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OBSERVATIONS ON DEBRIS IN THE BASAL TRANSPORT ZONE OF MÝRDALSJÖKULL, ICELAND

by

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ABSTRACT

Mýrdalsjökull is a temperate ice cap with an area of 596 km², covering the volcanic Katla massif in southern Iceland. Since 1900, extensive areas of ground moraine have been exposed during glacier retreat along the northern margin of the ice cap. The ground moraine surface is characteristically covered by a coarse layer of rock particles 10 to 150 mm in size. At the present glacier front, particles of corresponding size can be seen melting out from the lowermost glacier ice. Samples of ice and debris were collected from the basal transport zone, here generally 20 to 50 mm thick, and the volume, grain size, shape, and surface texture were determined. The orientation of rock particles in the englacial position, in the basal transport zone, and in the underlying lodgement till were analysed. The rock particles that dominate the debris content in the basal transport zone and constitute the coarse surface layer beyond the glacier margin are interpreted as a residual, which has escaped subglacial frictional deposition.

MÝRDALSJÖKULL

Mýrdalsjökull is located in the southern part of Iceland, about 150 km east-south-east of Reykjavík (Fig.1). The ice cap covers the volcanic Katla massif, and, at present, its surface area is 596 km², according to Landsat images and air photos, approximately 15% smaller than it was at the beginning of the century (Björnsson 1978). Several lines of evidence suggest that the ice cap is temperate: (i) the snow survey of Rist (1957), who recorded snow temperatures of 0°C in the accumulation area, (ii) the present author's observations of numerous subglacial melt-water streams, issuing from the glacier margin as small fountains, and (iii) the presence of striated bedrock along the glacier margin, suggesting movement by basal sliding.

The rate of subglacial erosion on Mýrdalsjökull has been estimated by Tómasson (1976), using measurements of sediment transport in glacier melt-water streams. He found a mean erosional rate of 4.5 mm a^{-1}, which is high compared to other Icelandic glaciers: Vatnajökull 3.2 mm a^{-1}, Hofsjökull 0.9 mm a^{-1}, Langjökull 0.4 mm a^{-1}, and other glaciers 0.3 mm a^{-1} (all values from Tómasson 1976). The glacier bed of Mýrdalsjökull is apparently among the most intensively eroded surfaces on Earth.

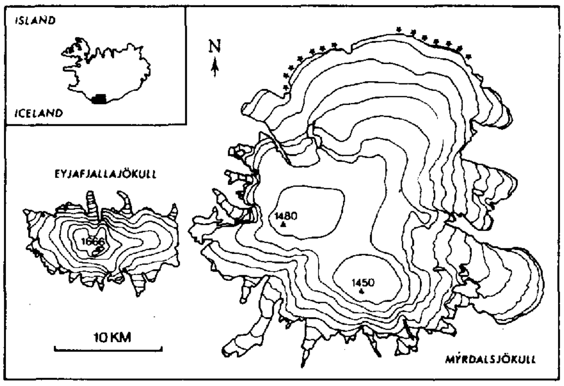

Fig.1. Surface topography of Mýrdalsjökull and Eyjafjallajökull, with 100 m contours. Sléttjökull is the northern part of Mýrdalsjökull. Pavements of coarse particles were observed where indicated by asterisks. Open circles indicate section of glacier terminus, which was not investigated in detail.

The northern part of the ice cap, known as Sléttjökull (Rist 1967), has a glacier terminus almost 21 km in length underlain by loose sediments. The pro-glacial area has a gentle relief, about 600 m a.s.l. During this century, Sléttjökull has retreated about 1.5 km from the outermost moraine system, which probably marks the Holocene maximum for this part of the ice cap. At present, the glacier retreats slowly at 8 to 10 m a^{-1}, compared to the 30 to 35 m a^{-1} retreat rate characterizing the period 1937 to 45, which is estimated on the basis of the spacing of small winter moraines and air photos (Krüger and Humlum, in press). During this retreat, large areas of fluted ground moraine have been exposed. The ground moraine has the form of flats or drumlinized areas. The individual drumlins are generally small, 20 to 60 m in length, 10 to 30 m in width, and about 3 to 5 m high.

The surface of Sléttjökull is clean compared with surfaces of outlet glaciers from the southern part of Mýrdalsjökull, which are partly covered by dark, fine-grained material, probably of volcanic or aeolian origin, melting out from englacial debris bands 10 to 100 mm thick. On the surface of Sléttjökull, only two conspicuous debris bands of this type can be seen. Most of the debris in Sléttjökull is concentrated in a glacier sole 20 to 50 mm thick. As there are only few and small nunataks on Sléttjökull, almost all debris in this part of Mýrdalsjökull appears to be subglacially derived, with the exception of the debris bands mentioned above. Only one debris layer was found along the glacier front, at the sole. No signs of folding were observed, and the basal debris layer was coherent, with no major changes of thickness, even where ice movement was over subglacial obstructions such as the small drumlins mentioned above.

The nature of the topography of the bed of Sléttjökull is unknown, but the almost horizontal ground surface exposed by the current retreat probably continues for some distance underneath the glacier. The uniform overall surface form of Sléttjökull probably reflects a relatively smooth bed; at some places, crevasse patterns are suggestive of isolated SW-NE ridges, probably of volcanic origin.

DEBRIS IN THE BASAL TRANSPORT ZONE

The ground moraine beyond the margin of Sléttjökull appears to be composed of very coarse rock particles, generally with a mean diameter of 10 to 150 mm (Fig.2). However, vertical sections at different places in the ground moraine landscape showed that the coarse particles always form a distinct surface layer (Fig.3), with a considerably finer-grained till below. This till is interpreted as a lodgement till because of the presence of a variety of small-scale deformations (Krüger 1979: 332-334, Krüger and Humlum, in press). Only occasional larger rock fragments are found in this till.

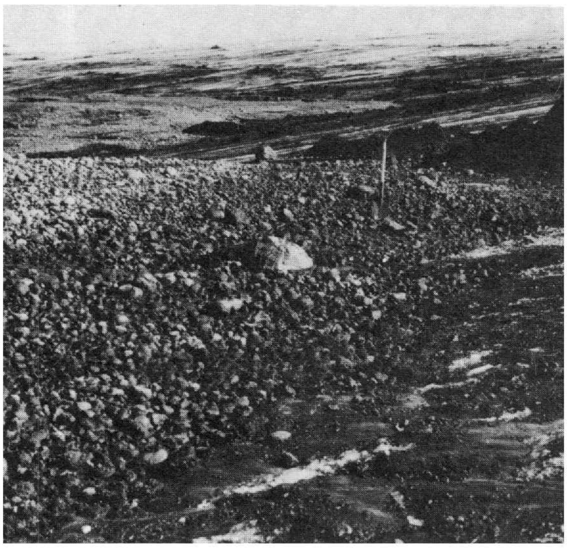

Fig.2. Glacier front of Sléttjökull, July 1979, to east. Stones and boulders cover surface of ground moraine. Notice spade for scale.

The coarse surface layer is not a lag accumulation formed as fines are washed or blown away after deglaciation (Boulton and Dent 1974). This is shown by detailed observations along the present terminus, at the junction of ice-covered and ice-free areas (Fig.4), where the coarse rock particles are seen to be melting out from the lowermost glacier ice. Furthermore, in gullies cut into the glacier terminus by supraglacial melt-water streams, similar particles can be seen in the basal transport zone (Boulton 1978), often in traction against the glacier bed (Fig.5). The coarse surface layer could not result from washing fines away during the summer ablation period in a narrow gap between the glacier ice and the bed, because the ice along the margin of Sléttjökull was observed to be in constant close contact with the soft till beneath. The surface layer thus appears to be the result of sub- or englacial processes, which are probably not unique to Sléttjökull, as the author has observed similar surface layers along the margin of some temperate valley glaciers in south Norway.

Fig.3. Vertical section in ground moraine in front of Sléttjökull. A coarse surface pavement of stones and boulders covers a fine-grained lodgement till.

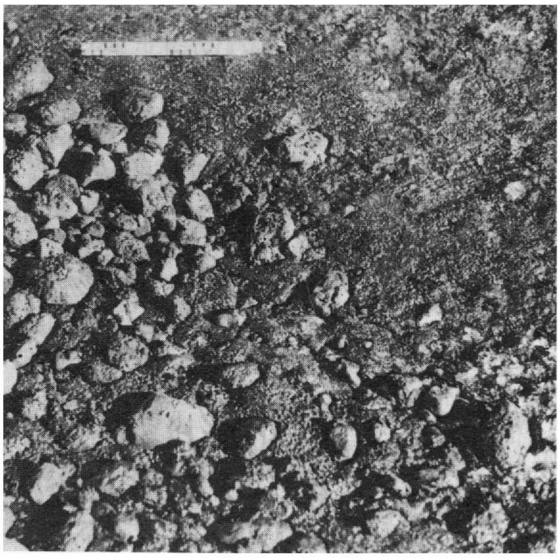

Fig.4. Detail of glacier front of Sléttjökull. Coarse particles are seen melting out from lowermost ice. 0.4 m rule is shown for scale.

SAMPLES FROM THE BASAL TRANSPORT ZONE

Exposures along erosional gullies at the terminus of Sléttjökull reveal that the glacier ice is generally clean, with almost all debris concentrated in a glacier sole 20 to 50 mm thick. To study this debris, five samples of 4.9, 5.4, 6.6, 7.5, and 4.8 litres were collected from the glacier sole, along a 4 km-long section of the glacier front. The ice was melted and the trans-

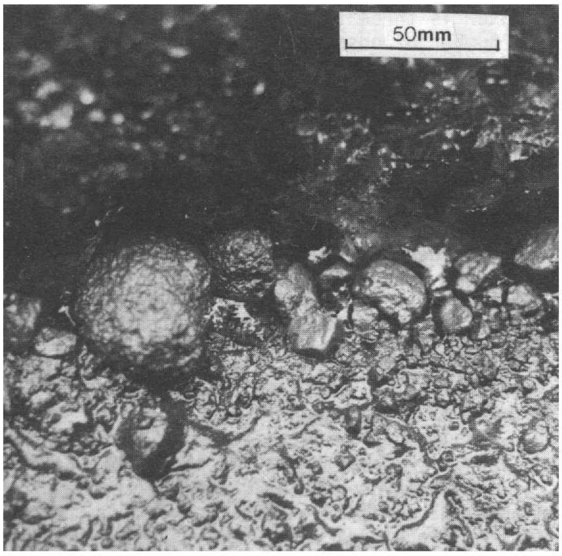

Fig.5. Basal transport zone in vertical section. Ice movement from right to left. Several large particles are present in lowermost glacier ice, overlying fine-grained lodgement till.

comprised about 15% to almost 31% by volume (15.2%, 22.4%, 24.1%. 25%, 30.7%), somewhat lower than preliminary estimates.

The debris isolated from the basal transport zone is dominated by particles with diameters ranging from 16 to 128 mm (-4 to -7Φ) (Figs.6 and 7), corresponding to those in the coarse surface layer in the ground moraine (Fig.2). Particles finer than 1 mm contribute less than 0.1% by weight to the debris content in the collected samples. This contrasts with the texture of the lodgement till below the surface layer, where particles finer than 1 mm usually make up about 70 to 75% (Krüger and Humlum, in press).

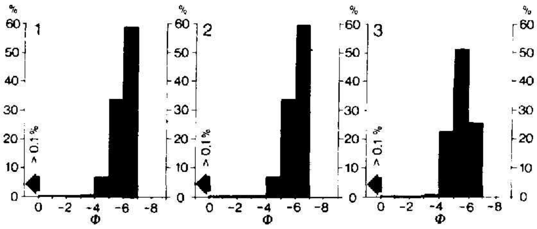

Fig.6. Size frequency diagrams for debris in basal transport zone of Sléttjökull.

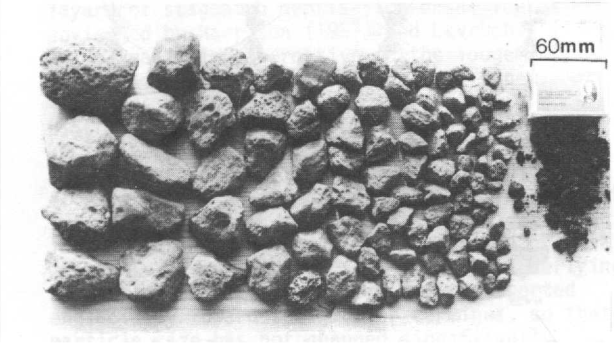

Fig.7. Basalt fragments found in a 5.4 litre sample collected from basal transport zone of Sléttjökull.

For three of the samples, the form of the largest particles was determined according to the classification of Zingg (1935), and the results are presented in Table I. All samples investigated appear to be dominated by cuboid particles; blades are rare, while rod- and dish-shaped particles are more frequent.

TABLE I. PARTICLE FORM AFTER ZINGG (1935) FOR THREE SAMPLES FROM THE COARSE SURFACE LAYER ON GROUND MORAINE BEYOND SLÉTTJÖKULL.

PARTICLE FORM	ROD %	BLADE %	DISH %	CUBE %
POPULATION 1	14.5	0.0	18.2	67.3
POPULATION 2	19.5	1.3	22.1	57.1
POPULATION 3	23.1	3.3	17.6	56.0

Several of the larger particles isolated from the samples showed striae and abrasional facets. To investigate the relation of these larger particles, three areas of 0.6 x 0.5 m² were selected at random along the study area, just outside the ice-covered section, as shown in Figure 4. Here the orientation of large particles in the surface layer are thought to correspond to the true orientation in the glacier sole, as detailed observations of particles melting slowly out from the basal ice (Fig.4) revealed only a small reorientation during this process. This is probably a consequence of many particles in the basal transport zone being in contact with the glacier bed. About 20% of the particles >25 mm (*b*-axis) in the coarse surface layer showed striated surfaces, most striations being on the lower surface (Table II). It follows that most of these particles did attain a relatively stable orientation while in traction against the glacier bed. On the other hand, particles with striations on both the upper and lower surface have probably rotated at least once during transport in the basal zone.

The angularity of particles isolated from the basal transport zone appears to be rather uniform, approximately subangular according to the visual classification scale of Power (1953).

FABRIC PATTERNS

Preferred orientation of particles in the coarse surface layer was investigated by macrofabric analysis. Only two-dimensional (horizontal) data are shown here, as the vertical component may be reoriented during melt-out. All analyses were done on freshly deposited material, with a maximum distance to the glacier terminus of 3 m, corresponding to the distance that the glacier margin has receded during the ablation season.

TABLE II. STRIATIONS ON PARTICLES IN THREE SAMPLES FROM THE COARSE SURFACE LAYER ON GROUND MORAINE BEYOND THE MARGIN OF SLÉTTJÖKULL.

SURFACE STRIATED	TOTAL %	UPPER %	LOWER %	BOTH %
POPULATION 1	20.0	5.5	5.5	9.1
POPULATION 2	19.5	1.3	15.6	2.6
POPULATION 3	17.6	1.1	14.3	2.2

Four typical horizontal fabric patterns are shown in Figure 8 as rose diagrams, one (extreme right) for rod-shaped particles (Zingg 1935), and three for particles of all shapes. Only particles longer than 15 mm (*a*-axis) were measured. The analyses generally show a somewhat dispersed pattern, but at the same time one or two density peak(s) oblique to the flow direction often rise above the background noise.

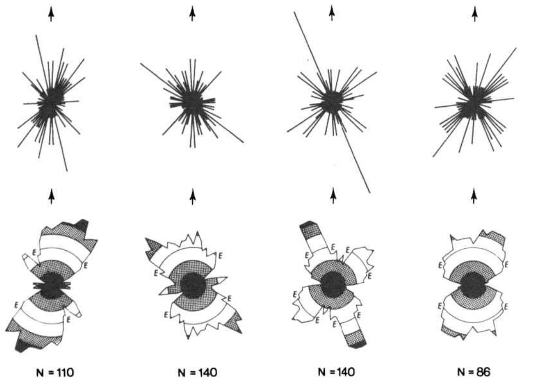

Fig.8. Horizontal rose diagrams for particles longer than 15 mm in surface pavement on ground moraine at Sléttjökull. Diagram to right is for rod-shaped particles only, and other diagrams are for particles of all shapes. Ice movement is shown by arrows. Upper diagrams are prepared with angular data grouped in 5° intervals, while lower diagrams are contoured at one standard deviation for a random distribution around the mean frequency *E*, using modified procedure of method proposed by Kamb (1959) for equal-area nets. Deviations which exceed 2 σ from *E*, and which are considered significant, are shown in black. Further discussion in text.

Obviously it is desirable to define important statistical characteristics of these particular data populations, to compare them with other angular populations, e.g. the orientation of particles in other till types. However, standard statistical tests unfortunately imply a symmetrical unimodal density function for a population of density data, commonly the circular normal distribution (see e.g. Mardia 1972 or Till 1974). The fabric analyses in Figure 8 are represented by nonsymmetric, irregular density functions, and segregating the measurements into single modal groups on a visual basis for individual analysis (Tanner 1955, 1959) is not considered possible. Neither can the numerical technique suggested by Jones and James (1969) be used in this particular case because of the very complicated fabric pattern. Moreover, the rotational vector method (Mark 1971) as well as the eigenvalue approach (Mark 1973), are not suitable for analysis of fabric patterns as shown in Figure 8 for the same reasons. Finally, the chi-square test cannot be used, as a wide range of χ^2 values can be calculated for one sample, depending on the choice of sectors into which the data are grouped (Ballantyne and Cornish 1979).

Therefore, in this study, a more graphic approach has been used, based on a modification of the contouring procedure suggested by Kamb (1959) for three-dimensional nets. The rose diagrams are contoured by a counter of angular size A, so chosen that, if the population of orientation data lacks preferred orientation, the number of observations E expected to fall within the counter is three times the standard deviation of the number of observations n, that will actually fall within the angular sector under random sampling of the population. Observed densities that exceed E by more than twice the standard deviation σ for random orientation are then likely to represent statistically significant preferred orientations, particularly if the significantly higher or lower densities are clustered in one portion of the diagram (cf. Kamb 1959: 1908). Observed densities are then contoured in intervals of σ, the expected density E for no preferred orientation being 3σ. Following Kamb (1959), for a counter of angular size A, expressed as its fraction of 2π, we find that, for a population without preferred orientation and of size N,

$$\sigma/E = ((1-A)/NA)^{-\frac{1}{2}} ,$$

where $E = NA$. If $\sigma/E = 1/3$, it is then possible to calculate the angular size A of the counter for a population with N observations. From this contouring procedure, densities that are probably significantly high or low can be distinguished from densities that are not. However, the analysis would need to be carried further to give levels as noted by Kamb (1959: 1909), and in some cases the number of standard deviations above or below the mean E, needed to ensure a significant deviation, may be larger than the 2σ used at first in this study (see also Dudley and others 1975: 688 for further discussion).

Returning to Figure 8, the oblique density peaks in the contoured fabric diagrams for particles in the coarse surface layer are seen to deviate about 2σ from the mean density E. It is therefore probable that oblique/diagonal density peaks represent a significant feature for rock particles in the surface pavement, and following the argument presented above, also for rock particles in the basal transport zone. Significantly low densities are usually found around the direction transverse to the ice flow. More work is needed on this subject, and the proposed hypothesis should be tested by field work on other glaciers.

Four typical till macrofabric analyses for rod- and blade-shaped particles from lodgement till in the ground moraine of Sléttjökull are shown in Figure 9. All these analyses show a pronounced longitudinal density peak, with no tendency for oblique peaks to occur. The adopted significance level of two standard deviations over the mean density E is clearly exceeded, and the longitudinal density peaks are highly significant. The fabric pattern characteristic

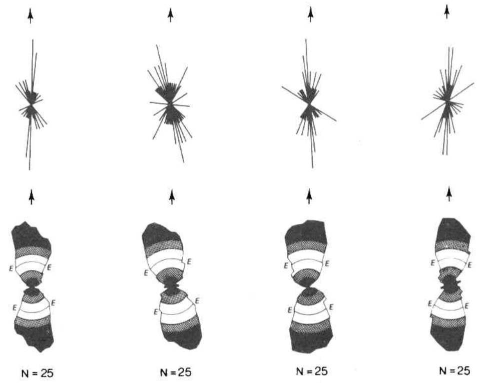

Fig.9. Horizontal rose diagrams for blade- and rod-shaped particles 6 to 60 mm long from lodgement till at Sléttjökull. Ice movement is shown by arrows.

for rock particles in the basal transport zone and for those in the lodgement till appears to be so different that they probably represent statistically distinct populations.

To investigate further if the apparent oblique density peaks are inherited from some englacial deformation episode, macrofabric analyses were carried out at one locality on rod-shaped particles (a) in glacier ice 2 to 5 m above the glacier-bed interface, (b) in the basal transport zone (represented by newly deposited particles just outside the glacier margin), and (c) in the lodgement till 0.2 m below the glacier-bed interface (Fig.10). This showed that rock particles in englacial transport, as well as particles in the lodgement till, displayed pronounced and statistically significant longitudinal density peaks. In the case of the lodgement till population a small transverse peak also appears. In contrast, particles representing the basal transport zone displayed the familiar dispersed pattern known from Figure 8, with a tendency for oblique density peaks to appear. This preliminary result suggests that major shifts occur in what may be called the stable or preferred orientation, when a rock particle initially suspended in glacier ice comes into the zone of basal transport, and again when it is eventually lodged by friction aginst the glacier bed. The difference between the fabric pattern for particles in the basal transport zone and those in the underlying lodgement till suggests, furthermore, that subglacial deposition at Sléttjökull by slow melting of layers of stagnated debris-rich basal ice as envisaged by Harrison (1957) and Lavrushin (1971), is no realistic alternative to the lodgement hypothesis presented earlier in this paper.

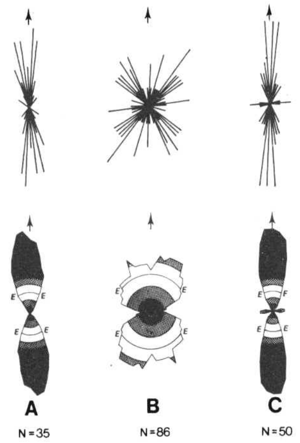

Fig.10. Horizontal rose diagrams for rod-shaped particles in: (A) englacial position 2 to 5 m above glacier base, (B) basal transport zone, and (C) lodgement till 0.2 m below glacier base. Ice movement is shown by arrows.

DISCUSSION

The unusual size distribution of debris in the glacier sole and in the surface layer in front of the glacier may be explained in at least two ways. Firstly, the population could more or less correspond to an original population of rock fragments loosened by erosion from the underlying bedrock somewhere up-glacier, and transported englacially toward the glacier terminus, so that particle size has not changed significantly. This could explain, why there are so many large particles in the samples (Fig.7) and only a relative small amount of fines. Secondly, some type of sorting mechanism at the glacier-bed interface, e.g. selective deposition, could be responsible.

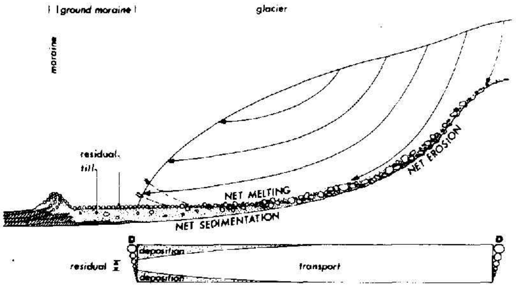

Fig.11. Idealized section of Sléttjökull, showing proposed gradual development of particle residual due to selective lodgement of very large as well as very small particles. Corresponding deposition-transport pattern is shown below in distance-size diagram. D is diameter of rock particles in basal transport zone.

Taking the englacial transport hypothesis first, the map of Mýrdalsjökull (Fig.1) should be considered. Because only a few small nunataks protrude above the ice cap, virtually all debris present in Sléttjökull must therefore be derived subglacially. The debris source is likely to be under the central part of the ice cap because such areas are generally recognized as sites of net erosion (White 1972, Boulton 1979). Non-central areas of Sléttjökull have probably been sites of net deposition as reflected in the nearly horizontal ground surface consisting of loose sediments that seems to extend for some distance underneath the glacier, while higher-lying and more rugged ground probably dominates under the central part of Mýrdalsjökull. This picture is supported by measurements of the ice thickness published by Rist (1967). The distance from the central part of the ice cap to the margin of Sléttjökull is 12 to 15 km (Fig.1), so, for the present analysis, a transport distance for the debris of the order of 10 km may be assumed. Taking a relatively high ice velocity of 0.025 km a^{-1}, rock particles may have been in englacial transport for about 400 a since they were eroded from the glacier bed. During this period a considerable amount of ice has probably been melted from the glacier base because of frictional and geothermal heat. Using a geothermal heat flux of 0.21 W m^{-2} (Lee 1970) and a mean basal shear stress of 10^5 N m^{-2}, about 0.03 m a^{-1} ice would melt from the glacier base per year, assuming that the ice is and has been temperate. During a period of 400 a, this would result in a loss of 12 m of glacier ice from the glacier base. This estimate is probably conservative, as the geothermal heat flow quoted above represents a mean value for a region larger than Mýrdalsjökull, and the local heat flow near Katla may be higher. However, even so, it is probable that an ice column of 10 to 15 m may have been lost from the glacier base while the rock particles were transported to the glacier terminus. This will tend to bring englacial particles into contact with the glacier bed, unless they are suspended in the ice more than 10 to 15 m above the glacier sole. Because Sléttjökull appears to be a temperate glacier, particles in excess of 15 m from the bed appear unrealistic for debris derived from the glacier bed because of the absence of a subglacial freeze-on mechanism (Boulton 1972). All debris eroded from the glacier bed will probably be held effectively in the basal transport zone. The hypothesis explaining the characteristics of the particle population as a result of englacial transport all the way to the glacier terminus thus appears unrealistic. Independently of this, the angularity of rock fragments and the presence of abrasional facets and striae on fragments suggest that the rock particles must have been in basal transport for some time.

The conclusion must be that the rock particles in the basal transport zone at the margin of Sléttjökull have managed to avoid deposition, even though, in the basal zone, they have passed through a zone of net subglacial sedimentation, probably to some extent parallel to the ice flow lines. The particle population is dominated by particles 10 to 150 mm in size, containing only few fine and few very coarse (>150 mm) particles. It is apparent, therefore, that particles in the basal transport zone represent an accumulation gradually formed by selective subglacial deposition, during which sorting by size occurs since large, as well as small, particles tend to be lodged more readily than those of size 10 to 150 mm (Fig.11). As small particles are continuously produced by abrasion of larger particles in traction against the glacier bed, the lodgement till below is naturally dominated by fines with only few large blocks.

The fabric analyses in Figure 10 suggest that, besides depending upon particle dimension, lodgement will depend upon particle orientation. More specifically, this analysis suggests that when particles are brought into the basal transport zone due to basal melting, particles with longitudinal orientation tend to lodge against the glacier bed, whereas particles with diagonal/oblique orientation tend to remain in basal transport.

Two final remarks should be made. Firstly, I suggest that studies of particle residuals, as described in this paper, may provide field data suitable for testing theoretical models of subglacial deposition and erosion (e.g. Boulton 1974, 1975, Hallet 1979). Secondly, it should be noted that if the surface layer of coarse particles in front of Sléttjökull were to be buried later beneath a subsequent lodgement till, the layer of coarse particles could resemble a glacial pavement between two tills. Inasmuch as glacial pavements are usually assumed to arise from either selective subglacial erosion of an older till during a period of maximum glaciation (Gripp 1973, 1974), or lag deposit created by subaerial erosion and later overridden by glacier ice (Flint 1971), it is important to stress that the pavement observed at Sléttjökull is a special type of meltout till. This pavement with textural characteristics, probably developed by sorting caused by selective subglacial deposition, is currently being deposited subaerially as the glacier retreats.

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