AN INVESTIGATION OF DRUMLINS IN THE NARVIK AREA OF NORWAY

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Abstract. An investigation of some drumlins has been carried out in the high mountains southeast of Narvik. These drumlins are situated along an elevation in a horizontal valley. The till is foliated. Sand and silt predominate and the clay content is approx. 4 %.

The long axes of the pebbles have a preferred orientation in accordance with the direction of the drumlins and the glacial flow except in the distal part, where they evidently tend to be oreintated transversally to the glacial flow.

The dip of the *a-b* plane of the pebbles is in general in accordance with the dip of the drumlin surface, except in the distal part, where the plane tends to dip towards the centre of the drumlin and out of the valley.

The proximal and distal parts of the drumlins occur close to, but separated from, a bedrock knob. The bedrock knobs have probably influenced the relations between the stresses in the ice, so that the accumulation conditions for the till were limited.

THE AREA

The investigations was carried out in the Norwegian high mountains, approximately between Narvik and Kebenekaise immediately north of Lake Baatsvatnet (Fig. 1). The drumlins in the specific area are situated along an elevation in a valley. This valley begins at the drainage limit north of Lake Kaisejaure on the Swedish side of the border. From this lake, a good many of valleys lead southwest and southeast, but only one valley leads strikingly northwest over to the Norwegian side. This valley runs from Lake Hukejaure (868 m a.s.l.) to Nuorjojokka (823 m a.s.l.); it is quite horizontal and to a great extent filled by a water system (Lake Vannaksvatnet (854 m a.s.l.), Lake Gautelisvatnet (852 m a.s.l.) and Lake Baatsvatnet (842 m a.s.l.)).

At Nuorjojokka, the valley contracts where it abruptly slopes towards Lake Kobbvatnet (646 m a.s.l.) and continues westwards to Sördalen, which emerges in Skjomdalen. The descent from Sördalen down to Skjomdalen is steep.

The high mountains and the small valleys at the side of the valley give it a somewhat variable character, so that Lake Vannaksvatnet makes a pass of 1 km in relation to the wider Gautelis basin, which in this respect is canalized to the north towards Lake Baatsvatnet. North of Lake Battsvatnet, the valley is more or less widened but is divided by an elevation. The investigation was carried out in the western part of this elevation (approx. 900 m a.s.l.) (Fig. 2 A).

The elevation, which in its upper part is relatively horizontal, is limited to the northeast by the ice-rounded canyon of Nuorjojokka (approx. 820 m a.s.l.), to the southeast by Lake Battsvatnet (approx. 840 m a.s.l.) and to the southwest by a Ushaped valley a few hundred metres wide (approx. 860 m a.s.l.) (Fig. 2 A).

To the northwest, the terrain is more intersected and does not limit the elevation as markedly as the steep slopes to the northeast, southeast and southwest. The U-shaped valley unites a few kilometres to the north with Nuorjojokka.

QUATERNARY DEPOSITS

The whole area from the Swedish side down to Skjomdalen is very poor in Quaternary deposits. The few existing accumulations are often isolated and border upon a larger area with no deposits. In the valley behind Lake Vannaksvatnet towards Lake Battsvatnet, the lake sediments are the most predominant. Some lateral eskers along the eastern shore of Lake Vannaksvatnet are the only forms of accumulation which clearly appear in the landscape. In other respects, the bare bedrock predominates completely all the way up to the northern shore of Lake Battsvatnet, where the drumlins bordering upon the bare bedrock are situated and where the sides of the U-shaped valley pass over into a horizontal elevation to the east.

In the western part of the U-shaped valley, on a terrace, a good many longitudinal accumulations are situated. The most prominent of them has a pronoun-

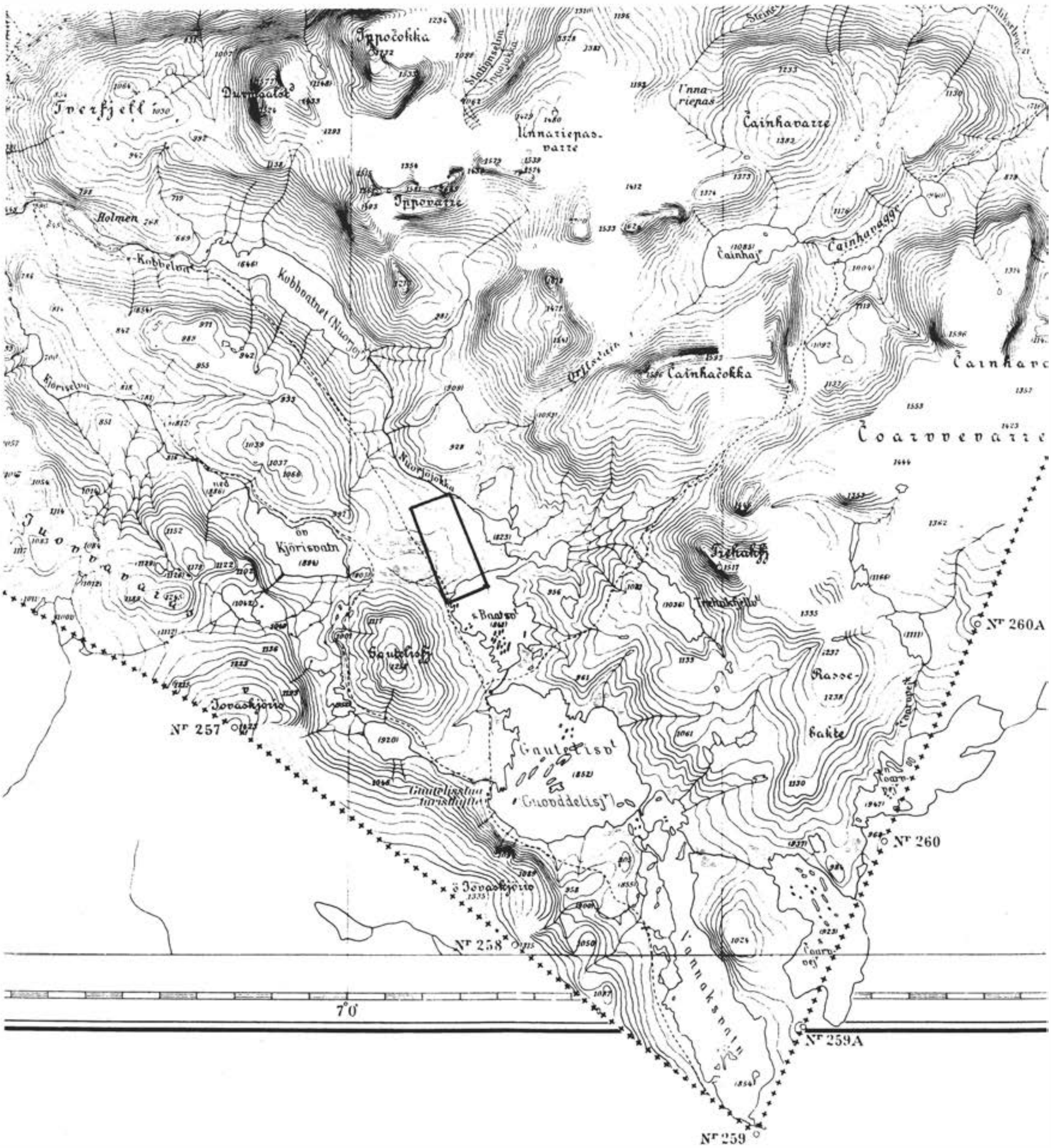

Fig. 1. A general map, with Lake Vannaksvatnet in the southeast, followed by Lakes Gautelisvatnet and Baatsvatnet to the northwest in a quite horizontal valley. The drumlin area with the U-shaped valley and the northern part of Lake Baatsvatnet are distinguished by a frame.

ced drumlin character. The others have more the character of lateral terraces but are easily associated as subglacial deposits of drumlin character. The bottom of the valley is very poor in deposits.

THE SPECIFIC INVESTIGATION AREA

Along the southwestern part of the elevation and close to the U-shaped valley, some drumlins are situated (Fig. 2 A and B). They have a width of 30—100 m and a length of 50 up to 300 m. All of them have a bedrock knob close to each proximal and distal part. In all cases the bedrock knobs play no role in the shape of the drumlin but are separated from it. The side slopes of the drumlins, in most cases, form low steeps (Fig. 2 C).

The depth of the predominant, most probimally situated drumlin has been estimated after seismic investigations as 10—15 m (Norges Geotekniske Insti-

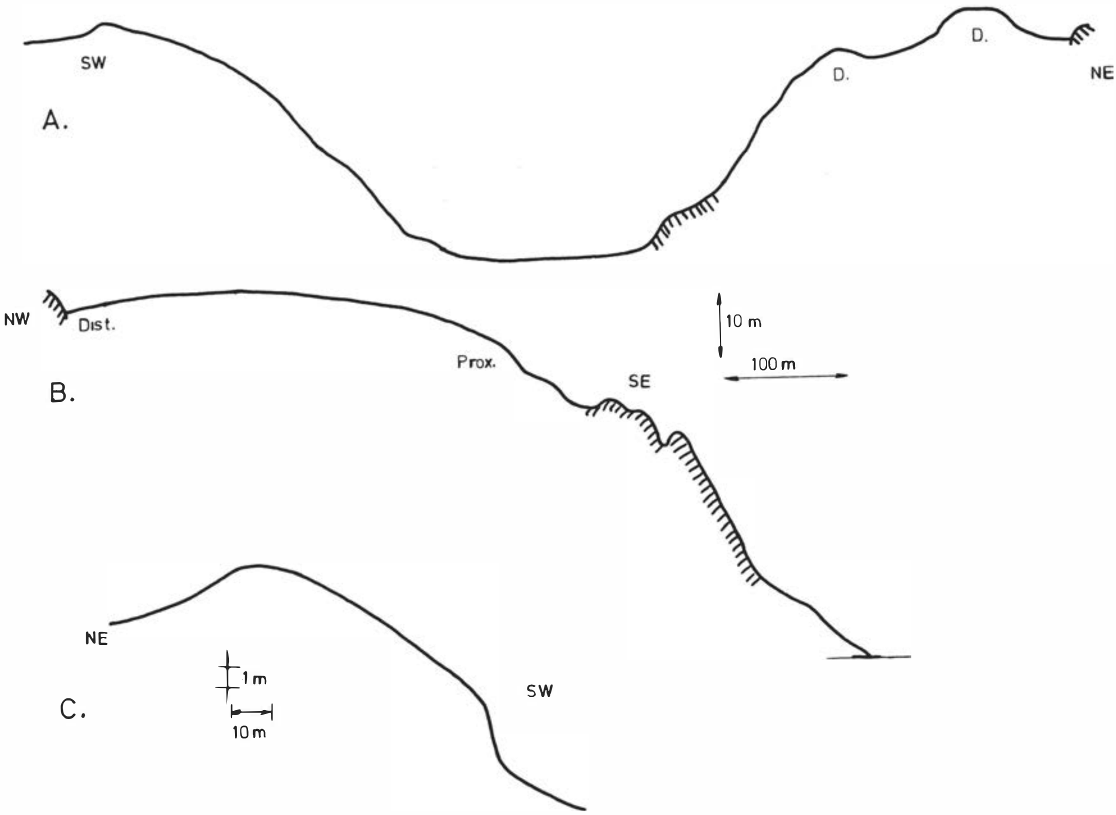

Fig. 2 A. A transversal profile of the U-shaped valley with some drumlins. In the southeast, where the U-shaped valley passes over into a horizontal elevation, two drumlins are situated (D for drumlins). In the southwest, on a terrace in the U-shaped valley, one drumlin-like accumulation is situated.
Fig. 2 B. A longitudinal profile of the largest and most proximally situated drumlin. The profile ends in the southeast at Lake Baatsvatnet.
Fig. 2 C. A transversal profile of one of the centrally situated drumlins.

tutt, 1970). This drumlin has a low, steep, proximal part which goes slightly up to the top (Fig. 2 B). The proximal part is at a distance of 50 m from the proximal bedrock knob. The bedrock knob is situated farther down on the highest part of the steep to the southeast towards Lake Baatsvatnet (Fig. 2 B). In the distal part, the drumlin lacks the low, steep, side slopes (Fig. 3). The distal part becomes more horizontal without broadening.

The till in the drumlin is pressed and foliated. Sand and silt predominate and the clay content is approx. 4 %. The foliation lies horizontally in the upper part but not on the side slopes, where it dips outwards.

The long axes of the pebbles have a preferred orientation parellel with the direction of the drumlins and the glacial flow (Fig. 4 A and B), except in the distal part, where they evidently tend to be orientated transversally to the glacial flow (Fig. 4 C).

The dip of the *a-b* plane of the pebbles in the central part of the drumlin in general coincides with the sur-

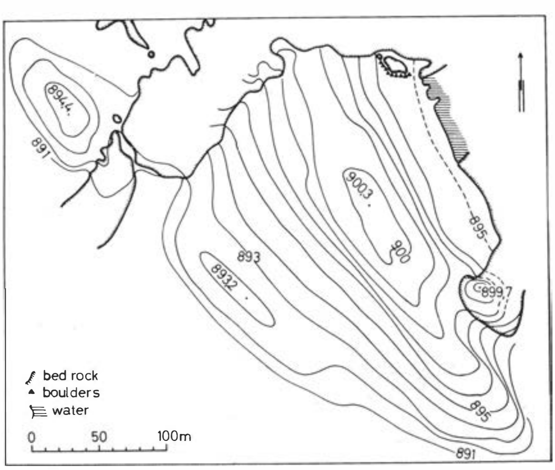

Fig. 3. Map of the upper part or "the roof" of the largest and two smaller drumlins. (Approximately 500 m northwest of Lake Baatsvatnet. Drawn by Hugo Minell in August 1971.) The proximal part of the largest drumlin is not seen, but the influence of the bedrock knob 899,7 on the side of the drumlin is quite distinct.

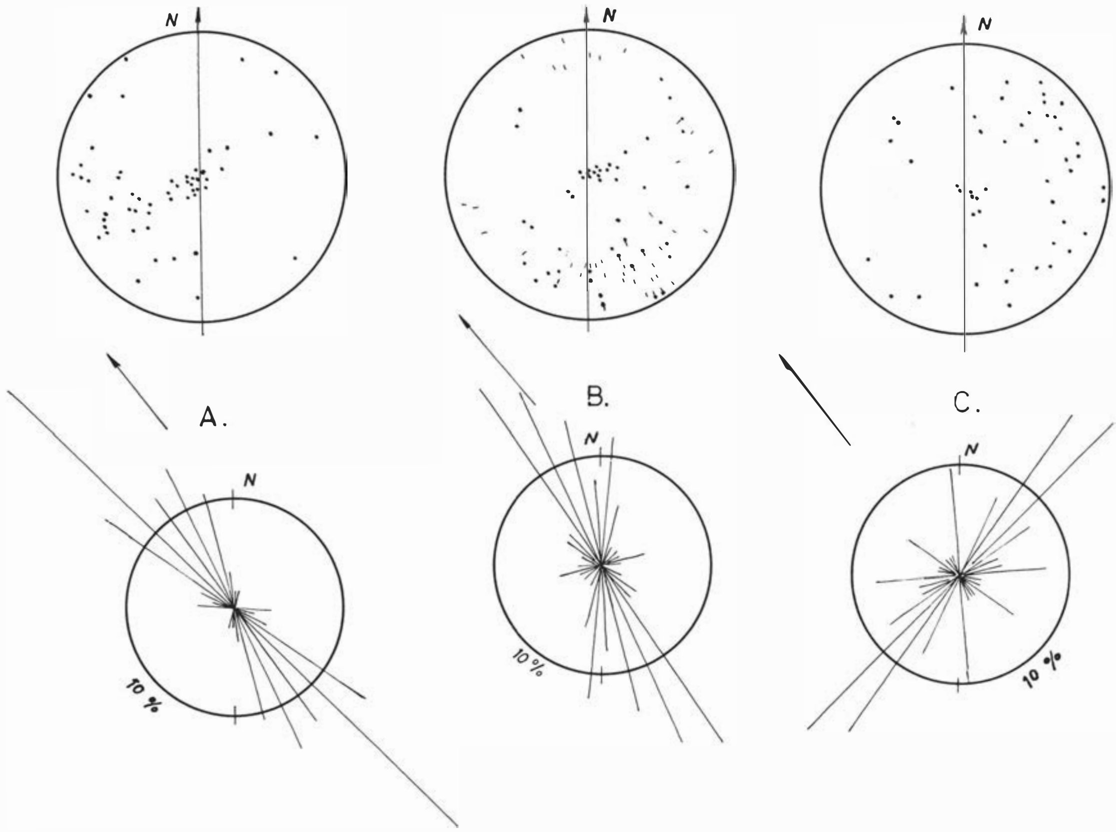

Fig. 4 A. The upper picture (stereodiagram) shows the dip of the *a—b* plane in a side slope. The side slope, in one of the central drumlins, dips towards the U-shaped valley. The lower picture shows the long-axis orientation of the pebbles.
Fig. 4 B. The upper picture (stereodiagram) shows the dip of the a—b plane, with points, and the dip of the long axes, with strokes, in the proximal part of the largest and most proximally situated drumlin. The lower picture shows the long-axis orientation of the pebbles.
Fig. 4 C. The upper picture (stereodiagram) shows the dip of the *a—b* plane in the distal part of the largest drumlin. The lower picture shows the long-axis orientation of the pebbles.

face. At the sides and in the proximal part, the plane has a very steep tendency outwards from the drumlin (Fig. 4 A and B). In the distal part, the plane tends to dip towards the centre of the drumlin and out from the U-shaped valley.

In general, the orientation of the glacial striation corresponds to the orientation of the drumlins. The difference between the older and the younger glacial striation is only 10 % (Minell 1972).

The question is, why these drumlins are limited by bedrock knobs which are separated from the higher proximal and distal parts and why the wide, convex, drumlin range is situated within an area between these knobs.

It is easy to show that these knobs caused stress variations in the ice. High shear stress causes a steep velocity gradient and with this a strong erosion (Johnson 1970).

PHOTO-ELASTIC EXPERIMENT

In order to get an idea of the shear stresses which may appear in a glacier in contact with a bedrock with bedrock knobs, I and my colleague Karl Strömgård made a semi-dimensional photo-elastic experiment.

The experiment was carried out by founding a warm gelatin mass in a plexiglass box. To the bottom of the box, two cut cylinders were attached (Fig. 5). They stood for bedrock knobs. When the gelatin mass had stiffened, the sides of the box were removed. The bottom and the front and backwalls were detached and lubricated with glycerin. The gelatin was subjected by manual force to vertical compression or horizontal shear or a combination of these; at the same time the model was illuminated throughout with monochromatic, circularly polarized light from a polariscope. The light is double-refracted in gelatin, which

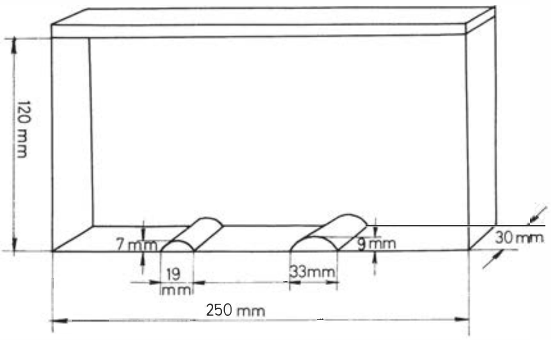

Fig. 5. A block model of the gelatin mass with the cut cylinders attached to the bottom. On the top, there is a piece of wood for imposing vertical compression, horizontal shear or a combination of these.

results in dark lines (isochromes) of different fringe orders. The fringe order of the isochromes increases with growing deformation. The deformation is proportional to the stress, so it is possible to fix the maximal shear stress $\tau max = \tau_1 - \tau_2$ (Frocht, 1948). The proportion of the shear stress in the load model is shown in Figs. 6–8.

Fig. 6. The gelatin in the model is exposed to vertical compression only (Fig. 6). The fringe order of the isochromes and thereby the shear stress increase mostly on the cut cylinders. Between the cut cylinders, the shear stress does not increase to the same extent.

Fig. 7 A and B. The gelatin is exposed to horizontal shear only. In case A, the bigger cut cylinder is the proximal one. The shear stress increases most on the proximal sides of the cut cylinders, while the shear stress on the distal sides increases very little. In case B, the smaller cut cylinder is the proximal one. The shear stress increases most on the proximal sides, while the shear stress on the base plane between the cylinders increases very little. On this base plane the fringe order of the isochromes forms arches.

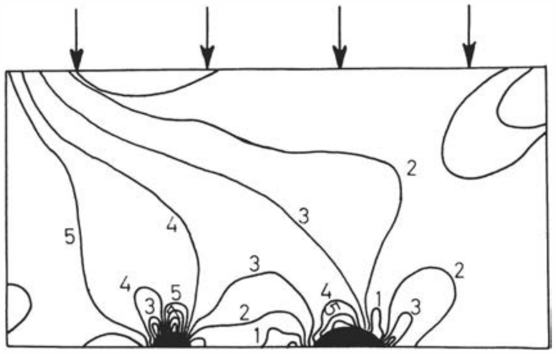

Fig. 6. The gelatin in the model is subjected to vertical compression only. The high fringe order of the isochromes (black lines) indicates high shear stress.

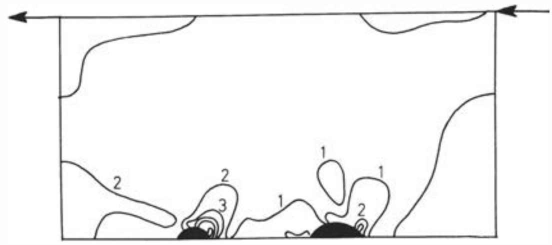

Fig. 7 A. The gelatin in the model is subjected to horizontal shear only. The bigger cut cylinder is the proximal one.

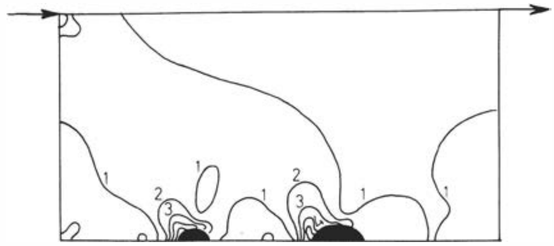

Fig. 7 B. The gelatin in the model is subjected to horizontal shear only. The smaller cut cylinder is the proximal one.

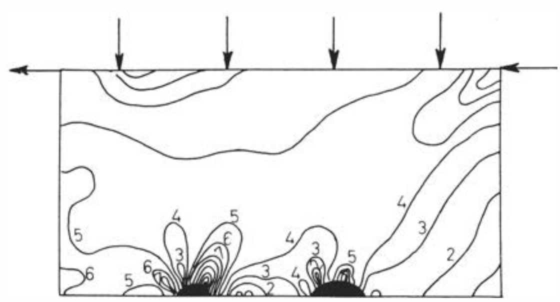

Fig. 8 A. The gelatin in the model is subjected to a combination of vertical compression and horizontal shear. The bigger cut cylinder is the proximal one.

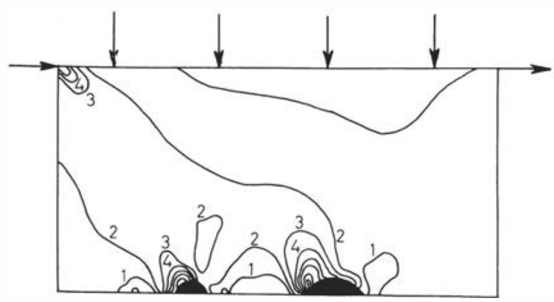

Fig. 8 B. The gelatin in the model is subjected to a combination of vertical compression and horizontal shear. The smaller cut cylinder is the proximal one. As in the foregoing figures, the high fringe order (black lines) indicates high shear stress.

Fig. 8 A and B. The gelatin is exposed to a combination of vertical compression and horizontal shear. In case A, the bigger cut cylinder is the proximal one. The shear stress increases most on the proximal sides but also to some extent on the distal sides. On the base plane, the fringe order (forming arches) is low and thereby the shear stress is low. In case B, the smaller cut cylinder is the proximal one. The shear stress increases most on the proximal sides, while the low fringe order of the isochromes, forming arches on the baseplane between the cut cylinders, indicates low shear stress.

All these experiments can easily be associated with drumlin accumulations. The drumlins are separated, just like low fringes of isochromes, between bedrock knobs. Fig. 3 illustrates a drumlin formation influenced by a bedrock knob (899,7). The proximal part and the side of the knob have been exposed to a high shear stress and thereby no accumulation has been possible, because of the higher velocity of the ice. Immediately behind the knob, there is no great amount of till. Not until the area between the knobs does the drumlin broaden.

Apparently the shear stress in the ice had to reach a certain minimum, in order to create favourable conditions for an accumulation. Below this minimum, the velocity of the ice on the bedrock is low and a gradual deposition, perhaps by plastering-on (Gillberg, 1955) may be possible.

CONCLUSION

During a period of re-activation, the ice was sliding forwards and brought earlier-accumulated till and possibly sediments from the valley (Dahl, 1967). In the U-shaped valley, the shear stress was high and all material was transported away. Further up, on the terrace in the west and where the eastern steep of the U-shaped valley descends into a horizontal terrain, the stress in the ice was changed. Stress variations were caused by bedrock knobs. On the proximal sides of the knobs, the shear stress was high, but between the knobs an area with lower shear stress was created. Within the area with low shear stress, favourable conditions for deposition (such as a lower velocity of the ice on the bedrock) were created, and there the till was gradually deposited, until the accumulation reached a level at which the shear stress in the ice did not admit of further accumulation. Around the knobs, no further accumulation was admitted. Earlier-deposited till was more likely transported away.

In front of the distal knob, a movement of the ice aside (Budd, 1970) may have been possible. It is also possible that the compression towards the distal knob grew so great that the shear stress was transferred to the underlying till (Smalley, 1968) and thereby the till flowed or was pressed aside and carried away by passing ice.

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REFERENCES

Budd, W.F. 1970. Ice flow over bedrock perturbations. *J. Glaciol.* 9, 55, 29–48.

Dahl, R. 1967. Senglacial ackumulationsformer och glaciationsförhållanden i Narvik-Skjomenområdet, Norge. *Norsk Geografisk Tidskrift* 1967–3.

Frocht, M.M. 1948. *Photo-elasticity.* John Wiley and Sons, New York, pp. 505.

Gillberg, G. 1955. Den glaciala utvecklingen inom sydsvenska höglandet. *Geol. Fören. Stockh. Förh.* 77, 481–524.

Johnson, A.M. 1970. *Physical Processes in Geology.* Freeman, Cooper and Company, San Francisco, p. 577.

Minell, H. 1972. Studier av några drumliner i en fjälldal sydost om Narvik (3-betygsuppsats), p. 47.

Norges Geotekniske Institutt. NVE-stabkraftverk. 1970. Resultat av massundersökelser utfört i 1970 for dam Baatsvatnet.

Smalley, I.J. and Unwin, D.J. 1968. The formation and shape of drumlins and their distribution and orientation in drumlin-fields. *J. Glaciol.* 7, 51, 377–390.