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ON THE ORIGIN AND TRANSPORT OF ENGLACIAL DEBRIS IN SVALBARD GLACIERS

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Abstract. Very considerable amounts of englacial debris derived from the glacier bed are contained in the polar glaciers of Svalbard. It is suggested that this debris is largely incorporated by basal freezing on the down-glacier flanks of bedrock obstructions, although other freezing mechanisms and thrusting may be important. The basal freezing hypothesis predicts that vertical and lateral variations in englacial debris content should reflect the variation in subglacial rocks over which the glacier passes; this prediction is tested against an actual englacial debris sequence. The mode of transport of debris, including its stone orientation fabrics, is described, and also the way in which it reacts in zones of intense compression.

A generalization is suggested: that polar glaciers tend to contain much larger amounts of basally derived debris than temperate glaciers. This supports the view that the englacial incorporation of debris is controlled by the temperature regime of the glacier, and could be of considerable importance in the interpretation of the regimes of ancient glaciers from their deposits.

Résumé. *Sur l'origine et le transport des matériaux rocheux enchassés dans la glace des glaciers de Svalbard.* De très grandes quantités de matériaux rocheux enchassés dans la glace et issus de lit glaciaire sont contenus dans les glaciers polaires du Svalbard. L'auteur suggère que ces matériaux sont le plus souvent incorporés à la suite de regel basal sur les flancs aval des inégalités du lit rocheux bien que d'autres processus dus au gel ou au mouvement de poussée puissent être importants. L'hypothèse de regel basal permet d'affirmer que les variations en épaisseur et en largeur de la quantité des débris enchassés refléteraient les changements dans la structure des roches sur lesquelles s'écoule le glacier. Cette hypothèse a été vérifiée par l'observation d'un échantillonnage de matériaux rocheux enchassés. Le mode de transport et la texture des débris sont décrits, ainsi que leur comportement dans les zones de compression intense. Une généralisation est suggérée: ces glaciers polaires contiendraient de plus grandes quantités de matériaux provenant du lit rocheux que les glaciers tempérés. L'incorporation dans la glace d'inclusions rocheuses est fonction du régime thermique du glacier et pourrait être d'une grande importance pour l'interprétation du régime des anciens glaciers à partir de l'étude de leurs dépôts.

Zusammenfassung. *Herkunft und Transport von intraglazialem Schutt in Svalbard.* Beträchtliche Mengen von intraglazialem Schutt, der aus dem Gletscherbett stammt, enthalten die Polargletscher von Svalbard. Es ist anzunehmen, dass dieser Schutt hauptsächlich durch Frostabhub an den gletscherabwärts gerichteten Flanken von Hindernissen im Felsbett aufgenommen wird, doch können auch andere Gefriervorgänge und Schubkräfte beteiligt sein. Die Hypothese des Festfrierens am Untergrund sagt voraus, dass vertikale und seitliche Unterschiede im Gehalt an Innenmoräne das subglaziale Felsrelief, über das der Gletscher hinwegfliesst, widerspiegeln sollten. Diese Voraussage wird an einer wirklichen Verteilung der Innenmoräne geprüft. Die Transportart des Schuttes, einschliesslich der Orientierung seines Gesteinsgefüges, wird beschrieben, desgleichen sein Verhalten in Gebieten mit starker Kompression.

Folgende Verallgemeinerung wird vorgeschlagen: Polargletscher tendieren zu einem wesentlich grösseren Gehalt an Schutt aus dem Untergrund als temperierte Gletscher. Damit wird die Ansicht gestützt, dass die intraglaziale Schuttaufnahme vom thermischen Zustand des Gletschers abhängt. Für die Feststellung des Zustandes früherer Gletscher aus ihren Ablagerungen könnte dies von beträchtlicher Bedeutung sein.

Introduction

The glaciers and ice caps of Spitsbergen and Nordaustlandet (Svalbard) (Fig. 1) contain considerable amounts of englacial debris which is eventually deposited either as supraglacial flow till (Boulton, 1968) or as basal till. The nature of these tills, their probable lateral and vertical variation in lithology and erratic content, and some of the stone orientation fabrics found in basal till, depend upon the way in which englacial debris is entrained, the subglacial zones in which this occurs and the mode of transport. In the following sections the englacial entrainment of a single englacial debris band is described, and it is demonstrated that this has taken place by a process of basal freezing. Observations also show that debris is transported to different levels within the glacier along thrust planes, and it seems entirely reasonable to assume that this debris can also be transposed from a subglacial into an englacial position by thrusting. However, general considerations and detailed observations suggest that the greatest part of the englacial load is derived by basal freezing, a conclusion which is verified in one glacier by the systematic variation in the englacial debris load.

MAKAROVBREEN

Makarovbreen is a short and steep valley glacier, the most northerly on the western side of Raudfjorden in north-west Spitsbergen. The glacier terminates in a series of ice cliffs, the central part of which lie in a shallow lagoon behind an old morainic bar (Fig. 2). These cliffs allowed studies of the moraine-laden basal layers* of the glacier and observations of the orientations of pebbles and boulders within the ice.

Fig. 1. Map of part of Svalbard, showing the locations of glaciers referred to in the text.

Figure 3b shows a section along the northern ice-front cliff of Makarovbreen. In this cliff the greatest concentration of moraine is found in the lowermost 5–7 m; there is a sharp dividing line between this zone and the upper zone in which only a little moraine occurs. The material in the topmost 2–3 m of the moraine-rich ice consists mainly of angular grains from medium–coarse sand size to angular boulders 2 m in diameter. Some of the finer material occurs in thin, high ice-content bands up to 5 cm thick. Beneath this level, much of the glacier load occurs in narrow bands up to 2 cm thick, and consists mainly of silt- and sand-sized particles of angular rock flour, although rounded grains do occur. These bands tend to lens out laterally, although many are of considerable length (up to 50 m). The ice content

* "Englacial moraine" is material carried in suspension within the ice other than englacial fluvial deposits. "Debris" specifically refers to material derived from the glacier bed ([Ward], 1953), whereas till consists of moraine (often debris alone) which is no longer contained within glacier ice.

of the bands is extremely variable, ranging from 85% to 10% by volume. In those with a high ice content there are no contacts between particles, but in those with a low ice content the majority of particles are in contact, and in some there is a prominent structural lamination of the concentrated particles parallel to the bounding ice walls of the band. In addition to moraine particles which occur in bands, many are disseminated throughout the much cleaner ice which occurs between debris bands, and vary from fine silt to coarse sand and gravel. Sand and silt grains are angular with highly pitted surfaces, and large mica flakes are common. Large angular boulders 2 m in diameter, which are occasionally striated, also occur in this zone.

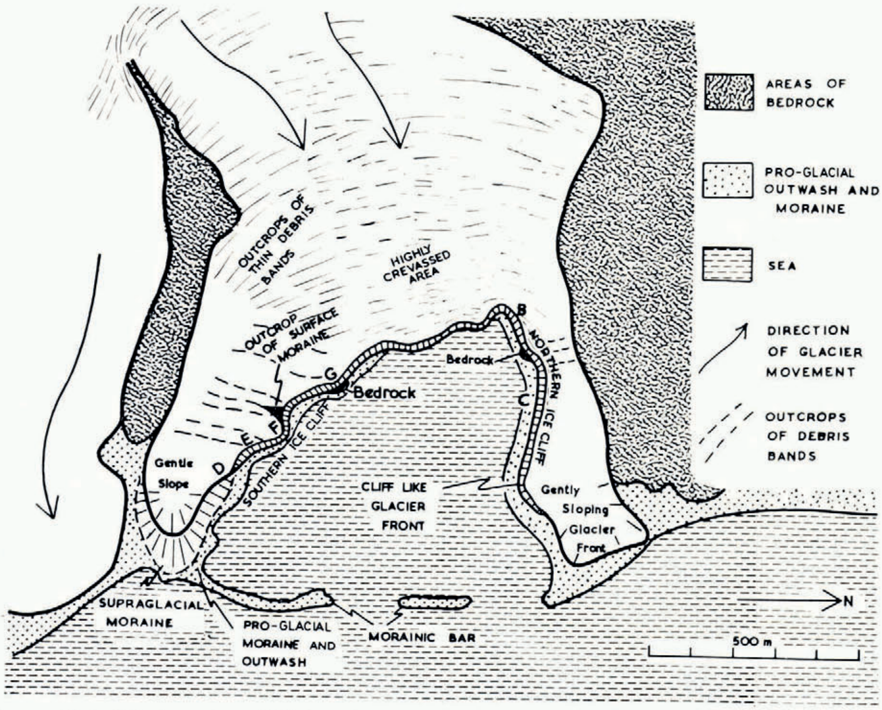

Fig. 2. Map of the lower part of Makarovbreen, showing the northern and southern ice cliffs BC and DEFG.

The coarse angular material contained in the topmost 2–3 m of the debris-rich ice appears to be derived from material which has fallen onto the glacier surface in the accumulation area, whilst the debris at a lower level consists largely of rock flour with a few rounded grains, and is derived from the glacier bed.

The foliation in the basal debris-rich ice is composed of two elements: layers of numerous gas bubbles, and alternating bands of ice crystals 0.5–1 mm and 3–8 mm in diameter. Ice rubbings made at points h and j (Fig. 3b) showed the long axes of coarse crystals are orientated normal to glacier flow. There also appears to be a minor amount of size differentiation of suspended debris in these different crystal bands, the bands of small ice crystals containing the smaller debris particles. The foliation is sub-horizontal, being arched upwards at two points where the glacier flows over bedrock obstructions. The bubble foliation is well developed, although it is better in the basal debris-rich ice than in the overlying cleaner ice; the crystal foliation is however poorly developed and often cut by the bubble foliation. A crystallographic study of the glacier ice was made using a portable Universal Stage and polarizing

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microscope. Specimens were collected from low levels within the ice at 1, 2, 3 and 3.8 m above the base of the cliff. Thirty-six readings of optic-axis orientation are plotted stereographically in X (Fig. 3b) and, although the measurements were so few, they show a strong orientation maximum of optic axes normal to the plane of ice foliation, an orientation which was very obvious on first inspection of the thin sections. A single strong orientation of this type is often found in cold polar ice. The average diameter of ice crystals in the topmost samples was 20 mm, whereas in the lowest sample it was 1–1.5 mm.

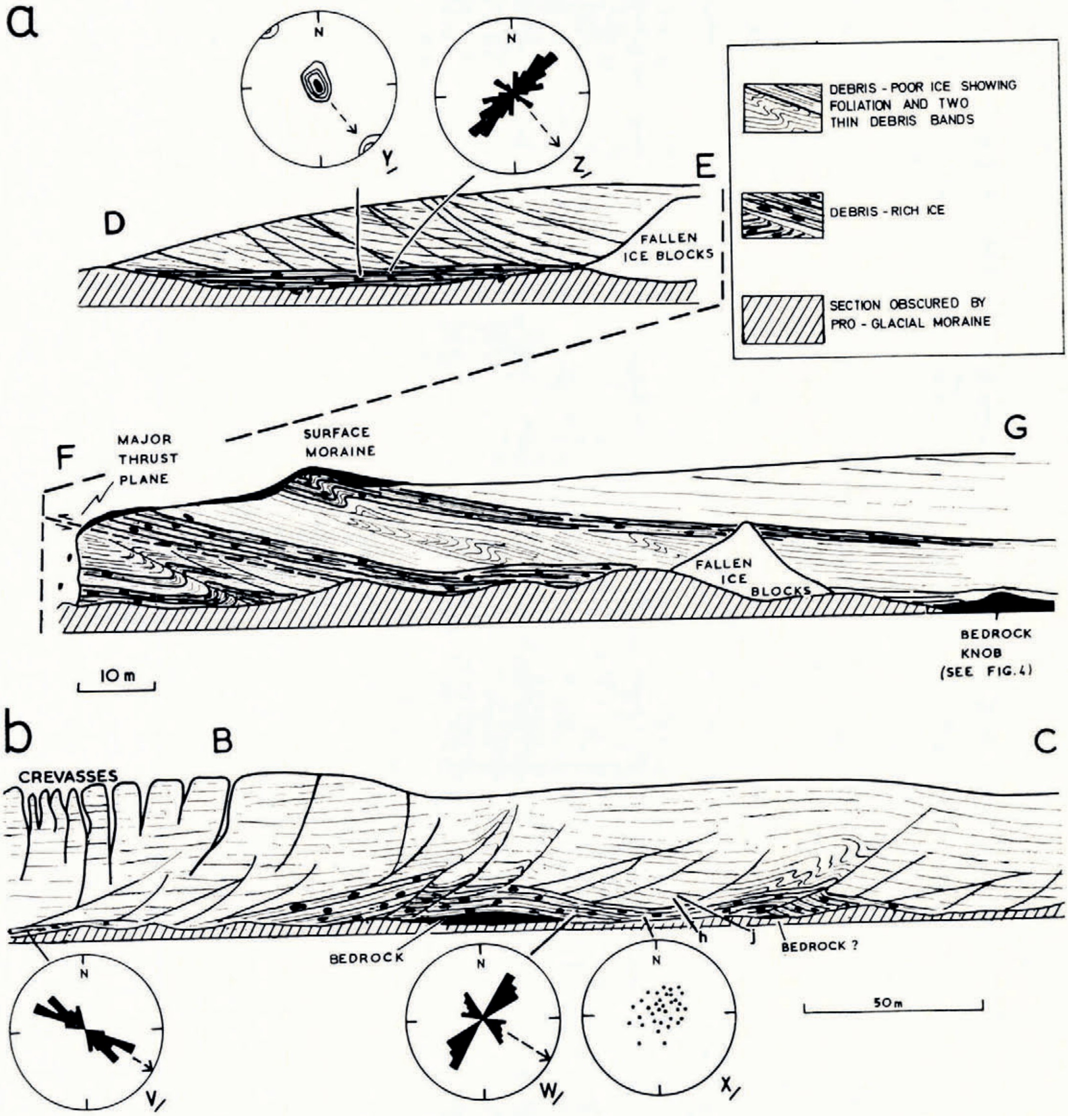

Fig. 3. a. Section along the southern ice-front cliff of Makarovbreen. b. Section along the northern ice cliff. V, W and Z are rose diagrams showing the orientations of the long axes of prolate- and blade-shaped stones projected onto the plane of ice foliation (49, 57 and 112 measurements, respectively). Y is an equal-area stereographic plot of poles to a–b planes of 128 blade- and plate-shaped particles (> 10 cm), the plane of projection being the plane of ice foliation (contoured at 0–1, 2–5, 6–10 and 11% per 1% of area). X is an equal-area projection (in the plane of ice foliation) of optic axes of 36 ice crystals. Dashed lines show the direction of glacier movement.

In the clean ice above the debris-rich zone there are a series of planes, often with debris entrained along them, which dip up-glacier at 20–85° and cut the crystal foliation which is often drag-folded. These planes have obviously acted as thrusts, but together with the crystal foliation they now appear to be relict as they are generally overprinted by the bubble foliation and when traced downwards are cut off sharply at or just below the junction with the basal debris-rich zone. However, at the two points where the glacier flows over bedrock obstacles, similar planes which are obviously active thrusts cut and displace both basal debris-bands and the bubble foliation in the overlying clean ice. Some high-angle planes which contain small amounts of relatively coarse angular material, and which are also cut off at the top of the debris-rich ice, appear to be old crevasses down which surface moraine has fallen and which have closed up in the zone of compression.

The orientations of boulders within the ice are easily determined because of their large numbers and elongate form. W (Fig. 3b) is a rose diagram showing the azimuths of long axes of prolate boulders in the lower debris-rich ice, and indicates a pronounced orientation maximum normal to glacier movement. However, to the west of point B (Fig. 3b) there are open crevasses indicating a state of tension, and measurements of long axes of prolate particles in the basal ice of this zone (V; Fig. 3b) reveal a pronounced peak parallel to ice flow.

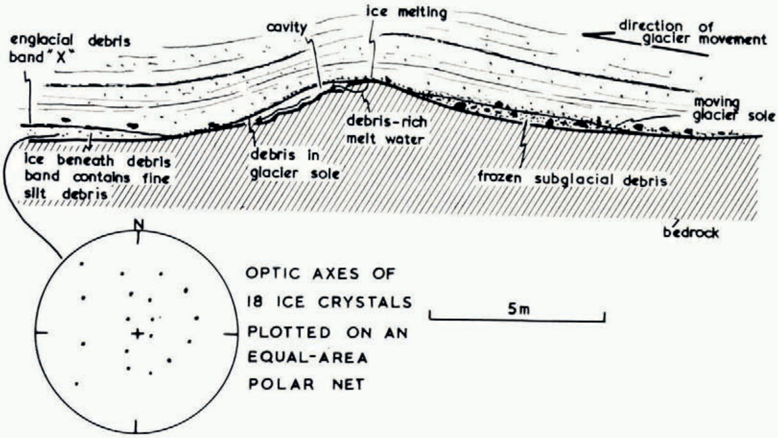

Fig. 4. A section of the glacier/bedrock contact exposed at G in the southern ice cliff of Makarovbreen.

The southern ice cliff of Makarovbreen (Fig. 3a) shows structures essentially similar to those of the northern cliff. Measurements of the azimuths of long axes of 128 rod- and blade-shaped stones in the lower debris-rich ice (Z; Fig. 3a) indicated, as at W in the northern cliff, an orientation maximum transverse to flow. In addition, poles to the *a–b* planes of blade- and plate-shaped stones from the same locality, plotted stereographically, indicate that *a–b* planes tend to lie in the plane of ice foliation, rarely showing any imbrication with respect to this foliation. (The *a*-, *b*- and *c*-axes of stones are the long, intermediate and short axes, respectively. The *a–b* plane is thus the plane in which the long and intermediate axes lie.)

Thrusting has also occurred at locality F (Fig. 3a), where active glacier ice has been thrust over the ice to the east, and the debris contained in the ice above the thrust plane is accumulating on the glacier surface as a prominent surface moraine. Two main series of bands give rise to this surface moraine. The uppermost consists of material derived from the flanking hills in the accumulation areas, but, if a correlation is assumed across part of the ice cliff obscured by a cone of fallen ice blocks, the lowest band can be traced to the glacier sole about 5 m west of the summit of a bedrock knob which lies beneath the ice. This is a low knob of granite-gneiss which has been partially uncovered by the ice (Fig. 4) and is exposed at the back of a shallow cave. To the right of the summit of the knob the glacier sole lies directly upon a maximum of 30 cm of till which lenses out both towards the summit of the knob and in an up-glacier direction where the sole lies directly on smoothed and striated bedrock. This subglacial till is partly frozen and consists of a few angular fragments up to 15 cm in diameter embedded in a fine-grained matrix of silt and sand. The glacier sole appears to be moving over this till which consists of rock fragments whose angularity and polymineralic composition indicate they are the products of glacier erosion. The 5–10 cm of ice immediately above the glacier sole contain a considerable amount of silt and sand with a few larger fragments up to 15 cm in diameter which protrude above this layer. Where the glacier sole lies on bedrock west of the subglacial debris pocket, a very thin wet layer of silt-sized rock flour occurs between the glacier sole and bedrock. On the down-glacier flank of the knob the glacier loses contact with bedrock for 4.5 m and below this cavitation the bedrock is comparatively irregular and unstriated. In sections normal to flow, the glacier sole above this cavity reflects the cross-profiles of the bedrock obstacle. There are few large particles embedded in the glacier sole above the cavity but the basal 4 cm still contains a considerable amount of silt-sized debris. At the point where the glacier loses contact with the bedrock knob, the ice contains interstitial water and some silt is melting out. 5 m east of the summit of the knob, a debris band 3–5 cm thick consisting of particles ranging from coarse sand to silt, and identical to those which occur over much of the basal zone of the glacier, intersects the glacier sole. The ice which lies between this band and bedrock contains only very fine silt-sized debris which is disseminated throughout it. A specimen of this ice was investigated microscopically using the Universal Stage. Eighteen measurements of optic axes of ice crystals were made and are plotted steroeographically in Figure 4 (inset). Notwithstanding the small number of measurements made, it can be clearly seen that the optic axes of crystals in this ice vary much more in orientation than those at higher levels in the northern cliffs recorded in Figure 3. The crystals in this ice rarely exceed 3–5 mm in diameter.

Discussion

Some of the structural history of the terminal part of the glacier and the way in which englacial debris is incorporated may be inferred from the above observations.

The terminal zone of the glacier in which overfolding and thrusting occur is a zone of compression, whilst the highly crevassed zone farther up-glacier is one of tension. The steeply dipping planes associated with drag folds and containing debris appear to be thrust planes, and large-scale overthrusting has obviously taken place in the southern ice cliff (Fig. 3a), resulting in emplacement of the surface moraine. It was noted, however, that prominent displacements occur only along those planes where the glacier flows over obstructions, whereas at other places the thrusts and folds are either cut out or "overprinted" by recrystallization in the basal debris-rich ice, or by reconstitution of a sub-horizontal bubble foliation in the upper debris-free ice. Thus it seems probable that thrusting only occurs in zones of increased compression at points where the glacier flows over bedrock obstacles. After the thrust structures have been carried beyond these zones by glacier flow they cease to operate and are overprinted by structures which are adapted to the new stress, which, though compressional, does not involve a sufficiently high rate of shear to give rise to shear fracture. Away from bedrock obstructions it is noticeable that, whilst relict thrusts and folds may survive in the upper debris-poor ice, they are destroyed in the basal debris-rich ice, and are often sharply cut out at the interface between the two. This appears to indicate that the greatest shear takes place in the basal debris-rich zone, and this is sufficient to cause rapid recrystallization and obliteration of thrust fractures which originally displaced the basal debris bands. In the overlying debris-poor ice, relict thrust planes and drag folds are not destroyed by rapid recrystallization, presumably indicating less shear and little differential movement in this zone, although the bubble foliation is rapidly reconstituted and overprints the thrusts and drag folds.

The measurements of particle orientation stress the contrast between the crevassed tensional zone of the glacier and the outer zone of compression. Long-axis orientation measurements of blade- and rod-shaped particles show a maximum parallel to flow in the horizontal direction in the former zone and transverse to flow in the latter. These variations suggest that particle orientations in these localities are controlled by the mode of deformation of the ice, and that long axes tend to align themselves in the direction of greatest rate of extension of the triaxial strain ellipsoid, which is parallel to flow in the tensional zone and transverse to flow in the outer zone of compression.

The material of the surface moraine above the southern ice cliff has been emplaced by the upward movement of debris-rich ice along an underlying shear plane but, although debris is transported from one place to another within the ice by thrusting, this does not necessarily imply that the debris was originally incorporated by this mechanism. Most of the high-angle planes, which are obviously thrusts, appear to have derived the debris which lies along them from the sub-horizontal debris bands which lie in the basal part of the ice. Thus the fundamental problem of the incorporation of basal debris in this glacier is that of the incorporation of the sub-horizontal debris bands. One of the latter which intersects the glacier sole is described on p. 217 and shown in Figure 4. Two mechanisms have been suggested which could have introduced supraglacial material into an englacial position at this locality:

(a) Thrusting.
(b) Regelation of water beneath the debris-rich glacier sole.

(a) It has been noted that thrust planes tend to form in ice which is over-riding bedrock obstacles. Thus the debris band "X" in Figure 4 could be a thrust plane which has developed because of the compression caused by flow of the ice over the bedrock knob. If this is a thrust, it is unlikely to be currently active as the ice east of the knob will be in a state of tension. The 5 m separating the crest of the knob and the debris band would thus represent the amount of basal slip since it was last active. There are, however, several objections to this hypothesis:

i. Identifiable thrust planes, such as those shown in Figure 3, truncate other structures in the ice, but the debris band "X" is completely conformable with other debris bands and does not truncate them.
ii. High-angle thrust planes occur in the same zone as the sub-horizontal debris band shown in Figure 4. Assuming that the angle of friction of glacier ice is constant, the inclination of thrust planes will depend upon the relative importance of the horizontal component of shear and the overlying ice load. Thus it is unlikely that sub-horizontal thrust planes could form in the same zone and at the same time as thrusts with a much greater inclination.

(b) An alternative explanation of the inclusion of the debris band in Figure 4 is that it is included within the ice by a process of basal freezing, similar to that suggested by Lliboutry (1964–65, p. 689). When a glacier flows over a bedrock step, a cavity is left on the down-glacier side, and subglacial water, produced by pressure melting over bedrock obstructions or by some other process, will tend to freeze in the low-pressure area formed by the cavity. Debris suspended in water derived from pressure melting at the summit of the knob, or from a subglacial fluid phase similar to that noted beneath the glacier sole, would then be locked up within the regelation ice beneath the debris band as widely disseminated debris. This process, operative during continuous flow of the glacier, could incorporate a debris band continuously until the obstruction is eroded. The present position of the debris band in Figure 4 can be explained by assuming that when the ice cliff fell away to reveal the summit of the knob the hitherto closed system was destroyed and regelation in the cavity ceased because subglacial water was able to flow away, and that the ice has flowed a distance of approximately 5 m since this event.

Some support for this hypothesis is provided by the crystallographic data. The optic axes of crystals in the obviously sheared ice in the basal part of the northern cliff are tightly grouped about the normal to the plane of ice foliation, whilst optic axes of crystals in the ice below the debris band which intersects the glacier sole (shown in Figure 4) have a much wider scatter. These two sets of readings were tested using Fisher's approximation (Irving, 1964) and showed a significant difference in the amount of dispersion at the 99% confidence level. This difference could be explained if the ice beneath the debris band were regelation ice in which shearing has not yet re-orientated the ice crystals to give a strong orientation normal to the ice foliation.

The type of regelation described above is on a scale which produces a relatively clean ice layer beneath a debris band which already exists immediately above the glacier sole, and is seen to the right of the summit of the bedrock knob in Figure 4. McCall (1952) has described a similar dense accumulation of the products of erosion in the basal ice of a temperate glacier. This initial introduction of debris into the basal part of a glacier may be a result of regelation against very small-scale obstructions, as described by Kamb and LaChapelle (1964), but there may well be other processes quite unrelated to regelation which could cause this. For instance, Hoekstra and Keeler have suggested that particles could diffuse into ice down a temperate gradient (Weertman, 1968; see also Hoekstra and Miller, 1965). It is also possible that particles could enter the basal ice for a limited distance down a shear gradient.

It is argued above that a specific mechanism of basal freezing accounts for one of the many sub-horizontal debris bands in the basal part of Makarovbreen. The arguments against thrusting presented above, and those given by Weertman (1961), appear to preclude a thrusting origin for most of the other sub-horizontal debris bands of Makarovbreen. As the only two mechanisms so far advanced to account for the englacial inclusion of originally subglacial debris are those of thrusting (Goldthwait, 1951) and basal freezing, and because the band "X" (Fig. 4) is identical to and conformable with the other sub-horizontal debris bands of Makarovbreen, it is suggested that the whole basal debris sequence is likely to be derived by a mechanism similar to that suggested for band "X" in Figure 4. The other basal freezing hypothesis proposed by Weertman (1961) seems inapplicable. This hypothesis applies to glaciers whose margins are frozen to the bed but which are melting basally in the interior, there being also an intermediate zone in which water freezes to the glacier sole, although the latter remains at the pressure melting point. Melt water forced outwards from the temperate interior by the pressure gradient freezes to the glacier sole at the margin, and cyclic movements of the surface dividing the outer and intermediate zones produce alternate freezing of subglacial sediment and water onto the glacier sole, thus incorporating a sequence of basal englacial debris bands. This hypothesis predicts that debris bands should consist of frozen subglacial sediment with intervening layers of clean ice, or ice with a very low debris content. However, much of the debris sequence on Makarovbreen consists of alternations of "debris bands", the majority of which have ice contents greater than 50% and layers of relatively clean ice in which the debris content is below 1%. The ice content of debris bands is thus much greater than would be expected in a frozen sediment. This debris-band sequence is thus much better explained as largely originating in the manner suggested for the debris band in Figure 4. The observations of Kamb and LaChapelle (1964) indicate that very small protuberances (0.5 cm) of the glacier bed are sufficient to cause cavitation and regelation, and thus potentially to include debris within the ice. Therefore, the large number of thin debris bands in the basal part of Makarovbreen could be produced by an irregular floor of very low relief. Erosion and accumulation beneath the glacier sole and incorporation of debris within the ice would thus be delicately balanced processes controlled essentially by the bedrock topography.

The hypothesis that debris bands in the basal part of Makarovbreen originated by the "freezing-in" of subglacial debris requires that much of the ice in the basal debris-rich zone has also been acquired by freezing onto the glacier sole. However, regelation of water derived from pressure melting against obstructions will not produce such net gain of ice but merely the redistribution of ice masses on the glacier sole. Debris bands produced by regelation on the down-glacier side of an obstruction will tend to be destroyed by melting against further obstructions, there being no cumulative addition of debris in the basal ice. Indeed, Kamb and LaChapelle (1964) showed that a basal debris layer incorporated by regelation against a projection never occurred more than 2.9 cm above the glacier sole, and that together with the regelation ice it was regularly destroyed by melting against further obstacles.

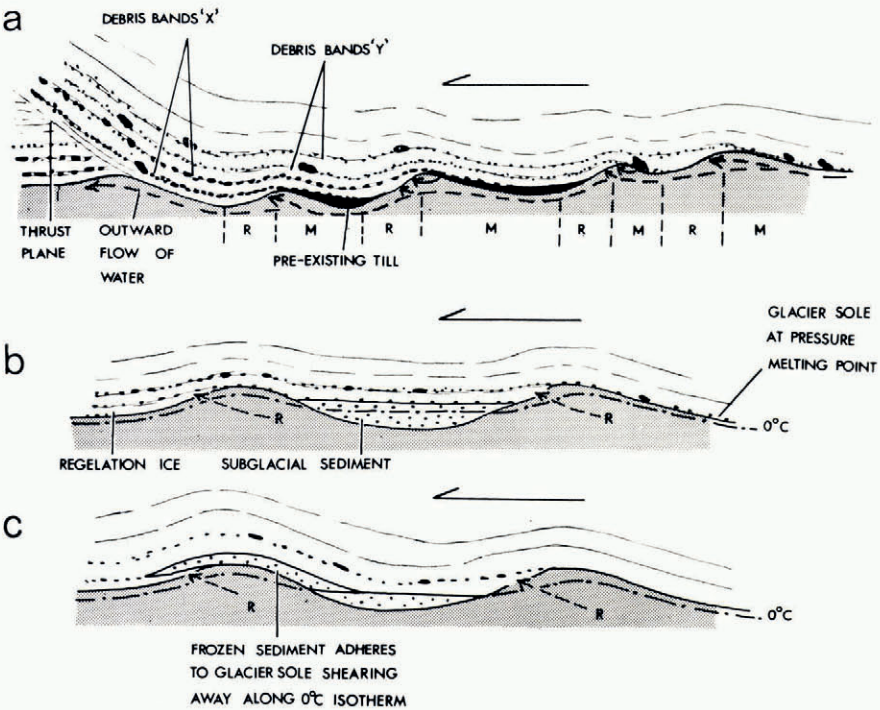

Fig. 5. Possible mechanisms for the englacial inclusion of subglacial debris at bedrock projections. In (a) debris eroded by the glacier adheres to its moving sole and is then incorporated englacially by the formation of regelation ice beneath it on the down-glacier flanks of bedrock obstructions. Most of the regelation ice forms from water moving subglacially outwards under a pressure gradient. This accretion of water pushes included debris bands above the regelation zone. Debris bands consisting of individual particles in suspension ("Y") are derived from the erosion of relatively hard bedrock, those consisting of suspended particular aggregates ("X") are derived from the erosion of relatively soft sediments, e.g. subglacial till. (b and c) show the way in which masses of subglacial sediment could be incorporated to form debris bands (which may be stratified) with a low ice content. R and M are zones of regelation and melting, respectively. Dashed lines show the flow of subglacial melt water from the glacier interior and from pressure melting against obstructions.

The net accretion of regelation ice necessary to build up a thick debris sequence in the outer zone of a glacier could however occur in a glacier with a cold-based margin by outward migration of melt water from the temperate interior (Weertman, 1961). A similar process is plausible for Makarovbreen for, although there are no temperature data, several facts suggest that this is a cold polar glacier. The close grouping of optic axes of ice crystals about the normal to the ice-foliation planes is a feature often noted in cold ice; and similar small north-easterly facing glaciers, 75 km south in Broggerhalvøya, have been found to be cold (Lliboutry, 1964–65). For these latter glaciers, [Corbel] (1966) suggested that the opening of large crevasses allows percolation of water to the glacier bed, and it is therefore possible that water produced in the highly crevassed zone of Makarovbreen could freeze to the bed in the outer zone, producing a net gain of basal ice and incorporation of basal debris in that zone. Whether pressure melting occurred on the up-glacier flanks of subglacial obstacles need not be important, for the regelation ice on the down-glacier flank could be derived largely from water migrating outwards from the glacier interior. Thus, although some of this regelation ice is likely to be destroyed against the next obstacle, there is still likely to be a net gain of ice. This migrating water could travel between the glacier sole and bedrock, or within the subglacial beds, if these are permeable. The amount of regelation ice forming in the outer zone would depend on the amount of melt water supplied and the temperature of the outer zone. The way in which accretion of such regelation ice could produce a sequence of englacial debris bands is illustrated in Figure 5a.

Origin of the debris load in other Svalbard glaciers

The excellent exposures on Makarovbreen are particularly valuable in that they give a relatively clear idea of the origin of the debris load in this one valley glacier. The other ice masses of Svalbard, ice caps, broad valley and piedmont glaciers, and areas of highland ice also display considerable volumes of englacial debris at their termini, and in order to attempt to infer generalized processes to account for the origin of this debris a summary of its main features is given below.

The englacial moraine load of most of the large glaciers is very much greater than that of Makarovbreen. By far the smallest part of this load is material derived from nunataks and valley sides in the accumulation area, and this tends to occur in relatively narrow bands and at a high level in any terminal ice cliffs. The load of englacial debris derived from the bed is however very much greater. It tends to occur in bands which vary from the thin (1 cm) bands noted on Makarovbreen to bands 5 m in thickness. Compositionally, four types of debris band derived from the glacier bed have been observed:

(a) By far the commonest are bands consisting of suspensions of individual particles in ice. The fine-grained particles are angular ranging from clay to coarse sand. The coarser particles, from cobbles to boulders several metres in diameter, are often striated and faceted. Ice contents generally exceed 50% by volume and bands may be of lenticular or planar form and of considerable length.

(b) Bands which are of similar dimensions and ice content to those in (a) but which consist of suspensions of grain aggregates (commonly clots of till) up to several centimetres in diameter.

(c) Bands of stratified debris with a very low interstitial ice content. These may be bands of silt, sand or gravel, generally lenticular in form, in which the stratification is planar, parallel to bounding ice walls. In a few cases the stratification is folded. The form and content of the bands is quite different from englacial fluvial accumulations (Boulton, 1967) and they are thus taken to be originally subglacial sediments.

(d) Bands similar to those in (c), in which the ice content is again merely interstitial but which consist of till (p. 220).

The four types of band noted above may be lenticular or relatively continuous and up to 5 m in thickness, except (b) which is relatively rare and has not been observed more than 0.5 m thick. The great majority of debris bands lie parallel to the glacier-ice foliation, and when zones away from the glacier margin are revealed in sea-cliff sections (cf. Fig. 3), or in dead ice masses, the debris bands are seen close to the glacier sole, forming a conformable sequence which is rarely more than 3–10 m thick. Such sequences have been described in several works (Garwood and Gregory, 1898; Lamplugh, 1911; Gripp, 1929; Donner and West, 1957; Klimaszewski, 1960; Szupryczyński, 1963; Boulton, 1968).

On the majority of glaciers there is no clear evidence for the origin of conformable debris-band sequences as there is on Makarovbreen, although the similarity between the sequence on Makarovbreen and other glaciers is striking. As yet, the two mechanisms of thrusting (Goldthwait, 1951) and basal freezing (Weertman, 1961) are the only ones which have been advanced to account for the origin of debris bands derived from the glacier bed. The second process certainly occurs and it is very likely that the first does too (Fig. 7). The main problem is one of their relative importance. The structural relationships of the conformable debris bands in Svalbard glaciers, which are by far the commonest types, are identical to those described by Weertman at the margin of the Greenland ice sheet, which provided a basis on which he rejected the thrusting hypothesis. Other equally applicable objections to the general application of this hypothesis are recorded in the discussion of the observations on Makarovbreen, and as was suggested for Sørbreen in Ny Friesland (Boulton, 1967), it is difficult to reconcile the occurrence of undisturbed bedded sediments along debris bands ((c) above) with an origin by thrusting. Perhaps the most important objection is that thrust planes cut and displace the glacier-ice foliation, whereas the debris bands referred to above are parallel to and conformable with this foliation (Fig. 7).

Thus it is suggested that a basal freezing hypothesis is the only one yet advanced which can account for all the features of basally derived debris bands which lie parallel to the glacier foliation. In this hypothesis the bands with only interstitial ice ((c) and (d)) would represent subglacial sediments, fluvial or lacustrine deposits and pre-existing tills, and could have been incorporated by Weertman's (1961) mechanism or by a variant of the mechanism suggested for the debris bands of Makarovbreen and shown in Figure 5b and c. This assumes that, whilst the glacier sole is at the pressure melting point, the 0°C isotherm lies some distance beneath the sole. Unconsolidated subglacial sediments would thus tend to freeze to the glacier sole, and slip would occur at the junction between the frozen and underlying unfrozen sediments, as the latter would have a relatively low shear strength. By this mechanism, subglacial accumulations of sediment could be incorporated within the ice without undue disturbance of their structure. As suggested on p. 220, Weertman's mechanism has difficulty in accounting for bands with a high ice content of types (a) and (b), but they can be explained by the hypothesis accepted for Makarovbreen. The bands containing suspensions of individual grains in ice would presumably represent accumulations in the glacier sole of the products of erosion of lithified bedrock (Fig. 5a, "Y"), which then became englacial by the formation of regelation ice beneath them. Those bands consisting of aggregations of particles suspended in ice would represent the products of erosion of unconsolidated subglacial sediments which had built up in the glacier sole (Fig. 5a, "X").

The hypotheses of basal freezing tentatively suggested for the glaciers of Svalbard require that considerable volumes of regelation ice should form on the glacier sole in the outer part of the glacier. Temperature studies indicate that such a process is quite plausible, for most glaciers are of sub-polar type (Ahlmann, 1936), and Palosuo and Schytt (1960) have shown that the ice of the ice cap of Vestfonna is cold in the ablation area and temperate in the accumulation area. Thus, on Vestfonna, melt water produced basally in the temperate interior and moving outwards under pressure could freeze to the glacier sole in the cold marginal area, and indeed the marginal ice of Vestfonna displays a considerable volume of englacial debris which could have been incorporated by this process.

Vertical variation in a conformable debris sequence

The hypothesis of basal freezing tentatively suggested for the conformable debris sequences in many of the glaciers of Svalbard makes a specific prediction that in an englacial debris sequence the basal material will be mostly locally derived and the topmost material will be farthest travelled. The thrusting hypothesis makes no such prediction; far-travelled and local material derived from the glacier bed would be expected to be randomly mixed.

An examination of the conformable debris sequence in that part of the frontal ice cliff of Aavatsmarkbreen in Oscar II Land (Fig. 6). This sequence lies in ice which is bounded above and below by thrust planes, and in which the foliation dips up-glacier ("X" in Fig. 7b). The lowermost prominent debris band, lying 1.5 m above the basal thrust plane, is 4 m thick and contains only interstitial ice. The dip of the band is 85° at the top of the section and 50° at the bottom. The basal part consists of a maximum thickness of 0.8 m of stratified gritty sand containing abundant whole and fragmental marine shells. This passes up through an interbedded junction into a black clay till which again contains marine shells, some of which, even the most delicate, are complete. The till contains joint planes, the most prominent of which are a conjugate set normal to the dip of the bed and orientated at 30° on each side of the direction of dip. There is also a less prominent laminar jointing which is parallel to dip surfaces of the band.

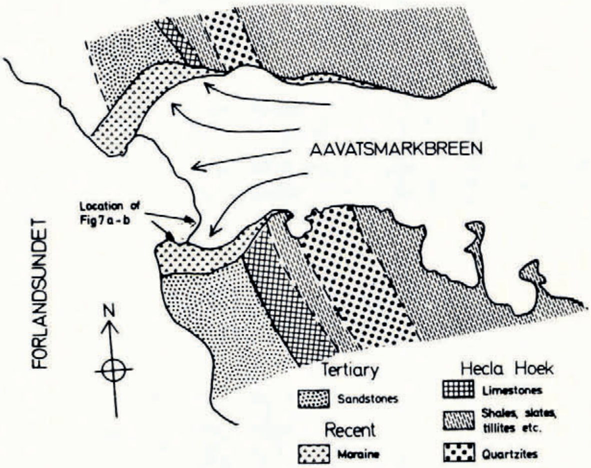

Fig. 6. Generalized and very approximate map of lithologies over which Aavatsmarkbreen flows.

The presence of whole fragile marine shells within this band, its low ice content and the bedding in the basal sands suggest that it is a marine sequence, that the till was released into the sea either from the ice-front cliff of the glacier or from calving icebergs, and that the glacier subsequently advanced over it and picked it up. When the black till thawed and was left to dry it changed colour to brown, a change characteristic of marine muds which are oxidized when exposed to the air.

Of the 10 m of ice above this prominent debris band and below the upper thrust plane, the uppermost 6 m contains little debris. The lowest 4 m contains bands varying from 1 cm to 0.4 m in thickness, most of which consist of suspensions of grains in ice with grain-sizes varying from silt and clay to boulders 0.3 m in diameter. They were sampled by taking specimens of particles at 0.5 m intervals, or from bands nearest to these points. Reference was then made to the geology of the bed over which the glacier moves (Fig. 6). This consists of a tightly folded sequence of Hecla Hoek limestones, quartzites, shales and tillite horizons in the east, which are faulted against sandstones and conglomerates of Tertiary age in the west, the whole sequence maintaining a north-north-westerly strike (personal communication from W. T. Horsfield). Each specimen was identified as being derived from one of the lithological units marked on Figure 6. Unfortunately, different horizons within the Hecla Hoek sequence are very similar, the massive quartzites and limestones, and sandstones of the Tertiary being the easiest to identify. Table I shows the vertical variation in erratic type.

Ignoring for the moment the four sandstone specimens at 8.5 m, above the unlithified marine sediments of the basal debris band, there is a systematic sequence in which Tertiary sandstones do not occur above 6.5 m, Hecla Hoek limestones above 7.0 m and massive quartzites above 8.5 m. Of the shales, phyllites, recognizable tillites, granites, etc. characteristic of the more easterly outcrops of Hecla Hoek, 72 were contained in the specimens collected at and above 7.5 m, and only 15 in the specimens collected below this level and above the basal debris band. As will be seen from comparison with the map (Fig. 6), this upward sequence reflects in the reverse order the lithologies over which the glacier has moved, recent unlithified marine sediments, Tertiary sandstones and Hecla Hoek rocks, in which some of the prominent lithologies are recognizable.

TABLE I. VERTICAL VARIATION IN ENGLACIAL DEBRIS TYPES ON AAVATSMARKBREEN

Height of sample above basal thrust plane m	*Number of samples of each debris type*						
	Tertiary sandstones	*Hecla Hoek rocks*					*Totals*
		Limestones	*Massive quartzites*	*Shales, slates, etc.*	*Tillite*	*Granite, vein quartz, etc.*	
9.5				12	2	6	20
9.0				9	2	3	14
8.5	4		2	7	3	4	20
8.0			10	4	2	2	18
7.5			8	7	3	2	20
7.0		9	5	3			17
6.5	2	14	3	4		3	26
6.0	21	2	3	5		2	33
1.5–5.5 Recent marine sediments							

This sequence thus agrees with that predicted by a basal-freezing hypothesis and is significantly different from that which would be expected if the debris sequence had been incorporated by thrusting. The anomalous position of the specimens of Tertiary sandstone at 8.5 m could be explained by movement along some cross-cutting structure such as a thrust plane.

It is interesting to note that, on both Makarovbreen and Aavatsmarkbreen, debris appears to have been incorporated englacially very near to the glacier snout, and in the latter case surface measurements indicate that the zone of incorporation appears to coincide with the outer glacier zone of cold ice.

UPWARD TRANSPORT OF ENGLACIAL DEBRIS

When the basal zones of glaciers are exposed far up-glacier of the point at which they would normally terminate (in terminal ice cliffs or stagnant ice masses), the englacial debris sequence lies just above the glacier sole and parallels the glacier foliation (Fig. 3b). In an advancing glacier, such a sequence is exposed in the steep terminus (Garwood and Gregory, 1898; cf. Lliboutry, 1964–65, pl. LXXIa), but on glacier retreat deceleration towards the snout causes these bands to warp upwards. However, if the glacier is in a state of intense longitudinal compression at its front, both folding and thrusting occur and again tend to transport englacial debris to a higher level. This is illustrated in a section (Fig. 7a and b) typical of many glaciers, where a sub-horizontal ice foliation exposed in the terminal sea cliff of Aavatsmarkbreen becomes progressively more intensely deformed as the glacier moves onto land at its southern margin (Fig. 6) and pushes against a marginal ice-cored moraine. The first-formed folds are concentric (Fig. 7a) but pass with increasing deformation into tighter almost isoclinal folds farther south (Fig. 7b). Axial planes of folds strike approximately transverse to glacier movement, although they may differ in trend by 45°, and folds may plunge in opposite directions; both combine to give complex traces on the glacier surface.

In addition to folds produced by longitudinal compression with transverse-to-flow axial planes resulting in transverse-to-flow surface outcrops of debris bands, transverse compression gives rise to folds with parallel-to-flow axial planes and surface outcrops. Large-scale structures of this type are illustrated in Figure 7c and d.

As noted on Makarovbreen, the main role of thrusting is to carry overlying debris-band sequences to a higher level within the glacier; such strong upward movement is illustrated in Figure 3 and in the complex imbricate zone shown in Figure 7b. Many thrust planes carry little or no entrained debris, but some appear to have developed preferentially along the lines of pre-existing debris bands when these consist of suspensions of grains or grain aggregates, again suggesting that such bands have a lower shear strength than the flanking cleaner ice. These debris bands lying along thrust planes are structures which distinctly cut across the glacier-ice foliation. Such a thrust plane which disrupts the core of a concentric fold and several others are illustrated in Figure 7. Also shown in Figure 7 are thrust planes which

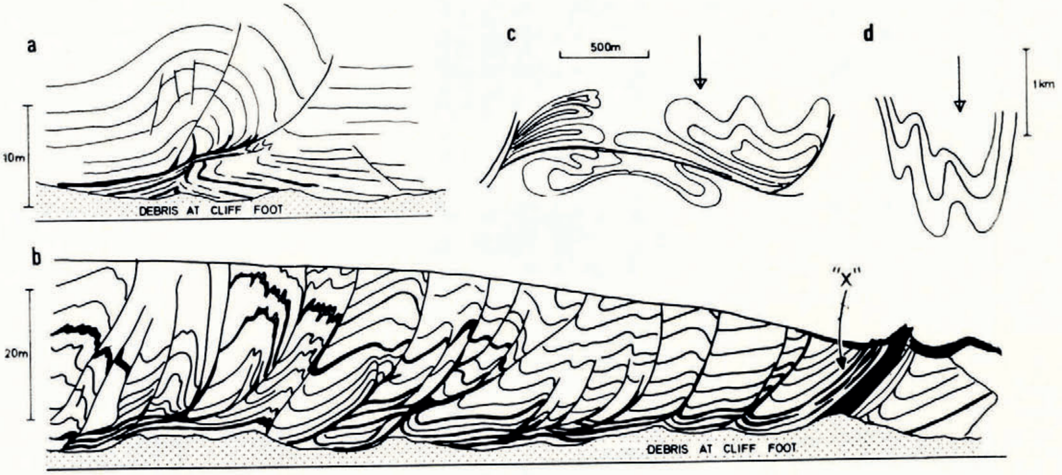

Fig. 7. a. Concentric fold developed in a zone of sub-horizontal foliation in the terminal ice cliff of Aavatsmarkbreen. The parallel-to-foliation debris bands at the base of the cliff are disrupted by thrusting in the core of the fold.

b. Intense folding and thrusting nearer to the southern margin of the glacier. Debris bands lie parallel to ice foliation and also cut this foliation along the lines of thrust planes.

c. Complex debris-band traces on the surface of Valhallfonna (Ny Friesland). Traces indicate polyphase folding and thrusting under predominantly longitudinal compression.

d. Fold traces resulting from transverse compression on Borebreen (Olav V Land). Arrows indicate direction of glacier movement.

derive their debris from below the level of exposure, leaving the possibility that this may be debris which was originally frozen to the glacier sole or had been thrust up into the ice from an entirely subglacial position, although the glacier–bedrock contact exposed at the foot of the ice cliff displays no intervening till which might provide material that could be thrust into an englacial position. It is interesting to note that many groups of thrust planes show signs of coalescence as predicted by Weertman (1961), and that different thrust planes in the same locality may vary in strike by as much as 60°.

The author would thus agree with Gripp (1929) in the identification of two types of debris band: those lying parallel to ice foliation and those cutting this foliation. However, the author would differ in suggesting that the former are the result of basal freezing rather than thrusting and that the latter are mostly thrust planes, some of which derive their debris from parallel-to-foliation bands and some from the glacier bed.

Debris bands as basal till-filled crevasses

Gripp (1929) suggested that englacial moraine bands which cut the glacier foliation had formed from water-soaked subglacial till which had been squeezed upwards into basal crevasses by the weight of superencumbent ice. This conclusion was based on observations that the trend of supraglacial outcrops of these moraine bands, or *Lehmmauern* (clay walls), did not seem to exhibit a preferred orientation and therefore "could not be shear planes" as had been suggested by Lamplugh (1911). It should be noted, however, that Schott (1934), Gripp's companion, disagreed with these observations in that he recognized *Lehmmauern* trending in two directions at right-angles. Gripp did not show that any one of the *Lehmmauern* was derived from a till-filled crevasse nor did he report a section which shows an undoubted till-filled crevasse. Of the many sections that have been investigated by the author which show closed-up crevasses, in no case is there any contained moraine material other than that derived from the glacier surface, whilst observations on some of the glaciers quoted by Gripp, and a study of aerial photographs taken in 1936, reveal a systematic orientation of *Lehmmauern*. For instance, Nathorstbreen, an example figured by Gripp, shows a preferred orientation of *Lehmmauern* transverse to glacier flow with a subsidiary parallel orientation and evidence of folding of the *Lehmmauern*. The moraine of Cora Island was also referred to by Gripp as having "criss-cross" *Lehmmauern*, whereas it is considered here that this is a supraglacial till accumulation which is sufficiently thick to conceal the orientations of the englacial structures from which it is derived; the orientations referred to by Gripp are merely the patterns of hummocks and hollows which develop when a buried ice surface melts under an uneven sediment mantle. It is therefore suggested that the orientations of *Lehmmauern* which Gripp observed can be explained as the effect of complex folding and faulting of a conformable englacial debris sequence, a process demonstrably capable of producing complex surface outcrops of debris bands as shown in Figure 7c and d.

Gripp's observations were used by Hoppe (1952) as the main present-day evidence to support a thesis that hummocky moraine is formed subglacially as a result of the pressing up of water-soaked till into basal crevasses. In fact, Gripp nowhere reported such subglacial material, it was merely a necessary part of the hypothesis that he used to account for the origin of his *Lehmmauern*. Indeed it is suggested here that it is an unnecessary hypothesis, as the *Lehmmauern* can be accounted for by processes which are not hypothetical and that there are not yet any data from Svalbard which support Hoppe's case.

Contrast between the debris loads of polar and temperate glaciers

A careful review of the literature suggests a generalization which, if valid, could be extremely important in glacial geology: that many polar and sub-polar glaciers, such as those of Svalbard, Greenland, Baffin Island, etc., carry very considerable amounts of englacial debris derived from the glacier bed, whereas temperate glaciers, such as those of Iceland, Norway, the Alps, etc., carry very little basally derived englacial debris. Studies such as those of Koch and Wegener (1917) in East Greenland, Gripp (1929) in Spitsbergen, Goldthwait (1951) in Baffin Island, Bishop (1957) in West Greenland, and Donner and West (1957) in Nordaustlandet, attest to the validity of this generalization in polar ice caps, ice sheets and valley glaciers. For temperate glaciers, such work as that of Okko (1955) in Iceland suggests that, although subglacially derived debris is sometimes thrust to the surface and sometimes pressed up crevasses in the terminal area, relatively small amounts of basally derived englacial debris are transported compared with material derived supraglacially from nunataks in the accumulation area. This point has also been strongly argued by Hoppe (1952), and the lack of basally derived englacial moraine in Norwegian glaciers has been commented upon by Lewis (1960). Unfortunately, there are few detailed studies of the debris load of temperate glaciers, and most authors have commented neither on the paucity nor the abundance of basally derived englacial debris. Of published photographs of temperate glaciers none shows such volumes of debris as have been recorded by the workers on polar glaciers quoted above. Although some temperate glaciers such as Malaspina Glacier carry supraglacial moraines of some thickness, their forms generally indicate that they are longitudinal features originating as lateral or medial moraines and derived from steep valley sides.

This apparent contrast between the englacial debris load of temperate and polar glaciers supports the suggestion that temperature regime is the controlling factor in the englacial incorporation of large volumes of basally derived debris, and that only those glaciers in which basal freezing is an important process show large amounts of such debris. This carries the corollary that glaciers which are entirely frozen to their beds will contain very little englacial debris.

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