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A FRAMEWORK FOR THE INVESTIGATION OF MEDIAL MORAINE FORMATION: AUSTERDALSBREEN, NORWAY, AND BERENDON GLACIER, BRITISH COLUMBIA, CANADA

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ABSTRACT. Morphology of medial moraines on Austerdalsbreen, Norway, and Berendon Glacier, British Columbia, depends upon englacial debris supply. Major sub-types of this "ablation-dominant" model are related to the zone of debris entrainment relative to the firn line, and the manner of entrainment.

On Austerdalsbreen, debris derived from extraglacial bedrock slopes is entrained via crevasses at the confluence of two ice-cap outlet glaciers below the firn line. Revelation of crevasse-bound debris generates a distinct ice-cored morphology which is destroyed as crevasse bottoms are revealed down-glacier.

On Berendon Glacier ice streams coalesce above and below the firn line. Above the firn line, debris from extraglacial rock outcrops, subnival and subglacial zones, undergoes seasonal sedimentation with snowfall, and extends throughout the ice depth. Distinct moraine morphology in the terminal zone is related to continuing debris supply. Most debris is transported at depth near the glacier base.

An "ice-stream interaction" model where medial moraines formed below the firn line from the confluence of ice streams with large lateral moraine load are morphologically controlled by flow, explains morphology on the Berendon Glacier in the main confluence zone only. Down-glacier, this moraine becomes "ablation dominant". A minor "avalanche-type" model is also recognized.

RÉSUMÉ. *Modèle de développement de moraines médianes: l'Austerdalsbre en Norvège et le Berendon Glacier en Colombie Britannique, Canada.* La morphologie des moraines médianes de l'Austerdalsbre en Norvège et du Berendon Glacier en Colombie Britannique dépendent de l'approvisionnement en sédiments intraglaciaires. Les principaux sous-types de ce modèle "à ablation dominante" se distinguent à partir de la situation de la zone d'entrainement des sédiments par rapport à la ligne des névés et du mode d'entrainement.

Sur l'Austerdalsbre les sédiments issus des pentes rocheuses non englacées sont entrainés à travers les crevasses vers la confluence des glaciers exutoires des deux calottes, en dessous de la ligne des névés. La réapparition de moraines liées à des crevasses engendre une morphologie particulière à coeur de glace qui est détruite lorsque les fonds de crevasses ressurgissent en bas du glacier.

Sur le Berendon Glacier, les courants de glace se réunissent au-dessus et en-dessous de la ligne des névés. Au-dessus de cette ligne, les matériaux issus des rochers extérieurs au glacier et ceux des zones sous-glaciales et sous-nivales se trouvent enfouis sous la sédimentation saisonnière due aux chutes de neige et se répartissent dans l'épaisseur de la glace. On peut mettre en relation dans la zone terminale une morphologie distincte de la moraine selon le type d'apport de matériaux. La plus grande partie des matériaux sont transportés près du fond du glacier.

Un modèle "d'interaction des courants glaciaires" où les moraines médianes formées sous la ligne des névés à partir de la confluence des flux glaciaires avec une forte charge morainique latérale sont contrôlées morphologiquement par le courant, explique la morphologie du Berendon Glacier uniquement dans la principale zone de confluence. Plus bas sur le glacier cette moraine devient du type "ablation dominante". On a reconnu également un "type à avalanches" de moindre importance.

ZUSAMMENFASSUNG. *Modelle für die Ausbildung von Mittelmoränen: Austerdalsbreen, Norwegen, und Berendon Glacier, British-Columbia, Kanada.* Die Morphologie der Mittelmoränen am Austerdalsbre in Norwegen und am Berendon Glacier in British-Columbia, Kanada, hängt vom Nachschub an Schutt aus dem Gletscher ab. Wichtige Untertypen dieses "ablationsbedingten" Modells stehen in Beziehung zur Zone der Schuttaufnahme relativ zur Firnlinie und zur Art der Aufnahme.

Am Austerdalsbre wird Schutt, der von Felshängen ausserhalb des Gletschers stammt, über Spalten am Zusammenfluss zweier Auslassgletscher der Eiskappe unterhalb der Firnlinie aufgenommen. Der Austritt spaltengebundenen Schutts erzeugt bestimmte Formen mit Eiskernen, die sich auf lösen, sobald die Spaltensohlen gletscherabwärts herauskommen.

Am Berendon Glacier vereinigen sich Eisströme ober- und unterhalb der Firnlinie. Über die Firnlinie wird Schutt aus Felszonen ausserhalb des Gletschers sowie aus schnee- und eisbedeckten Zonen im Wechsel mit Schneefallschichten sedimentiert; er durchsetzt den Gletscher in seiner ganzen Tiefe. Bestimmte Moränenformen im Zungengebiet stehen in Beziehung zum andauernden Schuttnachschub. Der meiste Schutt wird in der Tiefe nahe der Gletschersohle transportiert.

Ein Modell der "Wechselwirkung zwischen Eisströmen", worin die Morphologie von Mittelmoränen, gebildet unter der Firnlinie aus dem Zusammenfluss von Eisströmen mit starken Seitenmoränen, von den Fliessverhältnissen bestimmt wird, genügt am Berendon Glacier nur zur Erklärung der Morphologie in der Hauptzone des Zusammenflusses. Diese Moräne wird gletscherabwärts "ablationsbedingt". Ein untergeordnetes Modell vom "Lawinentyp" lässt sich ausserdem feststellen.

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INTRODUCTION AND OBJECTIVES

Medial moraines are marked and well-defined features of many glaciers, predominantly compound glaciers formed from the joining of two or more ice streams from basins in the accumulation zone. They are revealed in varying states of development over and along the time-transect of the glacier surface in the ablation zone.

This paper proposes several models for the origins and morphological development of medial moraines as described in the literature and as exemplified in two field investigations, one on Austerdalsbreen, Norway (Eyles, 1976), and one on the Berendon Glacier, British Columbia (Rogerson and Eyles, unpublished).

PREVIOUS WORK

A concise account of early ideas on the origins of medial moraines appears in Charlesworth (1957, Vol. 1, p. 406–07). He ascribes first recognition of their true origin to B. F. Kuhn in 1787, clarified over fifty years later by the works of Agassiz, Charpentier, and Godeffroy.

Heim (1885, p. 345–46) recognized that medial moraines need not be formed at the junction of ice streams through the union of lateral moraines, but may also be formed in compound firn basins and not revealed until further down-glacier. Salisbury, in a classic paper (1894) made a full exploration of glacier debris systems and included the further example of medial moraines formed from subglacial rock bosses as first suggested by Tyndall (1872). Thus, early ideas on medial moraine origins were quite comprehensive.

Detailed field examination of medial moraine morphology was less systematic although Salisbury described the widening of medial moraines down-glacier in response to continuing englacial sediment supply. Hess (1907[a], [b]) determined the supply of englacial and subglacial debris to medial moraines of the Hintereisferner, but concentrated more on the significance of the medial moraines in the general erosion of glacierized basins than to their morphological development.

A large literature discusses minor relief features on medial moraines without relating them to the type of origin of the moraine as a whole. Dirt-cones, rock tables and supraglacial melt-stream activity have been well researched (Agassiz, 1840; Forbes, 1859; Ray, 1935; Lewis, 1940; Sharp, 1949; Swithinbank, 1950; Wilson, 1953; Streiff-Becker, 1954; Krenek, 1958; Lister, 1958; Kozarski and Szupryczński, 1971; Drewry, 1972; Knighton, 1973): a literature on dirt cones has, for instance, existed since 1750 (Thorarinsson, 1960).

More recent work has drawn attention to the important relationships between medial-moraine morphology and the causal factors of origin, sediment supply, and sediment thickness. Rapp (1960) demonstrated that the medial moraine of Templefjorden, Spitsbergen is entirely supraglacial being essentially transported talus. Ives and King (1955) reached similar conclusions concerning the medial moraine of Morsárjökull, Iceland. Loomis (1970) working on the large medial moraine formed at the junction of the north and central arms of the Kaskawulsh Glacier, Yukon Territory, also considered debris to be predominantly supraglacial, as did Lister (1958) on Britannia Gletscher, north-east Greenland. On Kaskawulsh Glacier, moraine morphology was considered in terms of differential ablation of debris-laden and clean ice. Young (1953) had previously recognized a direct correlation between moraine height and thickness of debris cover on the medial moraines of Breiðamerkurjökull. Loomis considered that constant down-glacier moraine width on the Kaskawulsh Glacier did not reflect lateral compression between the confluence ice streams; low rates of englacial sediment supply provide a sufficient explanation. Small and Clark (1974) related the development of medial moraine morphology on the lower Glacier de Tsidjiore Nouve to a careful account of sediment incorporation and supply. Debris is entrained in crevasses at the confluence of two ice falls below the firn line. A lower limit of englacial debris supply can be recognized:

cessation of englacial debris supply results in the degeneration of relief, hastened by extensive new crevassing. Publication by Small and Clark coincided with field work on Austerdalsbreen which exhibits a similar pattern of moraine development (Eyles, 1976).

Models

Schematic models of medial-moraine formation and morphological development were constructed during, and have been refined since, work on the Berendon Glacier. They serve as a useful introduction to a detailed study of the medial moraines of both Austerdalsbreen and Berendon Glacier. Medial moraines can be seen (Fig. 1) to be formed of debris from a variety of sources, deposited on or in the glacier by a number of routes, and revealed down-glacier with varying morphological consequences. Important variables in the recognition of discrete models and sub-models therefore become:

1. moraine origin with reference to the firn line;
2. source and character of debris supply to or into the glacier;
3. source and character of debris supply to the moraine, when distinct from 2;
4. morphological development of the moraine including changing shape, height and breadth.

These variables form a framework for detailed examination of the moraines of both glaciers.

The total number of types and sub-types of medial moraines recognized could be considerable, but if the emphasis is directed to the relationship between sediment supply and morphological development, two important models emerge. Debris comprising medial moraines may be held englacially and revealed down-glacier by ablation, or be largely supraglacial and therefore not dependent on ablation for surface expression. Moraines formed from englacially transported debris are here termed "ablation dominant" (AD) since they

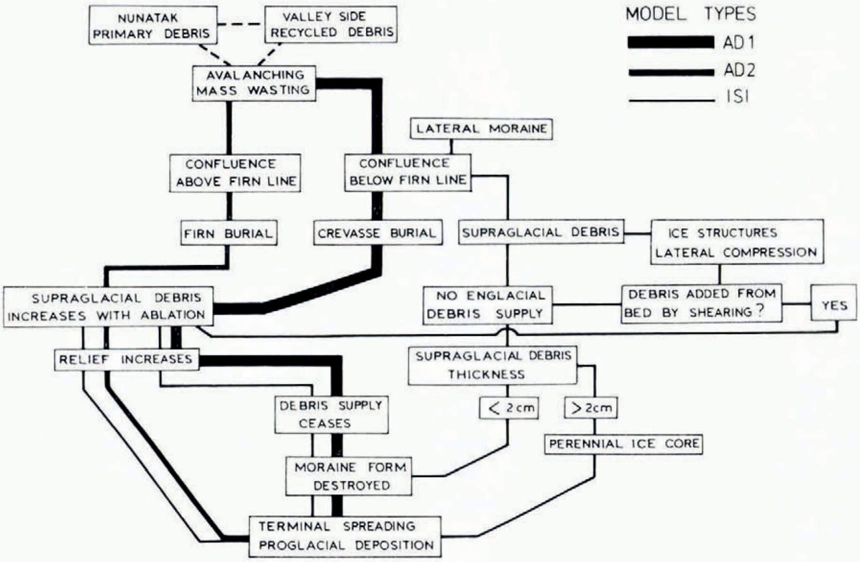


Fig. 1. Schematic models of medial-moraine formation.
AD1: "Ablation-dominant" model; below firn-line sub-type.
AD2: "Ablation-dominant" model; above firn-line sub-type.
Is I: "Ice-stream interation" model.
The figure of 2 cm was derived from Berendon Glacier.

depend on ablation for surface expression. Moraines formed with immediate supraglacial expression at the confluence of large ice streams, often by the joining of two lateral moraines, are here described by the "ice-stream interaction" model (ISI). A third, minor model, the "avalanche type" is also recognized and described (AT). The ablation dominant model has three sub-types dependent on whether englacial material is incorporated below the firn line, via crevasses (AD1: ablation dominant, below firn-line sub-type); above the firn line through the sedimentation of annual snow and debris layers (AD2: ablation dominant, above firn-line sub-type); or subglacially from an ice-covered rock knob (AD3: ablation dominant, subglacial rock-knob sub-type). This last sub-type was recognized on neither Austerdalsbreen nor Berendon Glacier, but is included from the reliable accounts of its existence elsewhere.

Field methods

Field methods on both glaciers were designed to elucidate the important relationship between englacial sediment supply and changing moraine morphology.

On Austerdalsbreen in 1974 a long profile of the moraine was surveyed by undergraduates of the University of Leicester and the ablation rates of moraine zones of varying debris cover were measured to examine the relationship between debris and moraine relief.

On the Berendon Glacier a more extensive programme was undertaken which included detailed sampling of sediments along the moraines and at nunatak rock walls in the firn basins and further experimental ice-melt studies reported elsewhere (Rogerson and Eyles, unpublished). Of particular interest to the investigation of models was the construction of debris clearance sites, where supraglacial debris was removed from moraines over areas of up to 500 m^2 to permit observation of the quantity of englacial sediment revealed by ablation at the surface. In addition the repeated tacheometric measurement of 50 stakes along the line of the medial moraines, allowed determination of ice velocity and strain-rate. In the absence of any marked correlation between the form of medial moraines and local ice velocity and strain-rate these measurements will only be briefly discussed. Detailed description of field methods and derived velocity and strain-rate data are to be found in Eyles (unpublished).

The "ablation dominant" model: below firn-line sub-type (AD1)—Austerdalsbreen

Austerdalsbreen lies on the southern margin of Jostedalsbreen, Europe's largest ice cap. The glacier is fed by two ice falls, Odinsbreen and Thorsbreen both about 800 m high and 300 m wide (Fig. 2). A third ice fall, Lokebreen, to the west, has thinned and ablated back to the regional snow line which traverses the ice falls approximately 1 600 m a.s.l. Ice velocity along the medial line of the ice falls decreases from approximately 2 000 m $year^{-1}$ at the apex (King, 1959), and inversely correlates with an increase in ice depth from less than 40 m in the ice falls to greater than 120 m below the junction (Ward, 1961).

Transverse surface waves immediately below the ice falls merge down-glacier into a double arcuate system of ogives with an alternation of diffuse surficial debris and clear ice bands. The lower albedo of the former results in alternating troughs and waves with a relief amplitude of 1 m. King and Lewis (1961) invoked wind-blown dust, longitudinal attenuation and high melt-season ablation rates to account for differences in ice types comprising the ogive suite. The medial moraine becomes a marked morphological feature in the same zone as systematic ogive banding emerges.

Dynamics and debris throughput of the AD1 model

1. The regional snow line lies 1 600 m a.s.l., close to the apex of the ice falls. None of the debris incident upon the margins of the two ice streams becomes bedded in firn, except where small units of firn fill shaded crevasses.

2. Bedrock material is derived by rockfalls and slides from an extensive outcrop between Odinsbre and Thorsbre ice falls, and is englacially entrained at the margins of the ice streams via deep crevasses. In addition, some debris is buried by occasional ice avalanches from the "Thor's Horn" avalanche site (Fig. 2). For such crevasse-bound debris a lower depth of englacial penetration can be suggested which may be well-defined (Small and Clark, 1974). Penetration beyond this general limit may occur (Glen and Lewis, 1961) although it is unlikely that entrained material penetrates to the base of the glacier. There is little contact between subglacial load and crevasse-bound debris for the compressive flow of the main glacier trunk at the base of the ice falls and resultant increasing ice depth (Glen, 1956; Ward, 1961) effectively sever such contact.

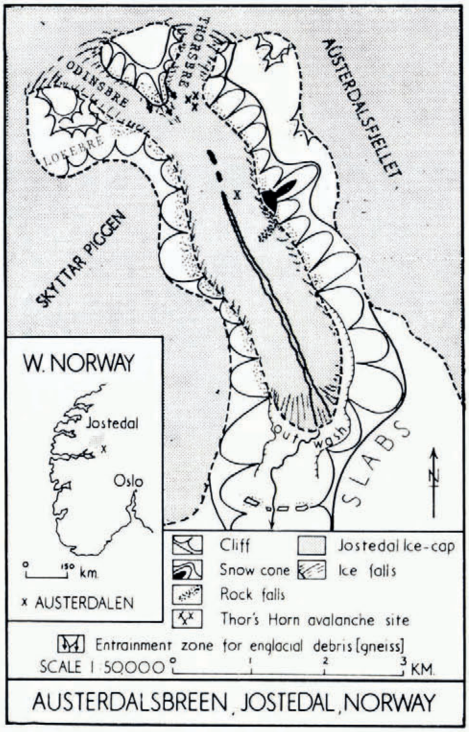
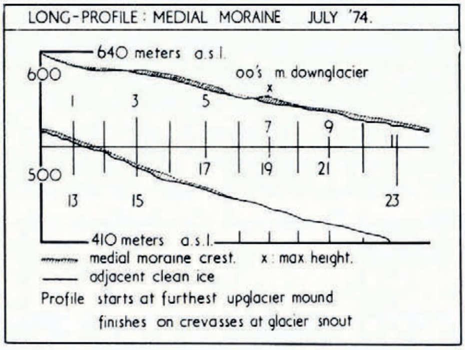


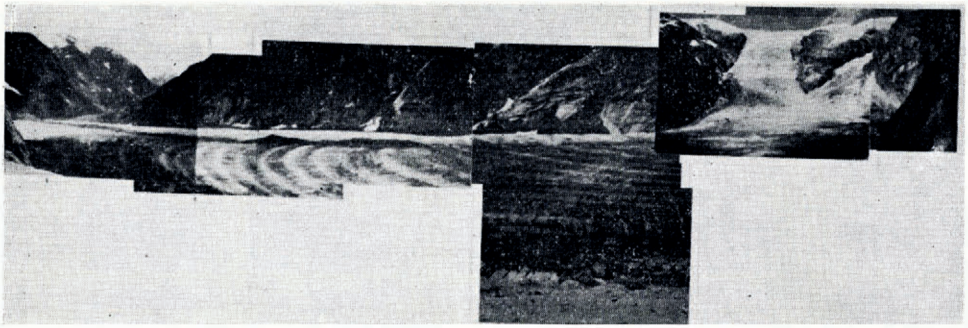
Fig. 2. Location of Austerdalsbreen, Jostedal, Norway. × *is that point where moraine height reaches a maximum (12 m) relative to bare ice.*

3. Englacial debris is progressively revealed down-glacier (Fig. 3). Discontinuous debris mounds along the medial line, with no observed systematic relationship to ogive bands, merge down-glacier to form a typical medial moraine in response to continuing englacial debris supply. The early appearance of isolated mounds approximately 500 m below the confluence may represent debris entrained in shallower crevasses on the ice falls. No evidence exists to suggest that shear planes have influenced sediment supply to the moraine. Shearing activity in the manner described elsewhere by Bishop (1957) and Boulton (1967) does not occur.

Approximately 1 200 m below the ice falls the englacial supply of debris ceases. Distinct beading of the lower part of the medial moraine, in harmony with ogive banding, does not represent seasonal differences in the quantity of englacial material but mass movement of moraine sediment into summer ogive troughs (Eyles, 1976). The insignificant quantity of



(*a*)



(*b*)

Fig. 3.

(*a*) *Long profile of Austerdalsbre medial moraine surveyed in July 1974. Note the absence of a positive moraine relief in the terminal area.*

(*b*) *The moraine viewed from the snow cone* (*Fig. 2*). *Note the base of the ice falls and irregular debris mounds along the medial line. Moraine morphology collapses down-glacier of that point at which moraine height is greatest relative to bare ice. Note also the winter ogive waves and dirty summer troughs. Composite photograph taken in July 1974.*

englacial debris in ogives has been well known since the studies of Huxley on Ghiacciaio della Brenva (Huxley, 1857), and the contribution of ogive debris to the medial moraine on Austerdalsbreen can be ignored. Elsewhere however, as for instance on Mer de Glace in the French Alps, an irregular discontinuous medial moraine exhibits large ice-cored debris mounds clearly derived from summer ogive bands.

4. Differential ablation between clean and debris-covered ice results in the formation of an ice-cored moraine 800 m down-glacier from the confluence (Fig. 3). The moraine increases to a maximum height of 12 m almost 1 200 m below the confluence. This greatly exceeds the 9 m of ice melt experienced in an average melt season on adjacent clean ice (King, 1959). The ice-core is thus perennial and possesses differential relief at the commencement of each melt season (Hannell and Ashwell, 1959). Down-glacier, height decreases rapidly and lateral attenuation of surface debris dominates over vertical development of the moraine (Fig. 3). The zone in which relief collapses is crevasse-free, unlike the equivalent zone described by Small and Clark (1976) on the lower Glacier de Tsidjiore Nouve. Width increases from 40 m in the vicinity of maximum relief to over 200 m in the terminal zone. In this zone the growth of ice cores is terminated by the lateral dispersion of debris over the flanks of the core. Topo-

graphic inversion occurs as accelerated ice-melt rates characterize the exposed crests of the ridges where debris is lost by sliding over the ice-core flanks. With debris covers of <1 cm, ice-melt rates were accelerated by up to 30% resulting in a depressed moraine morphology in the terminal zone (Fig. 3).

THE "ABLATION DOMINANT" MODEL: ABOVE FIRN-LINE SUB-TYPE (AD2)—BERENDON GLACIER

Berendon Glacier (lat. 56° 15′ N., long. 130° 5′ W.) has a drainage basin area of 53 km^2 within the Boundary Ranges of the northern Coast Mountains of British Columbia (Fig. 4). Its location adjacent to copper-concentrating facilities of the Granduc Operating Co. has attracted much attention (Untersteiner and Nye, 1968; Fisher and Jones, 1971). The glacier, which is receding at present, consists of two major tributaries, north and south arms, which coalesce 2.2 km above the glacier terminus and give rise to a broad medial moraine which will be considered later in this paper. Either side of this moraine prominent ice-cored medial moraines ablate out of north and south arm ice in the terminal area. The development of these moraines is explained with reference to the "ablation dominant" model: above firn-line sub-type (AD2).

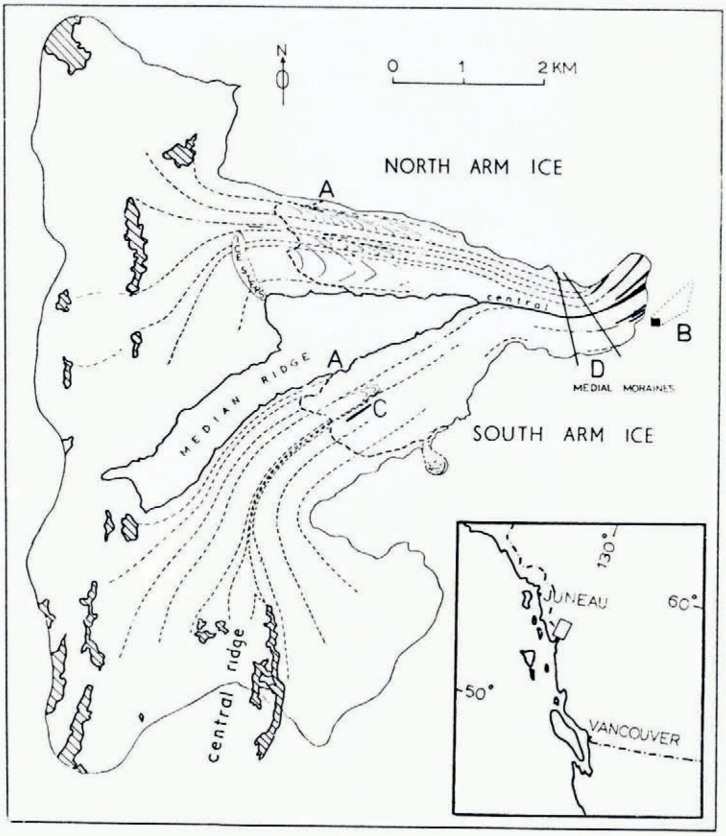


Fig. 4. Berendon Glacier, its location and medial moraines. Medial moraines in the terminal area of north and south arms can be traced up-glacier above the firn line (A) to individual accumulation basins where bedrock nunataks emerge. The location of Granduc Mill is depicted (B), as is the site of the "avalanche-type" moraine (C). D marks the terminal ice-falls.

Dynamics and debris throughput of the AD2 model

1. Debris septa can be traced up-glacier from distinct medial moraines north and south of the central moraine (Fig. 4). The septa appear immediately below the firn line and clearly relate to junctions in flow units above the firn line. Distinctive lithologies present in the moraines of south arm permit accurate extrapolation from the firn line to known bedrock outcrops up-glacier.

2. Source areas for debris septa can be related to subaerial sites of rock falls in the firn basins. Usually an upper ice and snow carapace is separated from the main firn mass in the valley bottom by free faces in bedrock up to 500 m high. Fresh, primary debris is generated subglacially by the upper ice carapace, appearing as well-defined debris bands in the glacier sole. This debris is released by avalanching to the firn below (Fig. 5) and undergoes compaction and sedimentation with seasonal snow loads.

Fig. 5. An avalanche of ice and snow bringing down bedrock debris from a nunatak rock-wall in the firn basin of south arm These dirty avalanches are the subaerial debris input for medial moraines.

Source areas of sediment must also exist subnivally and subglacially below the level of the main firn mass, where they may border on or merge with subglacial debris proper. No observations of such sites were possible in 1975.

3. Following confluence of ice flow units in the firn basin, debris is revealed at the firn line in distinct debris septa. The supply of englacial debris remains very low until very near the terminus. Debris septa revealed at the firn line are in the order of 2–3 m wide, varying little down-glacier until the zone near the terminus is reached. Consequently no ice-cored morphology is present, indeed enhanced ablation may occur on a minor scale, although this is confused with the effects of surface melt water.

Below the ice falls in the terminal area a great increase in the quantity of surface debris demonstrates an increased englacial debris supply to the moraines. A marked release of englacial debris at the surface is apparent from observations of those areas cleared of all debris. Below the terminal ice falls, well-defined ice-cored moraine ridges demarcate component ice-flow units; three on south arm ice but only one on north arm ice where morainal septa are relegated to a lateral position up-glacier by the thinning of lesser ice-flow units (Fig. 4). Moraine width increases down-glacier to 10 m before sediments merge and are subsequently consumed down splaying crevasses and the steep terminal ice front. Debris thickness along the moraine ridges seldom exceeds a few centimetres, and ice cores are seasonal, being accentuated during the summer but degraded in the fall, when ice melt is assisted by the better radiation absorption of debris over bare ice. Maximum moraine relief was 2.5 m and occurred within 150 m of the ice margin.

Clearly, the late development of distinct ice-cored medial moraines may be attributed to deep englacial transportation of debris from the firn basin. The bulk of medial moraine debris is transported through the glacierized basin at depth and is only revealed close to the terminus. While englacial debris extends throughout the depth of the ice, as suggested by de Martonne (1925–26), depicted by Sharp (1948), and demonstrated by Battle (1951), the distribution with depth is not constant. This may in fact represent two populations of sediment issuing from the firn basin; one derived subnivally and subglacially, and one derived subaerially such as from avalanches. The former unit may be part of the subglacial load proper. High rates of ice melt (6–9 m year^{-1}) and severe compressive strains measured along the moraines in the terminal area (Eyles, unpublished) may also promote higher concentration of englacial debris, after the manner proposed by Small and Clark (1976). It is not thought however, that these processes alone can account for the great increase in englacial sediments there.

THE AVALANCHE-TYPE MODEL (AT)

The Berendon Glacier exhibits only one major ice-stream junction below the firn line. Medial moraines visible up-glacier therefore may be supposed to result from junctions above the firn line. This, however, may not always be the case. A moraine on south-arm ice is evidently unrelated to any junction and is an example of the avalanche type.

On south arm a multi-ridged longitudinal moraine almost 1 000 m long is unrelated to surrounding AD2 septa. By its position close to the firn line the debris has been only

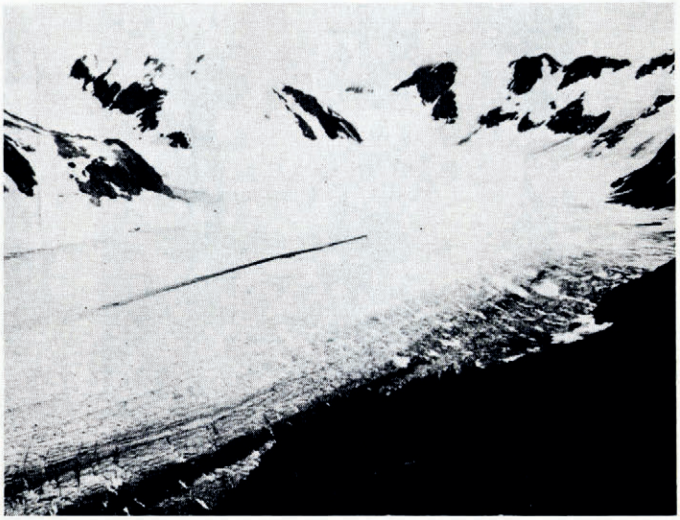


Fig. 6. "Avalanche-type" medial moraine on south-arm ice, looking up into the firn basin.

shallowly entrained and may be related to an exceptional rock fall from the ridge dividing the western and eastern firn basins. The moraine stops abruptly down-glacier (Fig. 6) and thus bears strong similarity to the "moraines de boulement" of Agassiz (1840). On Castner Glacier, Alaska, Nielson and Post (1953) attributed a similar unusual moraine to the sudden collapse of a rock spire, and another is described from Highway Glacier on Baffin Island (Ward, 1955). This moraine type is unimportant in the glacier debris system unless avalanching persists for many years resulting in englacial continuity of debris.

The "ice-stream interaction" model (ISI)

Distinct ice structures are known to develop where large valley outlet glaciers converge (Sharp, 1960; Brecher, 1969; Anderton, 1970; Loomis, 1970). In these zones, medial moraines are often formed by the merging of supraglacial lateral moraines. It is suggested that in many instances the character of ice flow such as lateral compression between merging ice streams, longitudinal strain-rate and ice velocity determine the morphology of the medial moraine rather than the nature of the englacial debris supply. This is termed the "ice-stream interaction" model, and while it appears to be better represented in the literature quoted, the model can be tested on Berendon Glacier where north and south arms combine to form the central medial moraine (Figs 1, 4 and 7).

1. Most of the debris supplied to the central medial moraine comes from the northern margin of south arm. At least two sources of debris are observed:

(a) morainal septa relegated to a lateral position by the thinning of lesser ice-flow units from the firn basin;

(b) recycled glacial debris from slopes of the median ridge down to the point of confluence.

In effect debris originates both above and below the firn line.

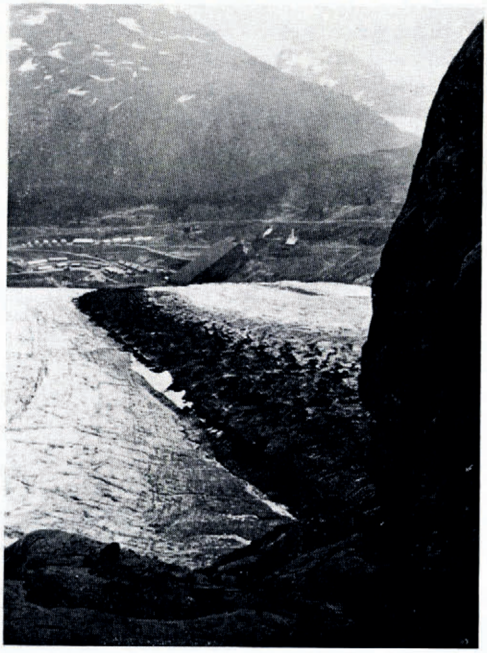


Fig. 7. The central medial moraine ("ice-stream interaction" type) with Granduc Mill in the terminal area. North-arm ice to the left. The longitudinal zone of shear along the glacier contacts (giving rise to the northern debris band) is visible as are transverse debris ridges on south-arm ice.

2. and 3. Moraine debris is entrained in crevasses of the south-arm ice fall, and in the fewer chevron crevasses along the southern margin of north arm. The crevasses penetrate to the bed on north arm, and ingested debris is contributed to the confluence as sub-marginal load. On south arm, in contrast, the crevasses above the confluence do not penetrate to the bed. With ablation and revelation of crevasse-bound debris, transverse till ridges are found in the confluence zone where they compose much of the south arm debris contribution to the medial moraine (Fig. 7). The confluence medial moraine consists of three lithologically distinct debris bands. The southern and central bands (volcanic conglomerate and tuff) are part of south arm ice and constitute the bulk of the debris. The northern band (argillite and siltstone) is formed by the shearing up of ingested submarginal moraine debris under the combined influences of severe lateral compression and differential ice-arm velocities (Fig. 7). Towards the terminus the three bands cannot be distinguished as the result of passage through the terminal ice falls. Debris clearance sites on the central moraine indicate that englacial debris supply above the terminal ice falls is absent (Fig. 8). Even the northern debris band, where debris is sheared up from submarginal zones providing maximum observed debris density, rapidly exhausts its supply. Below the terminal ice falls, the moraine is characterized by an englacial debris supply of increasing quantity. The emergence of a further debris band of distinct colour and lithology (volcanic conglomerate) well below the terminal ice falls is significant for it possesses no extraglacial outcrop in the firn basins and has been clearly derived subglacially or subnivally. In this zone subglacial debris is added to medial moraine sediments.

Fig. 8. A clearance zone across the entire central medial moraine, 40 m long and 3.5 m wide, at the end of August 1975. Note the absence of freshly revealed englacial debris, and the ice-cored mounds developed where debris was dumped during clearance. Elsewhere supraglacial debris thickness is insufficient to allow ice cores to develop.

4. The morphology of the moraine is best described with reference to three zones, the first in the immediate confluence area, and the others down-glacier; the second above and the third below the terminal ice falls.

Zone 1

In the first zone a distinct moraine morphology is found in response to the contrasting character of confluent ice streams. North-arm material sheared to the surface as described and comprising the northern debris band is generally 2–3 m wide and ice-cored, increasing in height down-glacier to a maximum relief of 1.5 m.

Ice-cored transverse debris ridges are common in the immediate confluence zone on south-arm ice but are rendered arcuate and lose their distinct form only 150 m down-glacier (Fig. 7).

No differential relief prevails on south-arm ice between clear and debris-covered ice as a result of the low depth of supraglacial debris. Severe lateral compression between the two arms has an important effect on the morphology of the moraine. Surface wave forms whose origin is in part due to severe compression at the base of south-arm ice fall have a wave-length of ≈ 60 m which approximates annual flow velocities. The lowermost wave crest is found along the contact zone, and consequently the surface of south-arm ice is higher than adjacent north-arm ice (Fig. 7).

Zone 2

The distinct morphology of the moraine in the confluence zone is lost down-glacier. Whilst individual debris bands can still be identified, they are not ice-cored and relief is indistinct. Rock tables and scattered dirt-cone groups add diversity. Moraine width (40 m) remains constant over a distance approaching 1 000 m. The immature morphology can be clearly related to the low volume of englacial debris as observed at clearance sites. In addition, differential velocity between north- and south-arm ice has ceased 800 m down-glacier of the confluence and is replaced by unified flow. Indeed it is significant that clearance of debris from these sites resulted in the development of an ice core over those areas where debris had been dumped (Fig. 8).

Zone 3

Below the terminal ice falls the release of englacial debris generates a more mature ice-cored morphology. The late appearance of the distinctly coloured volcanic conglomerate debris band generating a further ice-cored moraine ridge, is identical to the situation described in the AD2 model. A splaying crevasse system and terminal calving disrupts moraine form in the terminal zone where debris from englacial and subglacial sources has increased the width of the moraine to over 100 m. In all three zones of the moraine no correlation can be established between ice velocity and longitudinal strain-rate (Eyles, unpublished).

In conclusion, the morphological development exhibited by the central medial moraine below Zone 1 can be accommodated by the "ablation-dominant" model: complexity introduced by lateral compression of north and south arms is not a persistent determinant of moraine morphology down-glacier of the confluence zone. The moraine contains debris bands developed both above and below the firn line in the manner described for both sub-types of the "ablation-dominant" model (Fig. 1).

CONCLUSIONS

Two major models of medial moraine formation, the "ablation-dominant" and the "ice-stream interaction" model explain the development of medial moraine morphology exhibited on two temperate valley outlet glaciers.

(A) The "ablation-dominant" model relates moraine morphology to the nature of englacial debris supply and on this basis two major sub-types are formulated: (1) below firn-line sub-type, and (2) above firn-line sub-type. A third, minor sub-type is formed from subglacial rock knobs, but was not observed or studied on Austerdalsbreen or Berendon Glacier.

(1) Where moraines are formed below the firn line at the margins of ice-cap outlet glaciers (Austerdalsbreen), moraine debris is derived subaerially from nunatak areas in the confluence zone. Such debris is precipitated into crevasses and comes to occupy only a shallow englacial position. The quantity of englacial debris below the base of the deepest crevasses is small and is attenuated further by the thickening of ice in response to compressive strains at the base of the ice fall. Crevasse-bound debris is revealed down-glacier and an ice-cored moraine ridge generated. With the cessation of englacial debris supply as crevasses ablate out, moraine morphology collapses. "Annual" and "perennial" ice cores can be recognized.

(2) Where moraines are formed above the firn line (Berendon Glacier: north and south arms) debris released from rock walls is precipitated onto the firn surface where it undergoes sedimentation with seasonal snowfall. As a result, subaerially derived debris extends throughout ice depth, from the glacier surface to the bed, where additional debris derivation takes place. With the merging of flow units, a distinct vertical column of debris, a medial moraine or debris septum, is generated. The distribution of englacial debris with depth is not constant and the bulk of moraine debris is transported near the bed and only revealed in the terminal zone where it is associated with a developing ice-cored morphology. Subglacial debris is added to moraine sediments in the terminal zone. An ice-core is not present up-glacier, supraglacial debris quantities remain low, and moraine width remains constant. This is related to the decline in the quantity of englacial debris above the bed. This upper debris is derived entirely from extraglacial rock slopes and upper ice carapaces; the clarity with which medial moraines and debris septa are revealed immediately below the firn line reflects the rate of erosion in these areas.

(B) Medial moraines are generated in many instances below the firn line by the confluence of large valley outlet glaciers transporting lateral moraine debris. Medial moraine width is seen to remain constant down-glacier until the terminal zone is reached. An "ice-stream interaction" model of moraine formation relates unchanging moraine width to lateral compression between outlet glaciers and the complex patterns of ice flow found in these zones.

On Berendon Glacier the "ice-stream interaction" model is only substantiated in the immediate confluence area of two large valley outlet arms (north and south arms). Unchanging moraine width can be related to the low rate of englacial debris supply. Moraine morphology down-glacier of the immediate confluence zone is more clearly explained by reference to the "ablation-dominant" model, since debris septa contributing to the lateral moraine load of the arms are formed both above the firn line and below the firn line via crevasses.

(C) The "avalanche-type" model which accounts for medial moraines not formed at ice or firn junctions and with little or no englacial sediment supply, is regarded as a minor model. Such moraines may be quite transient features on a glacier surface.

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