth Islands. Although there is some discussion about the status of these islands during the Wisconsin glaciation (Blake, 1975; England, 1976), there is general agreement that they were

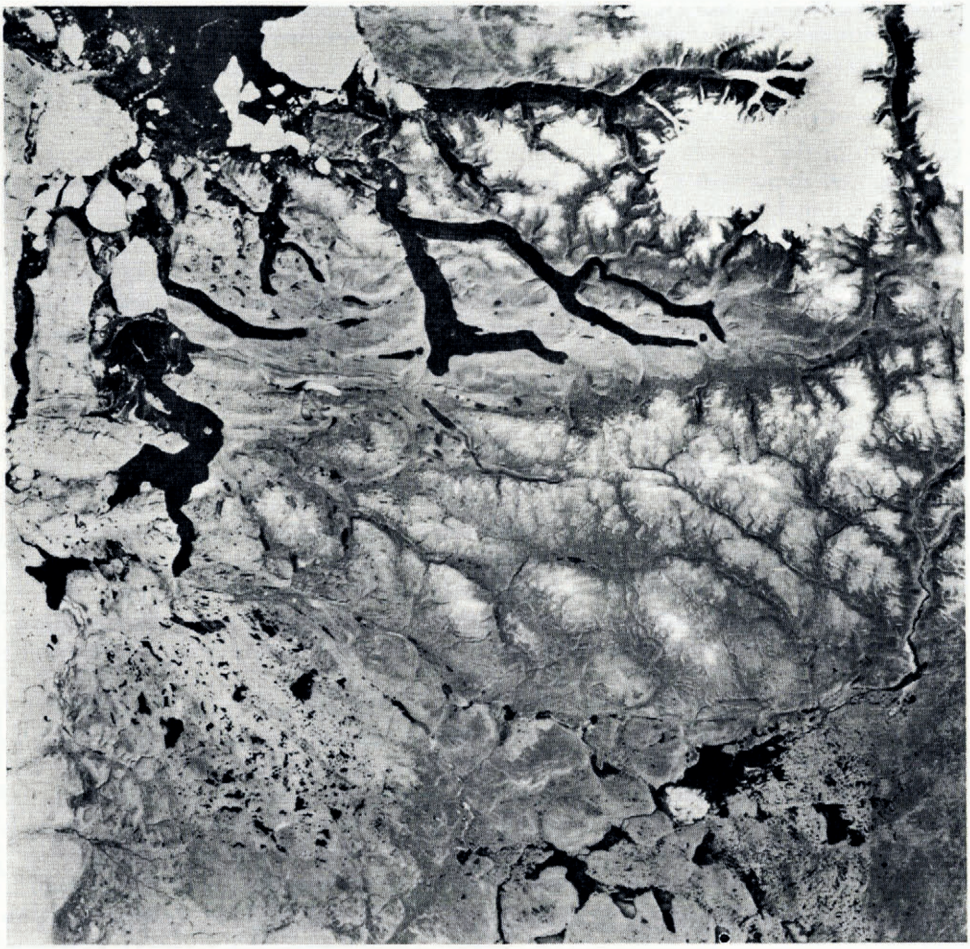

Fig. 5. The appearance of different landscape types on LANDSAT-1 imagery. The image is of an area south of Eclipse Sound in Baffin Island and shows areal scouring in the south, selective linear landscapes in the north-east and little or no sign of glacial erosion in the intermediate area in the east. North is at the top of the image. (E-1746-16434-6.)

covered by Laurentide ice at some stage during the Cenozoic, a conclusion apparently confirmed by the existence of Laurentide shield erratics on the Palaeozoic rocks of the islands. The topography beneath the straits is obviously not well known. However, there are indications that it includes both areal scouring and areas with little or no sign of erosion. For example, Bornhold and others (1976) described well-preserved river patterns as well as ice-scoured topography from the floor of Barrow Strait immediately north of Somerset Island.

Landscapes of selective linear erosion are, with one exception on Melville Island, restricted to the eastern upland periphery of the former Laurentide ice sheet. The landscape type is most common in the north and most restricted in the south-east. Probably the extent of selective linear erosion is underestimated in the north-west. Here, troughs appear to occur in some straits (Pelletier, 1966) and these could justify classification of more of the Queen Elizabeth Islands as selective linear landscapes, albeit well submerged.

Fig. 6. Main glacial landscape zones, Laurentide ice sheet, compiled from examination of LANDSAT-1 imagery. Topographic maps were used in the far north where imagery is unavailable.

Alpine scenery within the confines of the former Laurentide ice sheet occurs patchily along the north-eastern periphery and in part of Labrador. In all cases, alpine areas are adjacent to or surrounded by selective linear landscapes.

Figure 2 shows the erosional landscapes of the eastern Canadian Arctic in detail and relies mainly on the examination of several thousand oblique air photographs and field testing of crucial areas. Clearly, in any such map there will be areas of doubt but the map is offered as a representation of the main pattern and provides a basis for discussion. Landscapes of areal scouring cover most of the area other than the northern and eastern periphery. Both flanks of Hudson Bay and Foxe Basin and southern Baffin Island are heavily ice-scoured. One clear pattern is that uplands are often less intensely ice-scoured than surrounding adjacent lowlands. Many good examples of this relationship can be seen along the axes of peninsulas in southern Baffin Island, Boothia Peninsula and on Southampton Island. Landscapes with little or no sign of erosion form isolated pockets over the northern part of the area. It is clear that one category of this latter landscape type is associated with uplands. In the north the bulk of the central high parts of Devon and Cornwallis Islands fall into this category. Farther south the occurrences are less extensive but the same relationship is apparent. For example, in several places on Baffin Island, Southampton Island and Boothia Peninsula, areas of little or no sign of erosion include the culminating points of uplands which are increasingly affected by areal scouring down their flanks. Another type of landscape with little or no sign of glacial erosion includes the low-lying forelands of central and northern Baffin Island. Landscapes of selective linear erosion are extensive in the north in eastern Devon Island and Ellesmere Island and in northern and central Baffin Island, but are restricted to small upland areas in southern Baffin Island and the Torngat Mountains of Labrador.

Intensity of glacial erosion

Although Figures 2 and 6 are helpful in pinpointing the location of different types of glacial erosion, they are not able to provide quantitative information about the intensity of erosion from place to place. The information is potentially important and several attempts were made to derive it. Simple tests using such indicators as degree of stream derangement, streamlining as reflected by lakes, and preferred orientation of depressions proved either unwieldy or unhelpful. However, density of lake basins proved more helpful. Lake basins have long been regarded as diagnostic of glacial erosion and indeed Hobbs (1945) used their distribution as a means of determining the former extent of the Laurentide ice sheet. For the purpose of this paper, lake-basin density was measured for that part of Canada formerly covered by the Laurentide ice sheet. Each Canadian topographic map at a scale of 1 : 500 000 (latest editions available in 1975) was divided into four equal parts. Within each sector a quadrat representing an area 20 km by 20 km in size was randomly located and lake basins of 0.5–2.0 km in diameter were counted. Areas of sloping topography were avoided where possible as well as areas of large lakes. It is impossible to know how many of the lakes sampled were actually excavated in bedrock. However, structural control of the lake borders was obvious in about 90% of cases and it is unlikely that the inclusion of some non-bedrock lakes will seriously affect the pattern. One obvious area of difficulty was in the Mackenzie River delta, where there are many "periglacial" lakes, and as a result this area was left blank.

The resulting map (Fig. 7) reveals a clear pattern which is in full agreement with the maps of landscape type. The boundary between little or no sign of erosion in the Queen Elizabeth Islands and areal scouring to the south is borne out by the contrast in lake density. To the north there are less than ten lake basins per 400 km^2, whereas immediately to the south there are between 10 and 50 lake basins per 400 km^2. This latter density soon increases southward to densities of 50–100 lake basins per 400 km^2 or more. Also of interest is a zone with a low density of lakes along the eastern seaboard between Labrador and Lancaster Sound. Within this zone locally high densities occur in the vicinity of Hudson Strait, Cumberland Sound, Home Bay, and the Cambridge Fiord area.

Perhaps the most intriguing pattern is the zone of high lake-basin density ($>$100 per 400 km^2) situated approximately midway between the shores of Hudson Bay and the former ice-sheet margin. In the west the zone is continuous between the high western plains and the Arctic Archipelago. In the east it is less continuous but a recognizable zone swings round from the Great Lakes through the Ungava Peninsula and is continued in two places in Baffin Island. If lake-basin density is accepted as a measure of the intensity of glacial erosion, one can suggest that there is a zone of maximum erosion situated between the former ice-sheet centre and the periphery. The reality of this pattern is borne out by two independent maps which are reproduced in the *National atlas of Canada* (1974). One (p. 6–7), showing the *area of fresh water as a percentage of 10 000 km² grid units* brings out the same zone as one with as much as 10–20% of its surface area comprising water. The other (p. 37–38), showing *surface*

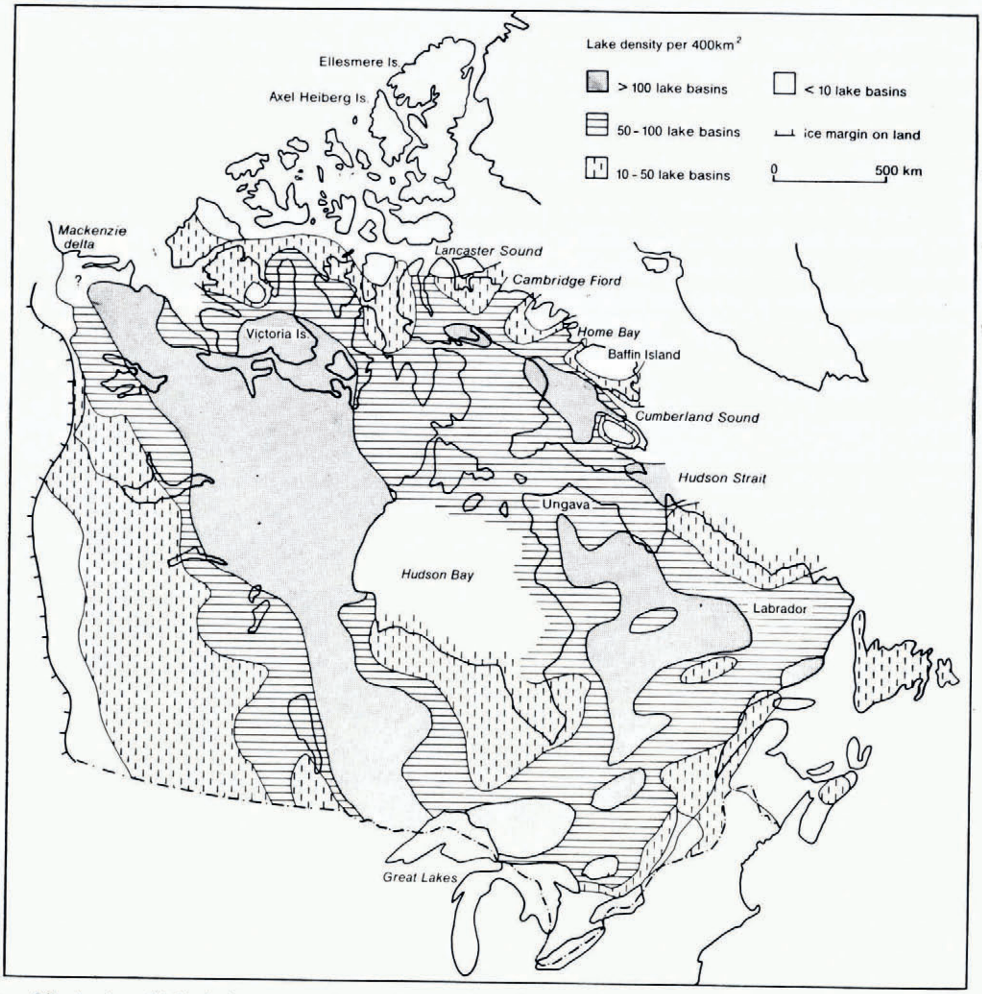

Fig. 7. The density of lake basins 0.5–2.0 km in diameter for unit areas of 400 km² in Canada. The data were obtained by sampling from topographic maps at a scale of 1 : 500 000. Lake-basin density at this scale is thought to be a measure of the intensity of glacial erosion.

materials, portrays areas where bedrock comprises most or half of the surface materials. In addition to steep mountain areas along the east coast, there is an arcuate zone running from the Great Lakes to Victoria Island which is coincident with the postulated zone of maximum erosion. On either side, most of the surface material consists of unconsolidated drift. Such a patterns would be expected if there were a zone of maximum glacical erosion approximately midway between Hudson Bay and the western ice-sheet margin.

At present there seems no evidence to contradict this view of a zone of maximum glacial erosion midway between the ice-sheet centre and periphery. For long there has been a view that an arc of exhumation between shield and Palaeozoic rocks may be the result of glacial erosion (Davis, 1920; White, 1972), although as Gravenor (1975) has pointed out, there is often good local evidence that this existed as a depression in pre-glacial times and has merely been deepened by erosion in places. It is notable that the greatest deepening of this arc occurs in the vicinity of the Great Lakes and coincides with the intermediate zone of maximum erosion postulated in this paper. In 1972, White suggested a contrary view that the zone of maximum glacial erosion occurred beneath the centre of the former Laurentide ice sheet, namely over Hudson Bay. However, this view was put forward as a speculative hypothesis and is contradicted by a great deal of field evidence (Gravenor, 1975; Sugden, 1976).

Relationship of landscape type to process

The maps in the preceding section provide information about the variation in glacial erosion beneath the former Laurentide ice sheet both on a sub-continental scale and at a more local scale. It is the purpose of this section to relate the pattern to the role of the three main variables influencing glacial erosion—namely basal ice conditions, bedrock topography, and bedrock geology.

Theoretical considerations

Of all glaciological variables, there are grounds for believing that basal thermal regime is the most critical affecting the nature of erosion beneath ice sheets. Following from the work of Weertman (1961, 1966), Boulton (1972) suggested that the basal thermal regime controls the occurrence or otherwise of basal slip between ice and rock, the amount of melt water at the base, the relative importance of the mechanisms of abrasion and plucking, and the processes of entrainment of rock particles. Some of the possible relationships have been discussed by Sugden and John (1976), and are illustrated in Figure 8 which shows an idealized sequence of zones and primary erosional processes associated with each. From this, it can be suggested that cold-based ice is essentially protective unless it contains basal debris, inherited perhaps from a zone of basal regelation up-glacier. In this latter situation, slight convexities on the bed may cause ice to diverge round the obstacle and bring debris into contact with the bed so that it may accomplish erosion, as suggested by Röthlisberger (1968); also some entrainment of debris may take place by plastic flow of ice round already loosened debris. Zones of warm melting (ice at the pressure-melting point and subjected to melting) are associated with erosion by abrasion, fracture, and melt water, while zones of warm freezing (ice at the pressure-melting point but with successive freezing on of melt water) are associated in addition with entrainment by regelation.

The different types of erosional landscape may reflect differing basal thermal regimes. Areal scouring reflects extensive abrasion and plucking, and would be most favoured by basal ice at the pressure-melting point. Probably, areal scouring can also result from the passage of

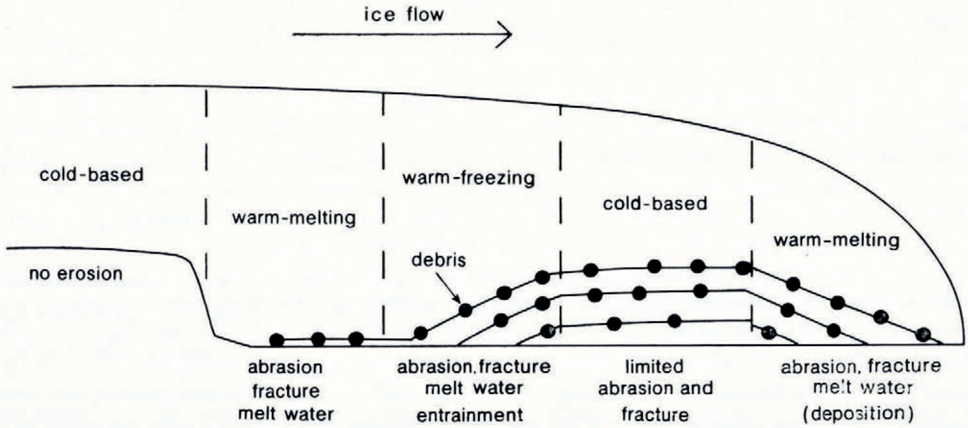

Fig. 8. Idealized model of the relationship between processes of glacial erosion and the basal thermal regime of an ice sheet.

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cold-based ice when it is carrying a basal debris load. Landscapes of little or no sign of glacial erosion would be likely to occur whenever the basal ice is cold-based and carrying little debris; in such situations most forward movement of the ice would result from deformation within the lower layers of the ice, rather than between ice and bedrock. Landscapes of selective linear erosion are intermediate in that they may reflect a situation where ice is warm-based over the sites of troughs and cold-based over the intervening plateaux.

Topography has an influence on landscapes of glacial erosion in two main ways. It can have a direct effect by determining whether or not a particular massif will be submerged beneath the ice sheet. Thus it can be suggested that topography will be the dominant factor in determining whether or not a particular massif is eroded by ice-sheet ice or local valley glaciers. Topography can also play an indirect role by influencing the basal thermal regime beneath the ice sheet. This may be through its influence on the thickness of the overlying ice. Temperatures beneath thick ice tend to be higher than those beneath thin ice because, with the exception of the surface layers, temperatures tend to rise with depth. Topography also affects basal temperatures through its influence on converging or diverging flow. In an area where the bedrock topography favours convergent ice flow, ice velocities will be increased and this will produce more heat by internal deformation and/or basal sliding. On the other hand, topography which causes ice divergence will tend to reduce overall velocities and thus the amount of frictional heat generated.

The geology of the ice-sheet bed can be expected to have important implications on the pattern of glacial erosion at a broad and local scale. The influence of joint patterns, fracture characteristics, and hardness are all variables which have yet to be considered from a detailed theoretical standpoint and little can be said about them at present. However, permeability is thought to be important in so far as it affects the amount of water present beneath warm-based ice and thus affects the rate of basal slip (Weertman, 1966) and the ice pressure applied to the glacier bed (Boulton, [c1974], [c1975]). Beneath the thick ice of the Laurentide ice sheet, it is reasonable to suppose that the main effect of permeable beds, especially if they are extensive, would be to allow basal melt water to flow through the beds rather than at the ice/rock interface. This in turn is likely to reduce the rate of erosion. One reason for this is that the rate of basal slip will be reduced and thus less glacier sole and abrasive passes a given point on the bed. Another reason is that the loss of water at the ice/rock interface may increase ice pressures to such an extent that debris particles are arrested by friction with the bed and are deposited as lodgement till (Boulton, [c1975]).

Testing the relationship between landscape type and basal thermal regime

The relationship between landscapes of glacial erosion and basal thermal regime can be examined by comparing the landscape distribution and character with the distribution of the differing basal thermal regimes beneath the former Laurentide ice sheet. Simulating the basal thermal regime of a former ice sheet is obviously an exercise fraught with difficulty and, in order to give adequate treatment of its limitations I have felt obliged to complete the simulation in a separate paper (Sugden, 1977). The main features of the simulation are the use of morphological and climatic input data obtained by analogy with the existing ice sheets of East Antarctica and Greenland, and the use of the steady-state ice-temperature model developed by Budd and others (1971). Figure 9 shows the result of this reconstruction of the thermal regime beneath the Laurentide ice sheet at its Cenozoic maximum. The main feature is a zone of warm melting beneath the central area of the ice sheet. Surrounding this central zone is a ring of warm freezing followed by a ring of cold-based ice and finally, in most places, a peripheral zone of warm melting. It is likely that the width of the warm-freezing zone is underestimated to some extent because the model used did not allow for the horizontal advection of heat by melt water flowing beneath the ice sheet or the complex problem of the amount of heat produced by the freezing of melt water in the cold-based zone. The pattern was subjected to a sensitivity test by changing the input data and it was concluded that the sequence of zones was relatively persistent but that small changes in the input data could shift zone boundaries and widths by hundreds of kilometres. This was especially true of the western plains where the pattern was least stable. The cold-based ice over the Queen Elizabeth Islands was found to be especially stable and persisted in spite of all reasonable changes in input variables. It is notable that the main feature of the simulation—the central zone of warm melting beneath the ice sheet at its greatest maximum—was discovered previously by Hughes (1973) using independently derived input data and the same ice-temperature model. The spatial extent of the zone agrees well in both simulations.

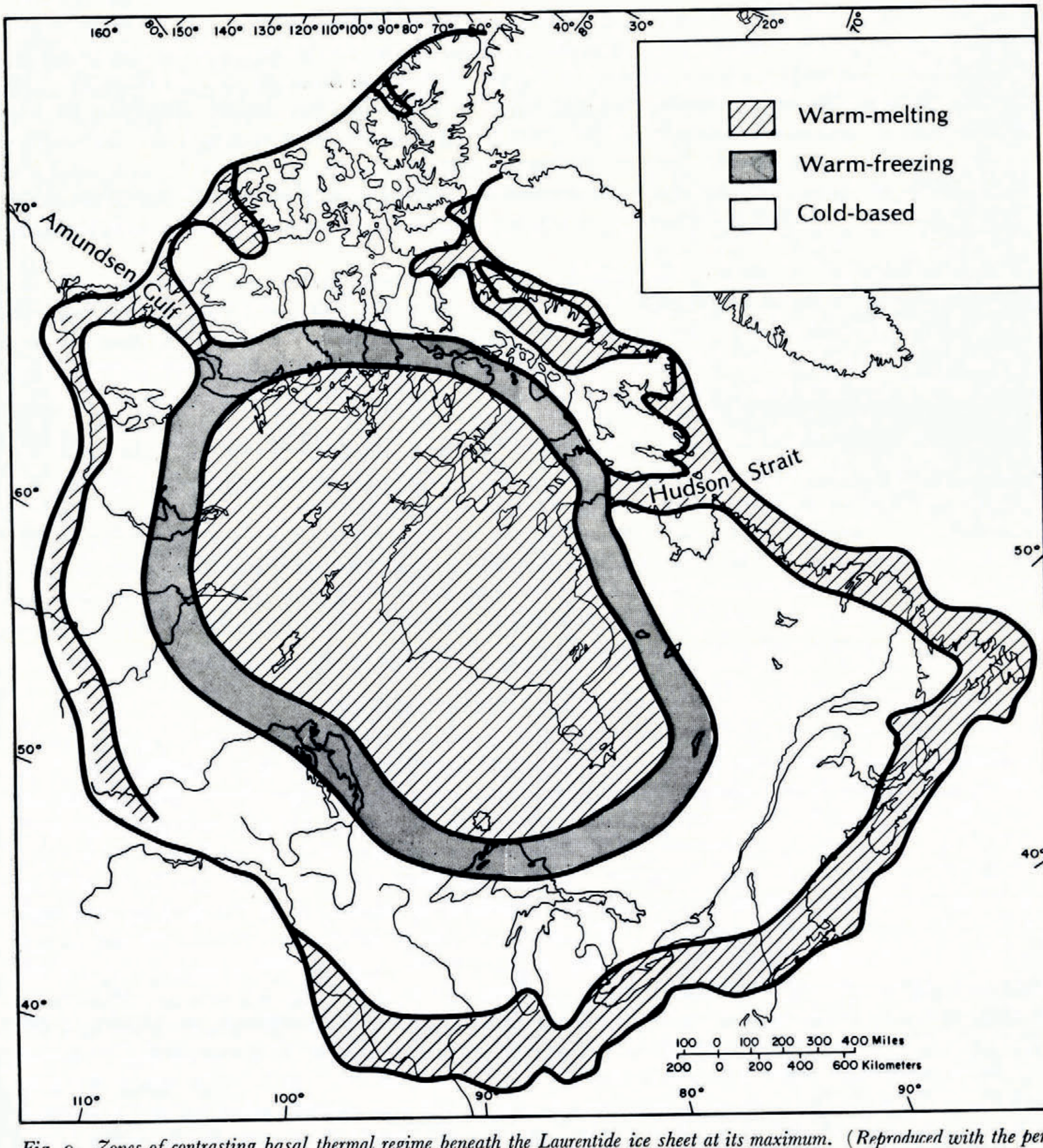

Fig. 9. Zones of contrasting basal thermal regime beneath the Laurentide ice sheet at its maximum. (Reproduced with the permission of the University of Colorado from Sugden 1977).)

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The simulation of the ice sheet was made for maximum steady-state conditions on the assumption that most erosion was achieved during *maximum* ice conditions. There are pieces of evidence which seem to suggest this assumption is realistic. One is simply that such ice-sheet landforms as the larger fjords of eastern Baffin Island and northern Labrador which cut through the main mountain crest occur at the peripheries of the ice sheet and can hardly have been occupied by ice unless the ice sheet was very close to its maximum. Another line of evidence is that erosional forms seem to relate to maximum ice-flow conditions and are relatively unaffected by subsequent changes, as for example occur during deglaciation. An example of this situation is provided by the Ottawa Islands in eastern Hudson Bay. Here, Andrews and Falconer (1969) noted that the streamlined outline of the islands reflects maximum ice-flow conditions out of Hudson Bay, and yet overlapping striations of completely different orientations tell of the phase of deglaciation during which the ice centre migrated to Labrador–Ungava. The deglaciation phases were capable only of carving some striations into the previously ice-moulded surfaces. Other similar associations occur west of the Barnes Ice Cap in Baffin Island where a complete reversal of ice direction during deglaciation has had little impact on the main ice-scoured forms (Ives and Andrews, 1963). Even if the view that most erosion was achieved during maximum conditions must remain an assumption at this stage, there is evidence that the less extensive Northern Hemisphere late-Wisconsin ice sheets accomplished little erosion and that therefore a reconstruction of earlier ice sheets is most relevant to a study of glacial erosion. This view of limited late-Wisconsin erosion is based on the juxtaposition of erosional forms, for example in Europe (Ahlmann, 1919), and on the location of interglacial deposits on glaciated surfaces, for example in West Greenland (Sugden and Miller, 1976), in eastern Baffin Island (Feyling-Hanssen, 1976) and around southern Hudson Bay (McDonald, 1969; Prest, 1970).

Comparison of the map of basal thermal regime with those of landscape variation poses several suggestive correlations. One is that the area of little or no erosion over the Queen Elizabeth Islands coincides with an area where the ice sheet was cold-based. In the absence of any obvious correlation with either topography or geology, it is reasonable to suggest that there may be a causal link between the former occurrence of cold-based ice and the areas of little or no erosion. Devoid of basal debris, it is to be expected that such cold-based ice would be essentially protective. The only exceptions occur in the area of the deeper straits where calculations suggest that the basal ice would have been at the pressure melting point. It is notable that the deeper straits often contain glacial troughs (Pelletier, 1966) and also that zones of light areal scouring are sometimes associated with the sides of straits, for example between Cornwallis and Devon Islands (Fig. 2).

Another interesting relationship is the apparent coincidence of the zone of most intensive glacial erosion with the zone of warm freezing. The warm-freezing zone provides an efficient means of debris evacuation because successive regelation of melt water and associated debris allows the build-up of a considerable thickness of debris-bearing ice. Sample calculations for the Laurentide ice sheet suggest that the layer would have been of the order of 20–50 m thick. It is tempting to suggest that the zone of most intense erosion is associated with this zone of efficient debris evacuation. There is not a perfect spatial correlation between the zone of intensive erosion and the warm-freezing zone but neither should this be expected. In the first place, the width and position of the zone as portrayed in Figure 9 is highly sensitive to the amount of melt water produced beneath the centre of the ice sheet. It may be that climatic conditions were different to those used in the reconstruction with the result that the position and width of the zone would have been different. In the second place, it is highly probable that the position of the zone fluctuated during the course of a glaciation as maximum equilibrium conditions took time to be established. In the third place, it is likely that the simulation underestimates the width of the warm-freezing zone.

The remarkable feature is that the correlation is as good as it is. One might point out

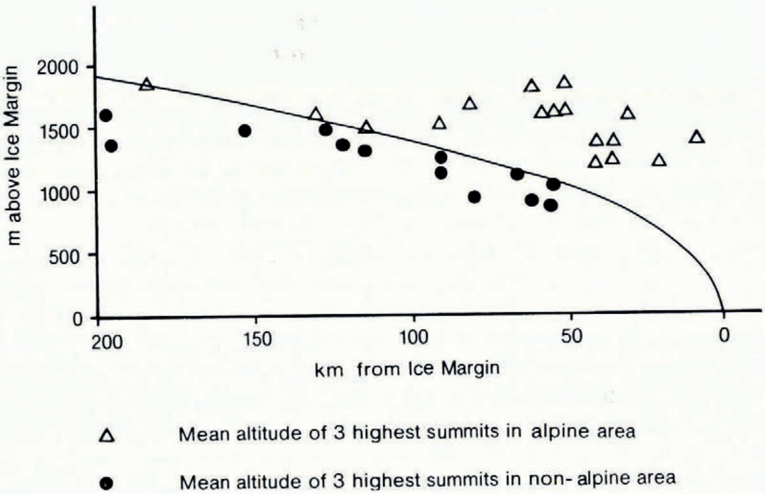

Fig. 10. The relationship of alpine landscapes to the former maximum Laurentide ice-sheet surface profile. Alpine landscapes are confined to massifs sufficiently high to have escaped inundation by the ice sheet.

that the correlation agrees over such details as the relative width of the zone which is wider in the west than in the east. It might be suggested that geological variations affect the position of the zone of intense erosion. For example, the western edge of the zone on the western plains coincides with the edge of the shield. Whereas such geological conditions may partly influence the position of the zone in this area, it is sufficient at this stage to note that the pattern also occurs in Labrador–Ungava where there is a more uniform spread of shield rocks both within and on either side of the zone of intense erosion.

The central area of areal scouring around Hudson Bay coincides with an area where the basal ice was at the pressure melting point. This relationship is as expected. However, the areal scouring that occurs between the zone of intense erosion and the former ice-sheet

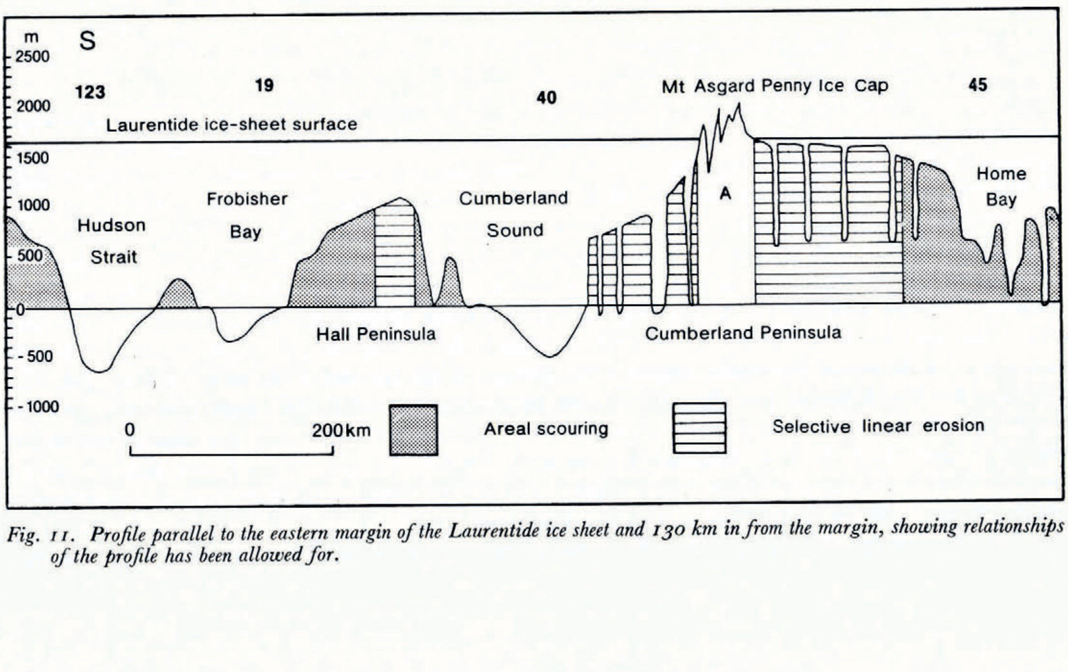

Fig. 11. Profile parallel to the eastern margin of the Laurentide ice sheet and 130 km in from the margin, showing relationships of the profile has been allowed for.

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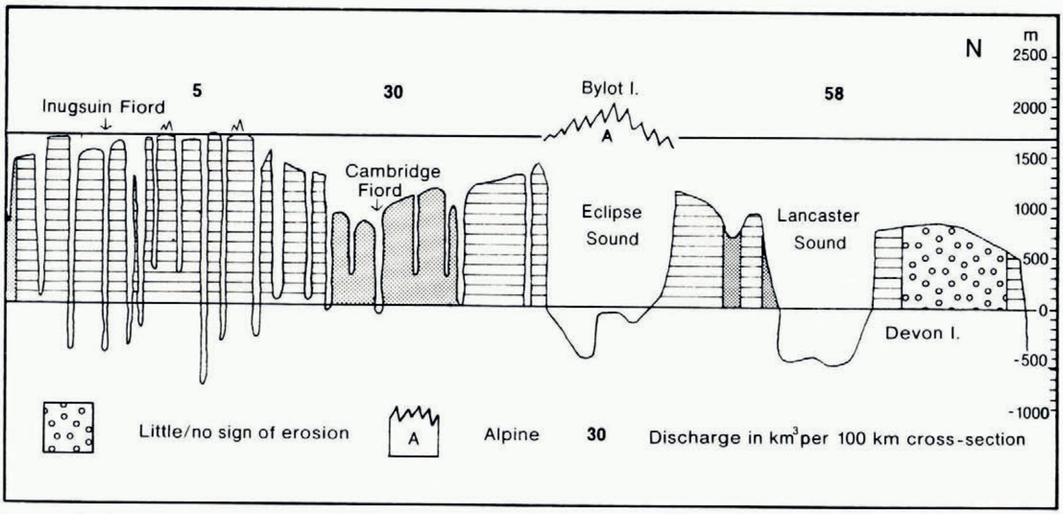
periphery coincides with both cold-based and warm-melting zones. There are several possible explanations and a full answer must await more detailed field study than has been attempted in this paper. One possibility is that the zone has been eroded beneath cold-based ice which was carrying a considerable thickness of debris inherited from the warm-freezing zone immediately up-stream. Another possibility is that some areas, especially nearer the ice-sheet periphery, have been subjected to erosion beneath the outer zone of warm-based ice. This zone was found to be the least stable of all and relatively modest changes in the climatic input variables could dramatically increase the width of the zone. Yet another possibility is that the areal scouring in this intermediate zone relates to conditions before or after the steady-state pattern of Figure 9 was established.

There is no obvious direct relationship between landscapes of selective linear erosion and broad variations in basal thermal regime. In Greenland there is a tendency for the landscape type to occur in environments where the maximum ice sheet was nourished under a continental climatic regime rather than a maritime climate (Sugden, 1974). Such a tendency may also be reflected in eastern North America where it can be seen that the landscape type occurs more frequently in the north than in the south.

Testing the relationship between landscape type and topography

At the scale of the Laurentide ice sheet as a whole, the role of topography seems subdued and relatively unimportant. Much of the bed of the former ice sheet is relatively flat and gently sloping. The main exception is in the east, where the land rises to form an uplifted, westward sloping plateau. It is in these eastern and northern areas that topography has played an important role in influencing glacial erosion.

Alpine landscapes occur along the western periphery of the Laurentide ice sheet and, as might be expected, appear to coincide with those massifs which rose above the maximum ice-sheet surface profile (Fig. 10). The ice-sheet profile in Figure 10 is based on the assumption that the ice was grounded as far as the 200 m submarine contour. Inland of this margin, the surface profile was obtained by analogy with existing stable ice sheets and has the form $y = a + bx + cx^2$, where $a = 0.607$, $b = 0.005$ and $c = -0.2 \times 10^{-5}$ (Sugden, 1977). The mountain altitudes were obtained by taking the mean of the three highest peaks in each



between landscape type, topography and ice-sheet thickness. Differential isostatic depression between the margin and the line alpine area and these were then plotted at the appropriate distance inland from the ice margin. In addition, the closest adjacent massif unaffected by alpine glaciation was also plotted on the diagram. Following Walcott (1970), an allowance was made for isostatic depression of the ground following inundation by the ice sheet which amounts to 100–200 m at the ice margin and 200–400 m at a distance of 200 km from the ice margin. These figures give differential isostatic depression of *c.* 200 m between the ice margin and a point 200 km inland and this has been built in to Figure 10. Bearing in mind the assumptions involved in constructing such a diagram, the apparent correlation in Figure 10 between alpine scenery and those massifs which rose above the ice-sheet profile seems too good to be fortuitious. This is especially so when one realizes that the summits of an alpine area may be only a few hundred metres higher than the summits of a non-alpine plateau only a few tens of kilometres away. A good example of this latter relationship is provided by the contrast between the Mount Asgard alpine area of Cumberland Peninsula and the adjacent slightly lower plateau upland around the Penny Ice Cap (Fig. 11).

In view of this apparent correlation, it seems fair to suggest that the contrast between plateau and well-developed alpine scenery reflects the contrast between those areas once submerged beneath the maximum Laurentide ice sheet and those massifs which were sufficiently lofty to escape inundation. As a result, these upstanding massifs were subjected to periglacial and local glacier action throughout the glacial age. As would be expected, the local glaciers were constrained by the shape of the massif on which they formed and thus exploited pre-existing river valleys to form the dendritic trough pattern of today. At lower levels some of these massifs are traversed by troughs whose orientations clearly reflect the action of ice-sheet drainage.

Topography has an important influence on the location of landscapes of selective linear erosion. All occurrences of the landscape type are associated with either the upland plateau which forms the eastern upland rim of North America or with uplands in the Arctic Archipelago (Fig. 11). The reason for this relationship may be that topography influences the basal thermal regime of the ice sheet so that the ice is warm-based over the troughs and cold-based over the intervening plateaux. The map of basal thermal regime in Figure 9 suggests that most of the upland rim of eastern Canada was covered with cold-based ice. The main exceptions are parts of Baffin Island where there were locally high ice velocities (owing to the thinness of the ice cover) which created sufficient frictional heat near the base for the ice to be warm-based. However, the calculations in Figure 9 were carried out for an average ice thickness over a 100 km wide "stream" of ice. This means that any channelling effect of valleys was ignored. In such a case, it is probably more realistic to imagine most ice being discharged down the valleys and that ice velocities and thus frictional heat was also concentrated in the valleys at the expense of the intervening uplands. Sample calculations assuming that 50–75% of the ice was discharged through the valleys confirmed that the ice would have been cold-based over the plateaux and warm-based in the valleys. Moreover, the calculations suggest that this topographic effect causing convergence or divergence was about ten times more important in creating this pattern of basal thermal regime than the other contributing factor of varying ice thickness.

The topographic relationships just described may help explain the pattern once the glacial troughs were excavated to approximately their present size. However, they do not necessarily explain the origin of the landscape type. To do so, it would seem necessary to postulate the existence of pre-glacial valleys incised into the upland edge of Canada. Any such irregularities would channel ice flow as soon as the ice sheet built up. It is notable that the existence of such pre-glacial river valleys has been postulated on various grounds by others (Mercer, 1956; Ives, 1957; Sim, 1964; Bird, 1967). Moreover, the plan view of many fjord systems would seem to support this hypothesis. Many fjords are sinuous and when viewed as a whole they form roughly dendritic patterns (with varying degrees of tectonic control)—just as would be expected if they followed pre-existing river valleys (Fig. 12). A particularly good example of a dendritic fjord system following pre-existing river valleys occurs in the vicinity of Nansen Sound between Axel Heiberg and Ellesmere Islands (Hattersley-Smith, 1961).

Topography clearly influences the distribution of landscapes of areal scouring at a local scale. A common pattern around Hudson Bay, Foxe Basin, and southern Baffin Island is for uplands to be lightly scoured and to be surrounded by lower, heavily scoured landscapes.

Fig. 12. Dendritic fjord pattern in the Cambridge Fiord area, north-east Baffin Island, as seen in LANDSAT-1 image.

In some situations the upland has escaped all visible signs of glacial erosion. In the central areas of the ice sheet, where thicknesses were of the order of 3 000–4 000 m, there would seem to be two main reasons for this, namely the reduced ice thickness over the upland and the tendency for ice to diverge round the upland. Both characteristics would cause lower than average temperatures over the upland. One could speculate that areas with little or no sign of glacial erosion, such as parts of Southampton Island and Hall Peninsula, may have been overlain by cold-based ice and that most debris-carrying ice was diverted round them.

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Calculations confirmed that the relatively minor modifications to the ice-temperature profiles accompanying such topographic differences would be sufficient to cause such a pattern in the basal temperatures.

Farther north, the topographic relationships of landscapes of areal scouring are different. As areal scouring becomes less common towards the north it is increasingly restricted to areas of ice convergence. Two excellent examples occur in Baffin Island in the vicinity of Home Bay and Cambridge Fiord. Figure 11 shows how these two areas are topographic lows across the uplands of Baffin Island. Calculations of ice discharge along the coast of Baffin Island, made on the basis of the form and flow lines of the ice sheet, suggest that these two zones were evacuating between six and nine times as much ice per unit length of coast than the intervening area. Clearly, such a contrast can be expected to lead to important contrasts in the creation of frictional heat. Other fine examples of the association of areal scouring with zones of convergence can be seen at the head of Eclipse Sound, on either side of Somerset Island and on southern Devon Island (Fig. 2). In all these cases it can be suggested that much of the ice sheet was cold-based and that frictional heat was able to produce enough heat to raise the basal ice to the pressure melting point only where there was convergent ice flow.

The relationships between topography and areal scouring may be conceived as different ends of a continuum in that they are local variations superimposed on an overall tendency for basal ice temperatures to fall from the ice-sheet centre towards the north. Areal scouring becomes progressively less common towards the north where it is increasingly confined to especially favourable topographic locations. The converse argument also applies to landscapes with little or no sign of glacial erosion.

Testing the relationship between landscape type and geology

Geological variations seem most important at a local scale, though their importance at a macro-scale cannot be overlooked in the particular case of North America. It can be suggested, for example, that in general there is a tendency for areal scouring to be associated with shield rocks and minimal erosion or deposition to be associated with younger Palaeozoic sediments. However, examination of the shield boundaries reveals many anomalies which do not fit this simple generalization. A particular example is Victoria Island which is clearly affected by areal scouring and yet which is largely underlain by Palaeozoic rocks. At a more local scale the role of geological variation is clearer. Examples may be taken from northern Baffin Island and Somerset Island where there are extensive outcrops of Palaeozoic rocks, mainly limestones. Although there are no field measurements on which to base a generalization, one might predict that these rocks are more permeable than the adjacent shield and that therefore there would be less erosion. Such appears to be the case. On Somerset Island, the western boundary between areal scouring and areas with little or no sign of glacial erosion roughly coincides with the boundary between Palaeozoic limestones and shield rocks. Moreover, an area of little or no sign of glacial erosion on Brodeur Peninsula coincides almost exactly with an exposure of Silurian limestone, although in this case it is impossible to exclude the contributory role of topography since the area is also an upland. To the west and south of northern Baffin Island and Somerset Island, there is no such relationship between permeable rock and landscapes with little or no sign of erosion. Large areas of Melville Peninsula, Southampton Island and southern Baffin Island are underlain by Palaeozoic limestones and yet are ice-scoured.

A partial answer to this apparent paradox may concern the relationship of geological variations to other broad trends within the Laurentide area. The north Baffin and Somerset Islands areas lie close to a boundary between areal scouring to the south and little or no sign of erosion to the north. In such a marginal position, variation in rock type may be able to play a role. Farther south, any local variation introduced by changes in rock type may be insufficient to overcome the overall tendency for areal scouring. As with topography, geological variations then seem to be able to produce only limited local variations to a dominant overall pattern. Clearly, this is an hypothesis which needs much more stringent testing than has been attempted here.

A model of Laurentide ice-sheet erosion

Figure 13 is an attempt to conceptualize the possible relationships between erosional landscapes and the main variables affecting glacial erosion for the Laurentide ice sheet. The left-hand part of the ice sheet may be envisaged as an approximately north–south profile from Ellesmere Island to Hudson Bay, while the right-hand side is a composite profile from the east coast to Hudson Bay. Areal scouring affects most of the central ice-sheet zone where basal ice conditions change from warm-melting at the centre, through warm-freezing to a cold-based zone (but containing debris). A maximum amount of erosion occurs in association with the warm-freezing zone which affords an effective means of debris evacuation. Towards the north, areal scouring gives way to areas with little or no sign of glacial erosion where an

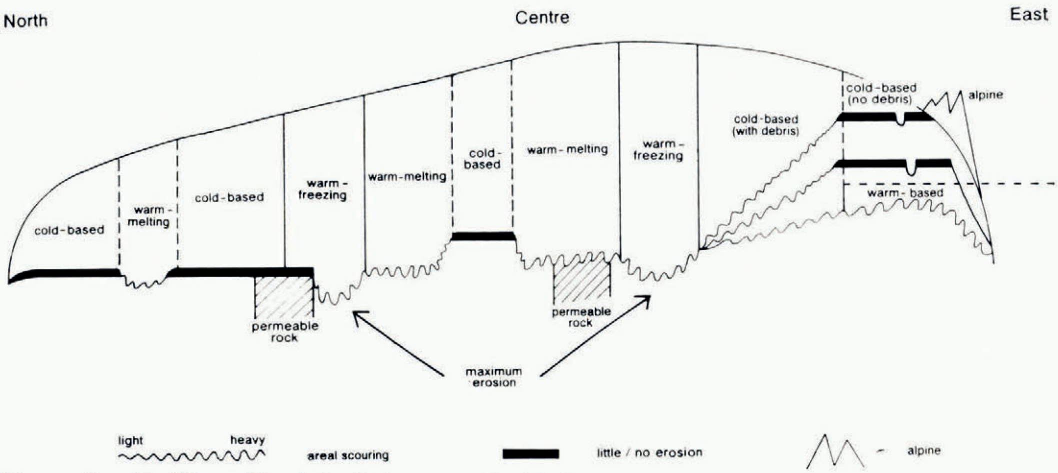

Fig. 13. A model of the possible relationship between erosional landscapes and main variables affecting glacial erosion, namely basal thermal regime, topography and bedrock geology.

essentially unmodified pre-glacial landscape has been protected beneath a cold-based, debris-free ice sheet nourished in a continental climate. The ice is free of debris because this area was a northern spur of the Laurentide ice sheet and as a result was largely unaffected by flow of debris-rich ice from the centre. Towards the upland rim of the east coast there are three type situations. In the maritime south, areal scouring extends over all surfaces, including high plateaux. Farther north, areal scouring does not affect plateau surfaces and the landscape type gives way to landscapes of selective linear erosion or, when the land rose above the ice-sheet profile, to areas of local alpine relief.

Local and regional variations are superimposed on these broad trends. In the centre, uplands are overlain by cold-based ice and have escaped modification by areal scouring. Farther north, areal scouring is confined to favourable topographic sites, such as depressions and zones of ice convergence. Geological variations in bedrock may have an effect on landscape type only near zones of transition from one basal thermal regime to another.

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Relationship of erosional landscapes to maximum ice conditions

Though long suspected in the case of small glaciers and ice caps (e.g. Penck, 1905; Haynes, 1972), it has not yet proved possible to demonstrate that landscapes eroded by ice sheets are equilibrium forms whose dimensions and morphology are adjusted to the amount of ice discharged during glacial maxima. There are indications that this is the case in North America.

The near coincidence of the reconstructed ice-sheet profile with the plateau of central Baffin Island between Clark and Macbeth Fiords offers a rare opportunity to determine whether the dimensions of the fjords which transect the upland are related to the discharge of Laurentide ice. In this case, it can be assumed that little ice-sheet ice moved over the plateau and that virtually all crossed the mountain rim by means of the fjord troughs (Fig. 11). Using the same ice-sheet reconstruction as before, the discharge passing down each fjord was derived from measurement of the width of the ice mass tapped by each fjord. Maximum depths of the fjords occur at the point where the fjords pass the mountain crest (Løken and Hodgson, 1971) and consequently cross-sectional areas were measured at this point, using 1 : 250 000 scale maps. Where known, the true depth of the fjord was used in the measurements. In the remaining cases, where the true depth was not known, a median depth of 600 m was taken (median between the shallowest and deepest fjords described by Løken and Hodgson (1971)). Even though there are many possible sources of error, it was interesting to discover a strong and significant relationship between fjord size and ice discharge (Fig. 14). There are signs that this relationship continues offshore where troughs are cut into the continental shelf. The deepest offshore troughs are associated with the convergence of several fjords. Moreover, the two deepest offshore troughs lie in the vicinity of Home Bay and Cambridge Fiord—the two main low-lying discharge routes across Baffin Island (Løken and Hodgson, 1971). This tentative evidence of a relationship between trough size and ice discharge at the maximum implies that the troughs have achieved some sort of equilibrium with ice-flow conditions of the maximum.

A similar conclusion is also suggested by the relationship of the alpine scenery to the projected ice profiles. It can be suggested that during the main periods of erosion the profile

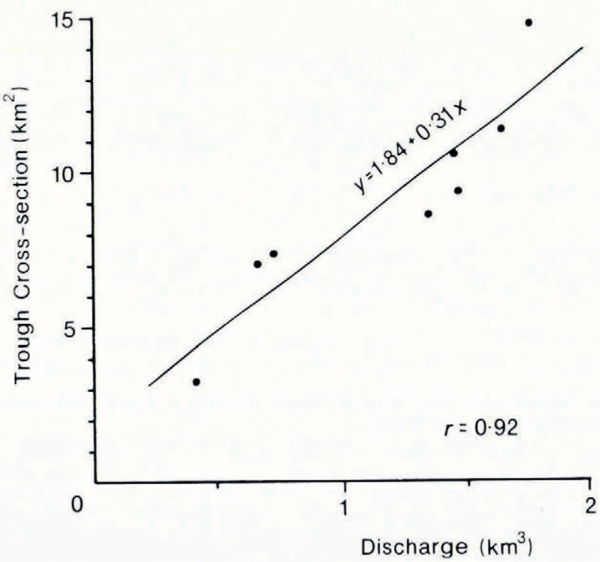

Fig. 14. The relationship between fjord size and ice discharge from the Laurentide ice sheet, central Baffin Island.

must have lain in approximately the projected position. If it was higher, more alpine landscapes would have been submerged. If it was lower, more of the high plateau areas would have been modified by local valley glaciers. The consistent and clear distinction between the two sets of summit heights strongly suggests long periods of maximum ice conditions.

A final piece of evidence concerns the broad landscape patterns. It has been suggested in this paper that there are consistent and predictable relationships between landscape patterns on the ground and the basal thermal regime reconstructed for full Laurentide maximum conditions. This coincidence implies that the erosional landscapes may reflect conditions of the full maximum.

The conclusion that ice-sheet erosional landscapes reflect maximum glacial conditions has several important implications:

(1) It affects the type of questions which may be asked about ice-sheet erosion. In particular, it suggests that the concept of an equilibrium landscape is potentially helpful in the analysis of links between process and form.

(2) It suggests that erosional evidence can be used to gain some indication of past ice-sheet behaviour. It is sometimes argued that the Laurentide ice sheet was intrinsically unstable and that it never attained maximum steady-state conditions for a long period of time. However, a period of the order of 100 000 years is probably necessary before steady-state thermal conditions as represented in Figure 9 become fully established. If this is the case and if the apparent relationship between basal thermal regime and erosional landscapes is justified, a long period (or periods) in a maximum steady-state condition is implied. This would suggest that the short-lived maximum of the late Wisconsin glacial age is not typical of earlier maximum phases responsible for erosion of the main landforms.

(3) Another implication concerns the long-term possibility of improving the understanding of basal temperature variations in ice sheets through study of the landforms on the ground. This offers the prospect of working back from the field evidence via basal temperature regime to the refinement of the original input data such as ice thickness, surface climate, and geothermal heat flow. This, in turn, provides another way of tackling the problem of reconstructing past Quaternary environments. A most interesting example of such an approach based on slightly different assumptions is currently being developed in association with the CLIMAP project (personal communication from T. Hughes, 1977).

Conclusions

It is perhaps useful to conclude on a cautionary note. The purpose of this paper has been to present some information about landscapes of glacial erosion in the area formerly covered by the Laurentide ice sheet. Relying on spatial correlations, it has been suggested that the landscapes can be interpreted in terms of variations in the basal thermal regime of the ice sheet at its maximum, with modifications introduced by topography and bedrock geology. These spatial correlations are of course no proof of the reality of the postulated relationships. Together they merely strengthen an hypothesis which is available for further testing and falsification. The hypothesis hangs around the following statements:

(1) Landscapes of glacial erosion are related primarily to the basal thermal regime of the ice sheet.

(2) Landscapes of glacial erosion are equilibrium forms related to maximum glacial conditions.

(3) Mechanisms allowing evacuation of debris rather than those of abrasion or fracture may be the most important in influencing the *amount* of glacial erosion achieved by an ice sheet.

(4) Cold-based ice may accomplish erosion if it has a debris load, inherited for example from an up-stream zone of regelation.

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