SVERIGES GEOLOGISKA UNDERSÖKNING

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HANS G. JOHANSSON

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With one plate

SUMMARY IN RUSSIAN

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ABSTRACT

The moraine ridges in Västerbotten have earlier been interpreted as drumlins. To find new information, the author has investigated some moraine ridges in the same region. Granulometrical analyses, fabric analyses, seismic investigations, and borings have been carried out.

The investigations have revealed that there is a considerable variety in morphology, structure, and texture of the moraine ridges. In the coastal area, below the highest shore line, there are crag-and-tail ridges. Farther inland near the highest shore line, there are a type of dead-ice moraine and hummocky moraine. With few exceptions, the moraine ridges in Västerbotten are related to bedrock knobs.

INTRODUCTION

In the beginning of the 20th century, A.G. Högbom (1905; 1906, pp. 125 ff.) made extensive investigations of drumlins in the county of Västerbotten, northern Sweden. They were studied mainly from a morphological point of view. The present work is an attempt to discuss and give more and new information about the moraines in the same region.

The investigated localities and areas (Fig. 1) have been chosen so that the genesis of different types of moraines can be compared. Localities 1 and 2 in the Ängersjö area, the Stöcke area with localities 3, 4 and 5, and locality 6 (Holmsund) are all situated below the highest shore line, *HK* (in Swedish "högsta kustlinjen"). The Sundö area with localities 7–11 is situated at or just below *HK*, and localities 12–14 (Yttersjö) and 15 (Ekträsk) are situated at or just above *HK*.

The primary aim of the investigations in Västerbotten was to study the texture and structure of the moraines, while the morphological aspects were of secondary interest. Several detailed investigations, e. g. granulometrical analyses, fabric analyses, seismic investigations, and borings for the depth to bedrock, have been carried out.

A BRIEF REVIEW OF THE LITERATURE ABOUT DRUMLINS

Among the many signs left after the last Pleistocene deglaciation, drumlins form a characteristic feature in several regions. The term drumlin was used as early as in the 1830's (cf. Charlesworth 1957, p. 389). Later, Chamberlin (1894) distinguished four different morphological types of drumlins: 1. Mam-

Fig. 1. Map showing the positions of the investigated areas and localities in Västerbotten.

millary hills (dome-shaped); 2. Lenticular or elliptical hills (a dophin-back form, the long axis two or three times longer than the transverse axis, maximum height in the proximal part); 3. Elongated ridges (very often a form with a rather steep proximal part and a gentle distal slope); 4. Till tumuli. Till tumuli were introduced tentatively and Chamberlin doubted their existence. The designation is never used nowadays. The different drumlin types can be supplemented with another closely allied form, the crag-and-tail, which is an accumulation of till on the lee-side of a bedrock knob.

Up to the present, several investigations and descriptions of drumlins have been published. The vast literature treating drumlins has been surveyed by Ebers (1926, pp. 153–270, and 1937, pp. 200–240), Weinberger (1957, pp. 26–33), and Charlesworth (1957, pp. 389–403). Many theories and opinions of the genesis of drumlins were presented in those papers. There is, even nowadays, an uncertainty in the explanation of their formation, and in the last decade, the question has been discussed from more theoretical and physical points of view.

Chorley (1959, pp. 339–344) compares the mathematical lemniscate loop with the shape of drumlins. From topographic maps and air photographs, Reed (*et al.* 1962, pp. 200–210) has made measurements of form, orientation, and spacing of drumlins in three different areas in the United States.

In the most easterly part of Ireland, Vernon (1966, pp. 401–409) has studied the geographical distribution of drumlins, and he discusses the ice flow in the area and the drumlin origin. He points out that the presence of some obstacle seems to be necessary for the formation of drumlins, i. e. a bedrock knob overridden by the ice creates pressure differences and a changing mobility of the ice. ”Pressure-melting on the front of the obstacle creates a zone of greater mobility in the ice, which moves to the zone of low pressure behind the obstacle, leaving the debris behind as till” (*op.cit.* p. 408).

Smalley (1966, pp. 1 379–1 380) suggests that ”drumlins are formed in a layer of boulder clay separating a glacier from certain types of terrain”. The boulder clay or till-layer with the right proportion of boulders constitutes a granular mass which can expand when deformed (a dilatant material). In a later paper, Smalley and Unwin (1968, pp. 377–390) further develop this theory, and they draw the conclusion that two things play important roles for the formation of drumlins: the dilatant material and the stresses in the interface zone between the till and the glacier.

Baranowski (1969, pp. 197 ff.), who has studied the regular distribution of drumlins on maps from two different areas, found an obvious regularity in the distribution. Baranowski is of the opinion that the formation of drumlins is similar to that of the fluted moraines and he presents a hypothesis for the origin of drumlins based on the conditions of the basal melting in a glacier.

In a recently presented paper, Hill (1971, pp. 14 ff.) describes investigations of drumlins in an area in northern Ireland. The internal composition of the investigated drumlins shows a considerable variation. Some of them consist entirely of one type of till, others have two beds of till. A bedrock core has been observed only in a few. Till fabric analyses have been performed at different depths of the drumlins. From the investigations of texture, structure, and till fabric, Hill suggests that till drumlins have been formed "mainly by deposition" (*op.cit.* p. 30). The erosional processes are important for the formation of the final streamlined shape of till drumlins and for the moulding of the rock outcrops.

EARLIER INVESTIGATIONS OF DRUMLINS IN VÄSTERBOTTEN

As a result of the last glaciation, most of Sweden is covered by till, lying in flat, even areas, or forming different kinds of moraine accumulations. Different types of moraine ridges can be found in the county of Västerbotten. A.G. Högbom and E. Granlund have studied this region and tried to explain the genesis of what they call drumlins. A brief review of their investigations and theories will be given in the following.

A.G. Högbom (1905 and 1906): Högbom described drumlins in the coastal area and in the interior of Västerbotten. The southern part of the coastal area had a striped pattern of moraine ridges. These ridges were 1–3 km in length and their average width were 50–100 m. Högbom found drumlins with a buried bedrock core, but most of the ridges had in their proximal part an exposed bedrock knob with typical stoss and lee side. The bedrock knobs, sometimes striated, reached a few meters over the distal part of the moraine ridges. For the most part, the striae corresponded to the orientation of the moraine ridges.

Högbom found that drumlins in the coastal area consisted of basal till. This till was, however, not always compact but rather loose and sandy. Sharp-edged boulders and stones were found commonly but he also found boulders in the till with their upper side rather streamlined, smoothed, and sometimes even striated (see p. 26).

Högbom described another drumlin area from the interior part of Västerbotten. This region, a plateau reaching 250 m a.s.l. (*HK* approx. 230 m a.s.l. according to Högbom; cf. p. 32) was best developed between the Vindelälv and the Piteälv. It was characterized by a terrain of irregular hummocky moraines where different morphological types of moraine ridges, mires, and small lakes formed a chaotic muddle. Högbom pointed out that although these moraine ridges were very small, just a few meters in height (rarely 10–15 m), they were very easily observed but they made the recognition of drumlins difficult, as the latter did not appear in typical morphological forms. The drumlins were shaped either as long, very low and flat, elongated ridges, hardly discernible over the surrounding mires, or as elliptical hills of large proportions. Högbom suggested that the last mentioned forms (called "moränlider" in Swedish) had a thin layer of till covering a relatively high bedrock core. The largest forms reached about 150 m above the surroundings and they always had a rather streamlined form with a smoothed surface. They were extended in NW–SE, parallel to the direction of the observed striae.

The different types of the ridges were composited either by till (sandy and silty) or stratified drift (gravel – silt). A combination of both also existed. Högbom characterized those of stratified drift and till as kames.

Högbom's discussion of the origin of drumlins dealt with the erosion and the deposition of the land-ice. He maintained that erosion was the most important factor. He interpreted the extremely elongated ridges in those regions as results of fairly strong erosion.

In the investigated areas, Högbom also found that the drumlins generally had been accumulated around or over a bedrock core (cf. Vernon 1966, p. 408). However, the extremely elongated ridges seemed to lack a bedrock knob. In this case he suggested that the first impulse for the development was a boulder, but it was also imaginable that englacial or subglacial debris locally could cause a similar obstacle. In his concluding remarks he inferred that there always seemed to have been some obstacle to the ice movement and to the ice transport, causing the formation of drumlins.

Granlund (1937, pp. 42 ff.; 1943, pp. 41 ff.): During the field work for the reconnaissance map of the Quaternary deposits of the county of Västerbotten, Granlund found several differences between the drumlins below *HK* and those above *HK*. Therefore he has made a differentiation on the map, between drumlins of coastal type (below *HK)* and inland-drumlins (above *HK)*.

Granlund observed in the area below *HK* that drumlins were generally few and far apart, except for in the southeastern coastal plain. He supposed that the moraine forms in the whole area above *HK* were influenced by the bedrock morphology. There also seemed to be a concentration of drumlins along the valley-sides, particularly in connection with eskers. Granlund interpreted the latter type of drumlins as intermediate forms between drumlins and eskers, and called them radial moraines (cf. G. Lundqvist 1943, p. 21).

According to Granlund (1943, p. 32) the average grain size composition of the till in the drumlins was: gravel 35 %, sand 35 %, fine sand 25 %, silt, and clay 5 %. However, there was a great difference between individual samples depending on the occurrence of sorted material. It was very common that ridges consisted of glaciofluvial sediments in one part, and of till in other parts; ridges of till with embedded sediments also occurred.

The almost complete absence of drumlins on the coastal plain, with the exception of its southeastern part, was explained by Granlund's assumption that oscillations of the ice front during the deglaciation of the particular area destroyed the drumlins and caused a redeposition of the superficial till. On the other hand, the preservation of the drumlins in the southeastern part could have been due to a floating ice front during the deglaciation. The basis for such a theory was the few end-moraines and the absence of eskers below 50 m a.s.l. Above that level the ice had basal contact. On the basis of other data, however, the theory has been discussed and rejected by Hoppe (1948, pp. 34 ff.; 1960, pp. 374 and 377; cf. Bergström 1968, pp. 9 and 12).

The genesis of drumlins above *HK* was not discussed by Granlund. He assumed that the radial moraines were formed as a combination of glaciofluvial sediments and till forced up into longitudinal, basal crevasses near the ice margin.

METHODS

Levelling and mapping of the Quaternary deposits

Profiles were constructed on most of the moraine ridges discussed in this paper by levelling with a Wild NK 10, chiefly for seismic investigations (see below), but also for morphological studies. Several of the profiles, as well as the highest shore line (p. 32), were levelled with reference to elevation points.

The topographic maps of the Stöcke and the Sundö areas (Fig. 7 and Pl. 1) were made photogrammatrically by the Geographical Survey Office of Sweden. On the basis of such a map, the Quaternary deposits of the Sundö area (Pl. 1) were mapped, for the main part in the field, and locally supplemented by aerial photo interpretation.

Seismic investigations and borings

The composition and the stratigraphy of the moraine ridges were investigated with seismic methods. For this project a Hammerseismograph type Md-3 (Automatic Engineering Seismograph, Soiltest Inc.) was used. The investigations in the field, as well as the mathematical calculations, were carried out by Dr. Ulf Thoregren (1971); the geological interpretations were done by the author.

Most of the seismic profiles were supplemented by borings. The primary aim of the borings was to make certain of the depth to bedrock in the moraine ridges. A Cobra-borer (Atlas Copco) was used for this project.

Particle-size analyses and presentation of analytical data

The particle-size distribution of till was determined by (1) the point inventory method on particles >20 mm (Hörner 1944, pp. 702 ff.), (2) field-sieving of

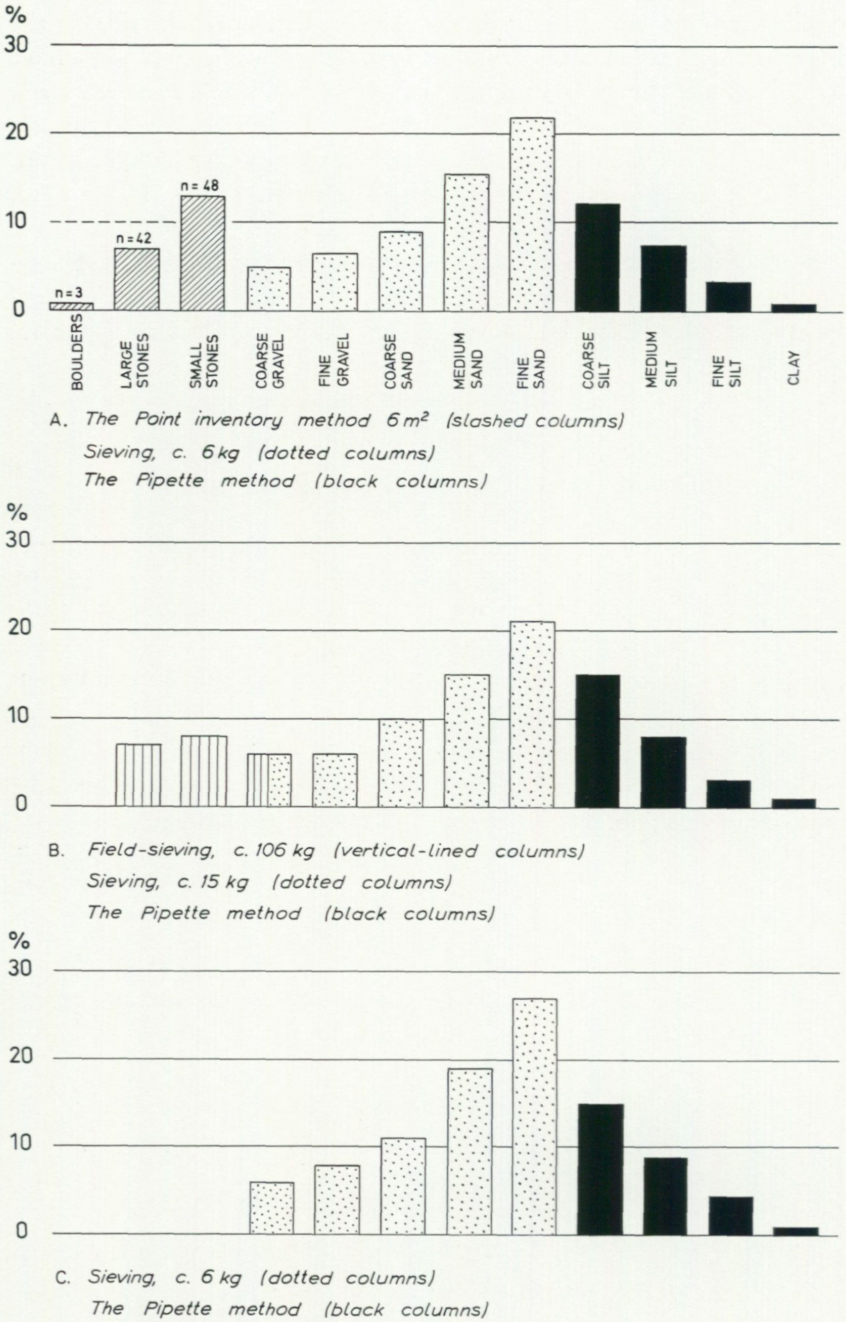

Fig. 2. The result of different particle-size analyses of a till in Holmsund, locality 6.

coarse material 200–11.3 mm, (3) laboratory-sieving of material 20–0.062 mm, and (4) sedimentation analysis (the pipette method) of material <0.062 mm.

For the point inventory method, a square net with 10 cm squares was used. The measurements were recorded on graph-paper with the x-axis and y-axis corresponding to the square net used. Thus, different structures in the exposure wall, e.g. layers, lenses, or contorted laminae of sediments could be recorded at the same time. When using the point inventory method, a reduction for porosity was done. The porosity, generally 33 %, was calculated from density measurements *in situ* with a Soiltest Volumeasure.

The till investigated with the point inventory method was also sieved in the field. Each sample was collected in conical piles and split by quartering by hand until an adequate sample was obtained. The total weight of the samples ranged from 75 to 125 kg.

A great number of till samples and samples of sediment from layers and lenses have been analysed, but only a few cumulative curves and histograms with results from these analyses are presented in this paper. The particle-size distribution of till and sediments is based on Atterberg's classes, although here presented according to square openings used in sieving. In the diagrams of particle-size distribution, no importance has been attached to the interruptions at 0.062 mm caused by the difference between sieving and sedimentation analysis.

Figure 2 shows the result of the different methods mentioned above, tested on the most usual type of till in Västerbotten (a till from Holmsund, locality 6 in Fig. 1; see p. 26). There is no doubt that the larger a sample is, the larger are the fragments that can be satisfactorily included for classification. It is even more apparent when analysing and classifying the coarse till types (cf. Fig. 18).

Fabric

The orientation of the particles was studied in order to obtain adequate information for interpreting the genesis of the moraines (H.G. Johansson 1968, pp. 207 ff.). The measurements were made with a Silva-compass (Type 15), with which the strike and the dip of the long axis (the A axis) and the dip of the middle axis (the B axis) were gauged. No account was taken of the relationship between the length of these axes, other than a clear distinction between A and B (cf. Holmes 1941). The particles with an A dip >30° were avoided as the observations of the strike were very uncertain (cf. West and Donner 1956, p. 71).

The orientation of A and B was plotted in the lower hemisphere of a Schmidt net. The true dip D of the flat particles (B:C ≥1.5) was reconstructed graphically (C.E. Johansson 1965, pp. 30 ff.). The measured particles had a long axis

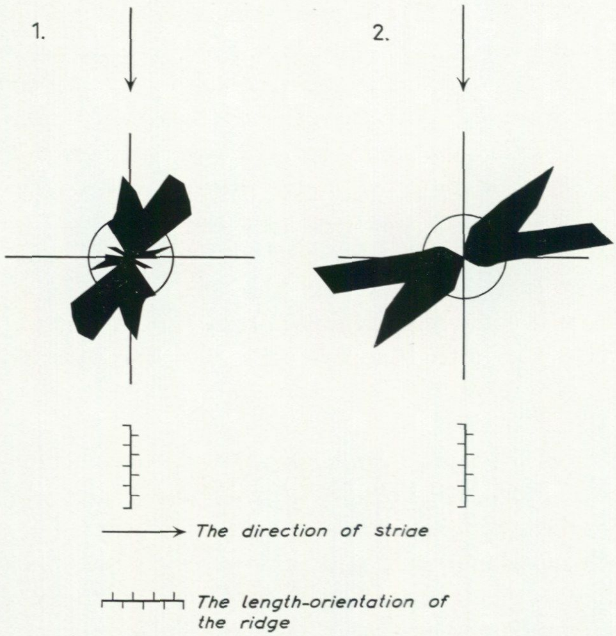

Fig. 3. The difference of particle orientation between measurements made in two vertical sections, perpendicular to each other (1) and one vertical section (2). The circle marks 5 %.

larger than 20 mm (macrofabric); the observed number varied, but was always more than 50. In some of the localities only the strike of A was measured, and the measurements were plotted in a rose diagram (cf. G. Lundqvist 1948).

The observations were made in exposures or dug pits in two vertical sections, which were perpendicular to each other and within rather limited sampling-areas (cf. Kauranne 1960, p. 90; Andrews and King 1968, p. 435). Figure 3 exemplifies the difference between measurements made in the same part of an exposure: 1. the right way in two vertical sections, perpendicular to each other; 2. the wrong way in only one vertical section (cf. Möller 1960, p. 191; C.E. Johansson 1960, pp. 140 ff.; Penny and Catt 1967, pp. 345–346).

The lithology was determined on each measured particle. The shape of the particles was classified according to Holmes' (1941, p. 1 354) and Zingg's (1935, p. 54) form classes. For determination of the roundness a visual-classification with the following classes was applied: well-rounded, rounded, subangular and angular (cf. Russel and Taylor 1937).

This paper presents only a part of the results from the fabric analyses. In the presented stereodiagrams the particles with A:B ≥ 1.5 are marked with bars while the particles with A:B < 1.5 are marked with dots.

INVESTIGATED AREAS AND LOCALITIES

1. The Ängersjö area with localities 1 and 2

MORPHOLOGY

The Ängersjö area (Fig. 4) is situated in the southern part of the Coastal plain (Rudberg 1954, pp. 149 ff., Pl. 4) and within the Nordmaling-plain. This plain is extremely flat and sharply separated from the Undulating transitional region (*op.cit.*) further inland by the Nordmaling escarpment, which is assumed to be a fault line (Granlund 1943, p. 13; cf. S. De Geer 1918, and Rudberg 1954, p. 152 footnote). The difference of altitude between the plain and the plateau hills west of the escarpment is 130–150 m.

GLACIAL GEOLOGY

Glacial striae. According to Granlund (1943, p. 25) there are three main systems of glacial striae in the southeastern part of the coastal region:

1. an oldest system trending N 15°–20° W, which, further towards the northwest, changes its direction towards the west;

2. a younger system in N 10° E, which only occurs in the coast-fringe and on the islands just off the coast (see p. 19);

3. a youngest, and dominating system, trending N 5° W, which, further north, changes its direction towards the northwest.

Bergström (1968, pp. 13 ff.) made several observations of striae and gave the following ideas about different ice movements on the coastal plain in the southernmost part of Västerbotten. The oldest observed system, N 15°–20° W, was "interpreted as local deviations, depending on plastic deformation of the ice during its flow over and around the bedrock hummocks" *(op.cit.,* p. 63). The direction N 10° E was probably striated by ice movements towards local estuaries.

The striae observed by the author in the southern coastal plain of Västerbotten always show the dominating direction N 2°– 5° W, which corresponds to the observations made by Granlund (see above) and Bergström (1968, p. 18). Sometimes, there are small local deviations towards N 5° E (cf. p. 20).

Moraines. The area around Ängersjö is characterized by moraine ridges trending NNW–SSE. The ridges are low and separated by depressions or basins filled with younger sediments, locally peat-covered. In places the ridges merge into each other forming groups or swarms of ridges.

As stated earlier most of the ridges are of the crag-and-tail type. Typical drumlins occur very rarely in this region (see p. 18). The till in the ridges has either sandy or fine sandy matrix.

Transversal moraines are very rare in the whole southern coastal plain. According to the map of the Quaternary deposits (Granlund 1943) there are two end-moraines east and northeast of Ängersjö. Closer studies of these ridges

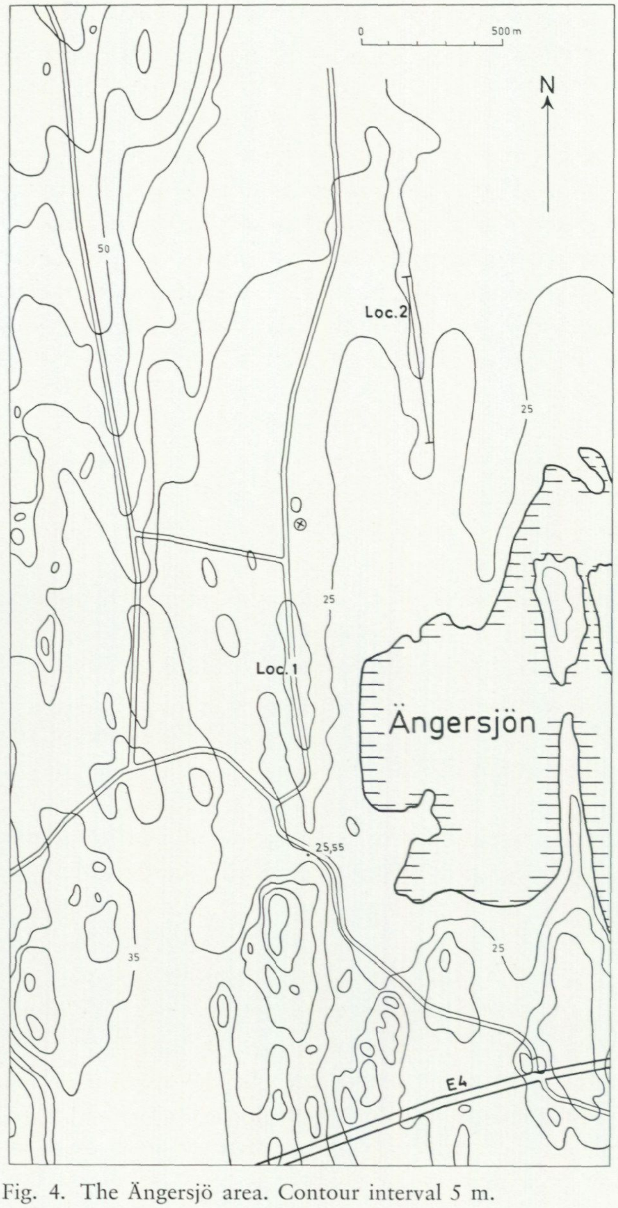

Fig. 4. The Ängersjö area. Contour interval 5 m.

show that the southern one can not be regarded as a true end-moraine. The northern ridge, however, is a distinct end-moraine, 200–300 m long, 20–30 m wide and 2–6 m high. It is extended in a more or less east-west direction.

Glaciofluvial deposits. As the glaciofluvial deposits in Västerbotten, especially the varved sediments, have been treated thoroughly by Bergström (1968), only a short description of the eskers in every investigated area will be given.

According to Granlund (1943, p. 59), there is almost a total absence of eskers in the coastal plain. Bergström (1968, p. 11), however, found a southern part of the Umeälv esker 50 m a.s.l. at Bjännberg in the valley of the Hörneån rivulet, approx. 7.5 km north-northwest of Ängersjö (Topographical map of Sweden 19 J/20 J Husum NO/Vännäs SO). He also pointed out that the older parts of the eskers might exist, "probably as small and discontinuous accumulations, carpeting the shallow depressions and occasional valleys and completely covered by younger sediments" *(op.cit.*, p. 62). The southernmost esker yet found on the coastal plain was, however, discovered by the present author in the neighbourhood of the village of Ängersjö (locality 2 in Fig. 4; see p. 19).

LOCALITY 1

Locality 1 (Fig. 4) is a moraine ridge, 800 m long, 100–150 m wide and 6–8 m high. The direction of the ridge is NNW–SSE and its longitudinal and transversal profiles are symmetric.

Numerous borings for groundwater in the ridge have shown that it is composed of a hard basal till, rich in boulders and stones (oral information). A thin layer of wave-washed gravel covers the till. The underlying bedrock has not been reached in borings as deep as approx. 30 m. Just north of the ridge at point X in Fig. 4, the bedrock has been found at the depth of 22 m (information from the municipal engineering officer in Hörnefors). However, at the elevation point 25, 55 (Fig. 4) approx. 150 m south of the ridge, there is a bedrock outcrop.

LOCALITY 2

Locality 2 (Fig. 4) is a ridge, approx. 1 200 m long, 30–60 m wide and 2–5 m high. The ridge is slightly winding with an average direction of N 5°–7° W. The southern part of the ridge (approx. 350 m) has a slightly asymmetric transversal profile with a steeper eastern slope. The asymmetric form is more pronounced in the middle part of the ridge. In the north it is symmetric.

The surface of the ridge has only few boulders, occasionally with concentrations of them. Observations in dug pits, seismic investigations, and borings indicate that there is great variation in the structure and the composition of the material (Fig. 5). On top of the whole ridge there is a superficial layer of wave-washed, gravelly sand. In the northern part, the sand is lying on a very loose, sandy–fine sandy till, which is rich in sand-lenses. This till is thin in the northernmost part but the thickness increases towards the south. The till seems to merge continuously into the underlying sediment-bed. The sediments are composed of well sorted and stratified gravel, sand, and silt with a thickness of about 8 m, and they lie directly on the bedrock.

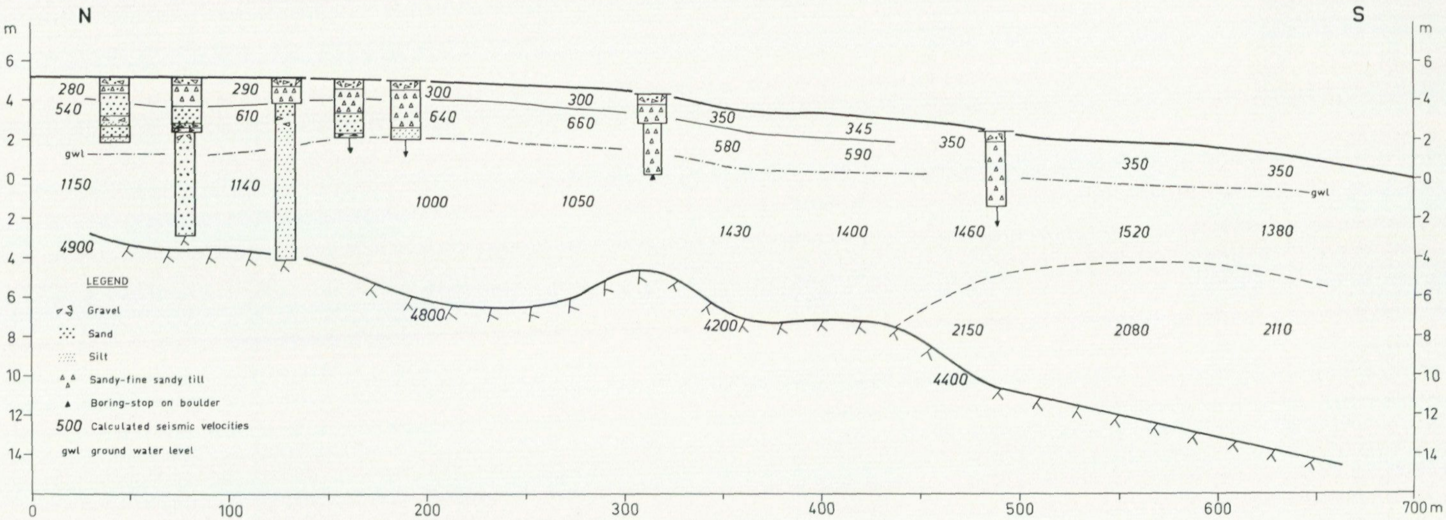

Fig. 5. A longitudinal seismic profile of locality 2 in Ängersjö.

In the southern part of the ridge, the seismic data (1 400–1 500 m/sec.) beneath the wave-washed layer may indicate a loose till or a coarse sediment. A small dug pit (approx. 320 m from O in Fig. 5) showed a hard sandy – fine sandy till with a fissile structure down to 1.5 m. A boring at the same point indicated a hard till to a depth of approx. 4 m (boring interrupted probably against a boulder).

A small dug pit and boring approx. 500 m from O in Fig. 5 gave the following stratigraphy (Thoregren 1971):

0.5 m wave-washed sand;
1.2 m a rather loose sandy – fine sandy till;
>0.5 m sandy – fine sandy till, rich in stones and boulders.

The boring continued down to a depth of 3.85 m in the same till. The ground water level was observed at a depth of 2.2 m.

The surface of the underlying bedrock has a low dip towards the south. In the middle part of the ridge, however, there seems to be an undulating bedrock-surface with two protruding knobs.

The fabric of the till in the first pit indicates a preferred orientation oblique to the direction of the striae and the ridge (Fig. 6). There is also a distinct up-glacier dip. The till is composed entirely of the local bedrock of granite and gneiss. Wedge-formed particles are almost as common as the varihedroid ones, and most of them are subangular.

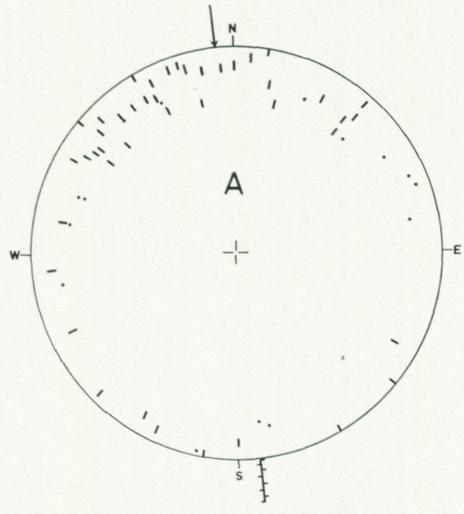

Fig. 6. Stereodiagram of particle orientation in the till in locality 2.

SUMMARY AND INTERPRETATION

The investigations made in the two localities in Ängersjö show that the ridge at locality 1 is a perfectly developed drumlin of the elliptical hill type, probably built up only of basal till and without a bedrock core. The ridge of locality 2 is more complicated as it consists of both till and stratified sediments.

The drumlin of locality 1 in Ängersjö is the only typical one found during the investigations in the county of Västerbotten. Therefore, it has to be considered as an exception. True drumlins appear very rarely in the low coastal plains in Sweden (cf. J. Lundqvist 1970, p. 317). The formation of this drumlin may have certain similarities with the southern part of the ridge at locality 2; therefore some of the theories for the probable genesis will be discussed here. The drumlin may have been formed: 1. by erosion of pre-existing material formed, for instance, in an early phase of the glaciation. Previous investigations have shown that "halts or a slow advance during the forward movement of a glacier can give rise to a wide irregular surface of drift which would be shaped into drumlins by the advancing ice" (Gravenor 1953, p. 680); 2. under very thick land-ice, i.e. "deposited by prolonged and powerful ice-modelling under the thick ice of maximum glaciation" (Charlesworth 1957, p. 395); 3. submarginally in a longitudinal crevasse parallel to the general ice movement. Such crevasses were probably very common in the marginal zone of the ice during the ice recession, and these crevasses were developed either directly by a bedrock knob (see below) or by tensional forces (cf. Hoppe 1951, pp. 162 ff.).

None of these theories can be preferred when interpreting the formation of the drumlin of locality 1 in Ängersjö. At locality 2, a bedrock knob probably was the initial cause of the formation of the drumlin. Thus, the land-ice moved over a convexity of the underlying bedrock, and a crag-and-tail was subglacially formed as an embryonic form of very hard basal till (seism. veloc. 2 000–2 200 m/sec.). The till-loaded basal ice continued the plastering of till (1 400–1 500 m/sec.) on the bedrock knob and formed a drumlin with a bedrock core. The orientation and the dip of the particles in the till are easily compatible with a formation in more or less well-defined, shear planes in the ice. The slight divergence between the particle orientation and the ice movement, parallel to the direction of the ridge, can be explained either with local, continuous differential ice movements caused by the bedrock knob (cf. p. 45), or with different mobility between debris-rich ice and pure ice (cf. J. Lundqvist 1969, p. 29). The last explanation, applied to the genesis of the basal till in the southern part of the ridge, presupposes a greater mobility of pure ice in the depression between locality 1 and locality 2 than of debris-rich ice over the convex bedrock surface east of the depression. There was not only a horizontal transition from pure ice to debris-rich ice but also a vertical transition; a basal, slow moving, debris-rich ice overridden by a rather debris-free and active ice (cf. Boulton 1970, p. 243).

The narrow proximal part of the ridge of locality 2, formed as an esker, was probably built up in a short, subglacial tunnel. During a later stage of the ice recession, a fracture line, initiated by the bedrock knob, was enlarged to a tunnel and a channelway where meltwater collected and flowed southwards. The variations of the bedding and the composition of the sediments testify large and rapid variations of the velocity and capacity of the meltwater-stream. No glaciofluvial sediments have been found in the southern part of the ridge. Possibly, the subglacial river when facing the proximal part of the moraine ridge, turned off and escaped along the eastern or western slope of this ridge.

The retreat of the land-ice over the southern part of the coastal plain in Västerbotten has been governed by calving from a terminus standing in deep water. According to Bergström (1968, pp. 52 ff.) the velocity of the ice recession over the Ängersjö area can be calculated to 250–300 m/year. In combination with either an intense calving in a local estuary developed in the glaciofluvial river mouth or an east-westerly ice border, the subglacial river very soon found another drainage channel. There could possibly have been a diversion of the subglacial river from the flat depression east of Ängersjö to the deep valley of the Hörneån rivulet (see above p. 15; cf. Granlund 1943, the map of Quaternary deposits). After the disappearance of the subglacial river the upper loose sandy – fine sandy till was deposited by the melting of the land-ice.

As a conclusion of the previous discussion, it seems to be reasonable to state that the glaciofluvial accumulation in the northern part of locality 2 represents the southernmost part of the Umeälv esker (see p. 15; cf. Granlund 1943, p. 59; Bergström 1968, pp. 9 ff.).

2. The Stöcke area with localities 3—5 and 6 (Holmsund)

MORPHOLOGY

The morphology south and southwest of Umeå is nearly the same as in the southern part of the Coastal plain. The Stöcke area is situated within the Umeå-plain (Rudberg 1954, p. 152 and Pl. 4), and from the coast-fringe towards the west, this plain gradually changes from a flat plain to a plain with hillocks. The whole zone is 15–20 km in width. A hilly terrain follows further towards the northwest.

GLACIAL GEOLOGY

Glacial striae. Granlund (1943, pp. 24 ff.) found on Holmöarna (islands in the Gulf of Bothnia) a system with the direction N 10° E, which changes to N–S in the area around Umeå (Bergström 1968, p. 13).

At locality 3 (Fig. 7) there is a large gravel-pit (see below) on the stoss-side of a bedrock knob, forming a crag. In the bottom of the gravel-pit the flat-lying bedrock has been stripped of its cover and three different sets of

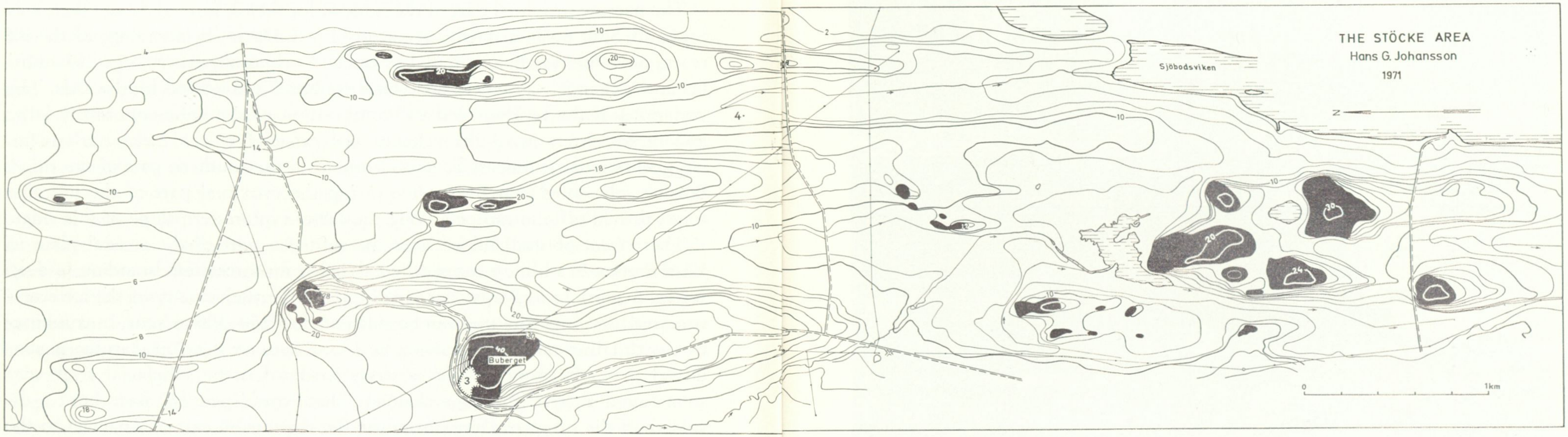

Fig. 7. Map of the Stöcke area with localities 3, 4, and 5. Black areas exposed bedrock. Contour interval 2 m.

striae may be seen. The first set of striae, probably the oldest, is in N 8°–10° W and the striae are few, but coarse, appearing on a westward-inclined facette. The second set is younger and has an orientation of N–S. These striae represent the main ice movement. There also exists a third set oriented in N 2°–5° E (cf. Bergström 1968, p. 14).

On a flat bedrock surface approx. 100 m west of locality 6 (Fig. 1), there are striae oriented in N–S.

Moraines. In the area south of Umeå moraine ridges of the crag-and-tail type dominate the morphology. The crags in the northern part of the ridges are usually bare, and reach a few meters above the crest of the tails. There are, however, also ridges where the crag is covered with thin till. The ridges have the same direction as the main ice movement, i.e. N–S with a slight deviation towards NNE–SSW. Sometimes several small crag-and-tail ridges are gathered into a large ridge (see southern part of Fig. 7; cf. p. 23).

The ridges have always a surface-layer of wave-washed sediments (0.3–0.5 m deep) lying on a hard sandy – fine sandy till. The till is usually rich in lenses, layers or contorted laminae of sediments, especially fine sand and silt.

A few transversal moraines exist in the vicinity of the village of Ansmark, approx. 12 km southwest of Umeå (cf. Bergström 1968, p. 12; Granlund 1943, the map of Quaternary deposits). They are true end-moraines with an orientation in E–W.

Glaciofluvial deposits. According to the map of Quaternary deposits (*op.cit.*) the southernmost part of the Vindelälv esker is located southeast of Stöckesjön at about 19 m a.s.l. and approx. 12 km inside the coast-fringe. Bergström (1968, p. 11) supposes, however, that the littoral sediments further south consist of entirely abraded and redeposited glaciofluvial sediments. Thus, the esker is completely destroyed, and it is therefore impossible to distinguish the esker from the littoral sediments. From Stöckesjön towards the north, the esker is very large and continuous as far as to the village of Röbäck at the Umeälv. After crossing this river, the esker continues northwards and, finally reaches the valley of the Vindelälv.

LOCALITY 3

South of Buberget (Fig. 7) there is a moraine ridge, approx. 2 km long and 400–500 m wide, oriented in N–S. It is a large, typical crag-and-tail.

On the northern slope of Buberget (Fig. 7), there is an exposure with littoral sediments and till. In the lowest part of the exposure, there are gravel, sand and silt in complex alternate bedding (Fig. 8). Higher up on Buberget a bed of boulders and stones, 6–10 m in thickness, is lying directly on the bedrock.

According to borings made by local building-contractors, the tail of the ridge consists of hard till (in Swedish "pinnmo"). It has also been pointed out that the frequency of boulders and stones in the till sharply decreases from Buberget towards the distal part of the tail.

Fig. 8. Littoral sediments in alternate bedding on the northern side of Buberget, locality 3. – Photo H.G.J. 1967.

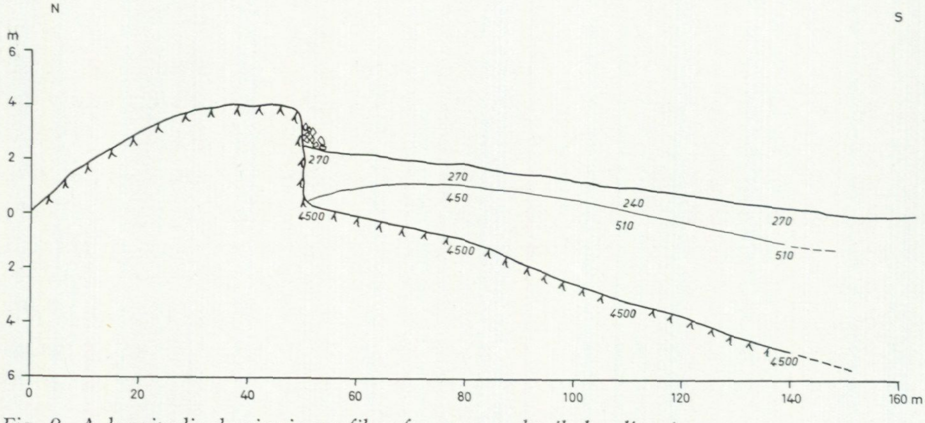

Fig. 9. A longitudinal seismic profile of a crag-and-tail, locality 4.

LOCALITY 4

Locality 4 (Fig. 7) is a small, very typical crag-and-tail oriented in the same direction as the main ice movement (cf. p. 20). The ridge is approx. 150 m long and approx. 30 m wide in the proximal part, and the highest point lies approx. 4 m above the surrounding sediment-plain.

The seismic investigation in a longitudinal profile (Fig. 9) indicates a rather thin, superficial layer of littoral sediments. This layer is either underlain by a sediment or a loose sandy – fine sandy till accumulated directly on the bedrock. However, the low seismic velocities may either indicate a dry and rather homogeneous sediment (cf. Lethinen, 1966, p. 5), or, more possibly, a very loose till, rich in sediments. The last interpretation is based on studies of exposures in similar ridges in the same area (cf. below, locality 5).

LOCALITY 5

Locality 5 (Fig. 7) is an exposure in the middle part of a crag-and-tail, approx. 2.8 km long and oriented in N–S. It is probably composed of a number of small crag-and-tail ridges. The proximal part is a bedrock ridge with its crest approx. 24 m a.s.l. Farther south, two marked heights rise above the rest of the ridge. These heights probably have a bedrock core with only a thin till cover. The tail has a moderate boulder cover; in some patches boulders are scarce.

In the exposure (Fig. 10), a thin surface-layer of littoral sediments, gravel, and sand is resting on a compact basal till, more than 5 m thick. It is a sandy–fine sandy till with normal frequency of stones (cumulative curve *a* in Fig. 11). There is a fissile structure in the upper part of the till.

The basal till has numerous lenses and contorted layers of sediments of sand–coarse silt. Approx. 3 m under the surface, a wedge-shaped layer, 0.2 m thick, of alternating sand and silt laminae occurs (cumulative curves *b* and *c* in Fig. 11). In the middle part of the exposure, the whole layer has been faulted almost half a meter.

Orientation measurements of stones were performed in two sections of the till above the sediment-layer. The sections 1.5–2 m and 3 m respectively below the surface, had a sampling area measuring about 0.5×0.5 m. The long axis orientation of 100 particles with A=20–100 mm was measured in the upper section, and the diagram (Fig. 12) shows a preferred orientation from NE and a small secondary maximum from NNW.

The stereodiagram of the lower section (Fig. 13) with particles A=20–120 mm, shows an obvious preferred orientation from NNW with a dominating up-glacier dip.

Particles of gneiss and granite dominate in the till. The analysed particles are generally varihedroid and angular, or, sometimes, subangular.

Fig. 10. A section of the moraine exposure in locality 5. A compact, basal till interrupted by a layer of sand and silt laminae. – Photo H.G.J. 1966.

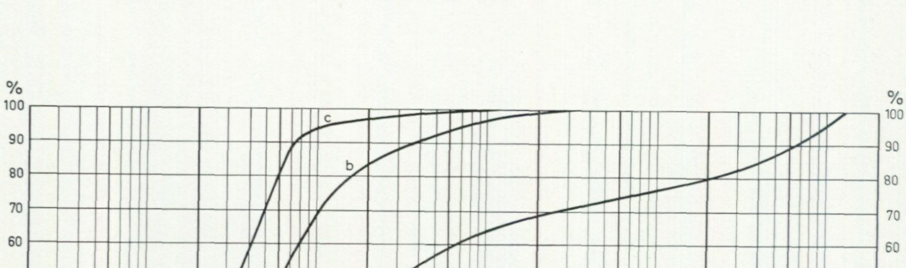

Fig. 11. Cumulative curves showing the till (a) and the sediments of the laminae (b and c) in locality 5.

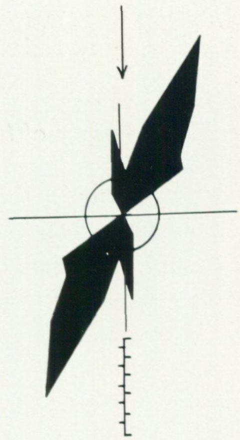

Fig. 12. The long axis orientation of the particles in the till approx. 1.5 m below the surface in locality 5. The circle marks 5 %.

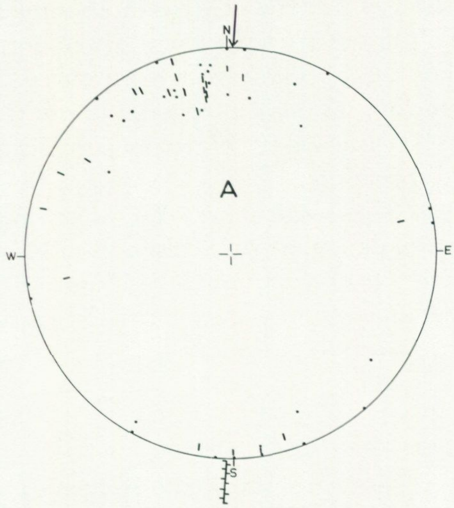

Fig. 13. Stereodiagram of particle orientation in the till approx. 3 m below the surface in locality 5.

LOCALITY 6 (HOLMSUND)

A large excavation made in the middle part of a long crag-and-tail, approx. 1.5 km east of the railway station in Villanäs, created two east–west sections across the ridge. The ridge has an asymmetric transversal profile and is oriented in N–S.

The northern section is 50–75 m long and 2–4.5 m deep. It has the following stratigraphy:

0.8 m littoral sediment (gravel), which decreases in thickness towards the eastern side. In the western slope there is a layer of varved silt with 10–12 varves under the gravel;

>3.5 m hard sandy – fine sandy till with normal frequency of stones, and locally, a well developed fissile structure. The frequency of boulders in the matrix seems to increase with depth.

A boulder pavement is found 2–2.5 m under the surface. The stones and the small boulders seem to be extremely flat and have an up-glacier dip of 20°–30°.

The southern section, 2.5 m deep, has the same stratigraphy as the northern one; however, the basal till here is very rich in thin layers or lenses of fine sand or coarse silt. The material within the lenses is very often finer at the bottom and the top than in the middle part of them.

At the bottom of the excavation there are a number of boulders, a few detached, but most of them still embedded in the matrix. Several of these boulders have their long axes parallel to the direction of the ridge. In the southern part of the excavation, striae parallel to the main ice movement have been noticed on the tops of some boulders (Fig. 14; cf. Högbom 1905, p. 189).

Fig. 15 shows the result of a fabric analysis in a sampling-area, measuring 0.5×0.5 m, just beneath the boulder pavement in the northern section. One hundred particles with A=20–120 mm have been measured. There is a preferred orientation from NE to SW, but also a secondary peak from NNW to SSE. There is no distinct dip. The true dip (D) of the flat particles gives an even girdle with a heterogeneous distribution .

Another fabric analysis (mentioned above on p. 12 and Fig. 3:1) at the depth of 1 m in the till shows two dominating directions, from NE and from NNW. The lithological composition of the basal till is characterized by a high percentage of gneiss and granite. Almost every measured particle is varihedroid, and 70 % are angular, the rest sub-angular.

SUMMARY AND INTERPRETATION

The investigations in the Stöcke area show that the whole area is characterized by a regular pattern of parallel crag-and-tail ridges elongated in N–S. Except for the superficial wave-washed layer, most of the ridges consist of hard, sandy – fine sandy, basal till. Very often a fissile structure occurs in the till. Lenses, thin layers and contorted laminae of sand and silt are common features within the till. A boulder pavement, and boulders firmly rooted in the till, with striae in the direction of the main ice movement on their smoothed upper sides, have been found in one locality. The long axes of coarse particles (stones) have an oblique angle to the direction of the ridges.

The primary reason for the formation of the crag-and-tail ridges was the structure of the substratum, i.e. a pronounced undulating bedrock surface. When moving over this surface, the ice eroded the stoss-side of the bedrock

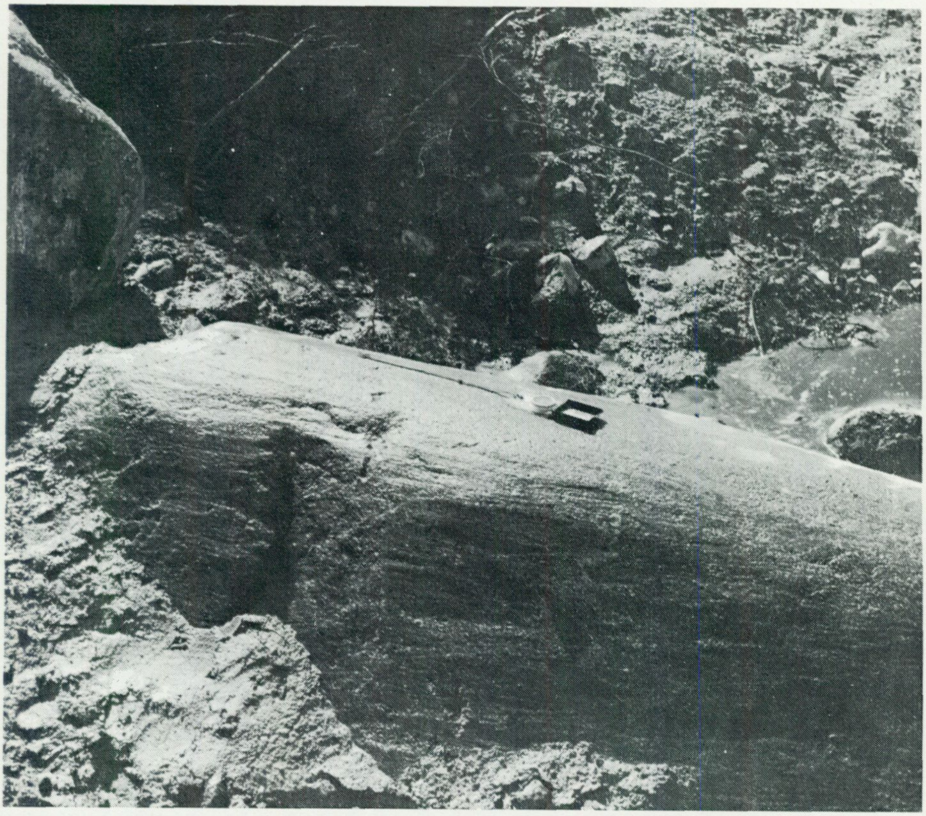

Fig. 14. Striae in N–S on a boulder embedded in till in locality 6. The string on the compass towards the south. – Photo H.G.J. 1966.

knobs; but on the lee-sides, there was quarrying, deposition of till and moulding. Most of the till was probably deposited in the cavities south of the knobs. The oblique fabric of the particles agrees fairly well with an idea of squeezing from the sides towards the center of the tail. South of the bedrock knobs there was squeezing from both NNW–NW and NE–NNE. In the center and towards the distal part of the tail, the particles were, however, deposited with their long axes parallel to the main ice movement in N–S.

The general opinion is that the deposition of basal till occurred in a narrow submarginal zone of the ice. The crag-and-tail ridges in Västerbotten have probably been formed only in the submarginal zone of the land-ice. The interesting thing about the formation of these ridges is that the deposition of basal till sometimes must have been interrupted by an interval of erosion. The striae on the boulders and the boulder pavement in the same locality, are probably results from such an interval of erosion. Dreimanis and Reavely (1953, p. 243) also suggested that a boulder pavement could have been formed

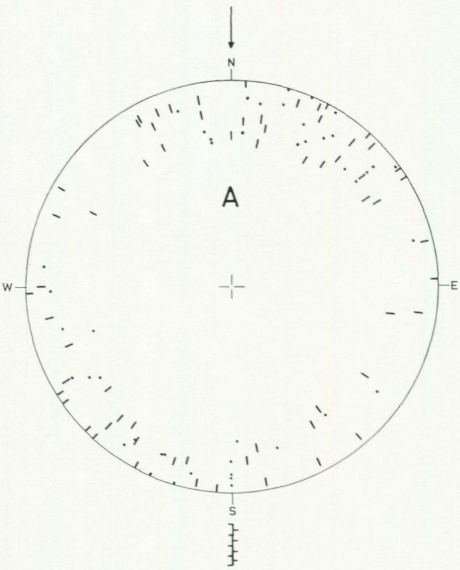

Fig. 15. Stereodiagram of particle orientation in the till in locality 6.

"by erosion of finer debris around them leaving the firmly anchored stones as a pavement". They observed striae on flat tops of the boulders in the pavements; however, striae have not been observed on the boulders in the pavement at locality 6. Therefore, it is not improbable that just this pavement is the result of a more pronounced erosion on the stoss-side of the bedrock knob, and by a gradual deposition of a layer of coarse particles on the lee-side (cf. Holmes 1941, p. 1 350).

Embedded sediments are common features in till in Sweden. Such features occurring in the surroundings of Stockholm have been investigated and described in detail by Möller (1960). As these phenomena also are a general feature in the till of the crag-and-tail ridges in Västerbotten, further interpretation about their genesis will be discussed here.

Meltwater on, in, or below the ice has been the primary agent for the formation of these sediments (cf. Boulton 1968, pp. 408–409). During the deglaciation, the surface of the ice probably was covered with debris of varying thickness. Superglacial melting resulted in small waterstreams, which worked their way down through temporary, vertical crevasses to the basal parts of the ice. At the bottom of the ice, water-transported and well sorted sediments were accumulated at the same time as the deposition of the till. The sediments were probably accumulated in small shallow hollows. The lenses and the layers very often seem to have fine material at the top and at the bottom, but coarse material in the middle. The last mentioned feature is probably due to an accumulation of fine material when the vertical crevasse had a small opening, or when the transport-capacity of the meltwater-stream was very low. With increasing melting, more water, and, consequently, coarser material were transported and accumulated at the base of the ice. As the ice moved all the time, the crevasses could not remain open for a long time. This fact, in combination with new channels for the superglacial meltwater-streams, resulted in decreased transport through some of the crevasses, and, thereby renewed accumulation of fine material. A rather rapid closure of a crevasse could also result in only one or two different bodies of sediments in a hollow. G. Lundqvist (1951, p. 56; cf. Granlund 1943, p. 43) suggested that some of the lenses in a till were made when the basal parts of the ice melted rapidly and short open-water channels with short duration transported and accumulated sediments just before the ice-masses settled again. He also remarked that the thorough gradation of the particles must have started earlier, probably superglacially.

However, the sediment-features observed in the till in the Stöcke area are not always so regularly formed or accumulated as those described above. On the contrary, there are different types of sedimentary structures generally attributed to other genetical causes. These sediments were accumulated subglacially at the same time as the basal till and they were also compressed under thick ice-masses and till. The compression resulted in drying and, therefore, such features as wedged lenses, contortions, faults or joints, etc. are quite common in the till. The fault of the layer in locality 5 (p. 23) is probably the result of melting of embedded ice-blocks (cf. Boulton 1968, pp. 405–406) or drying.

During the land uplift, the regression of the sea has exposed the superficial deposits to wave-washing. The regional investigations in the coastal plain of Västerbotten show a very intense wave-washing in the southern or southeastern part of the ridges (cf. Hoppe 1959, pp. 195 ff.). Most of the littoral sediments, which derived from this part of the ridges and from the thin till-covered crags, nowadays bare, have therefore been redeposited on the northern or northwestern slopes of the ridges (cf. p. 21).

It appears from what has been said above that the theory of a thin and floating land-ice during the retreat over the coastal region in Västerbotten, suggested by Granlund (1937, p. 45 and 1943, p. 44), must be seriously doubted (cf. Hoppe 1948, pp. 34 ff.). Nevertheless, one piece of evidence supporting his interpretation remains, viz. the absence of end-moraines (cf. however p. 20); but this is not due to a floating ice but rather to a rapid ice-recession caused by local conditions (cf. Bergström 1968, pp. 52 ff.).

3. The Sundö area with localities 7—11

MORPHOLOGY

The Sundö area, approx. 15 km east of Örträsk (map sheet 56 Degerfors SV), is situated in the region of the inland plains and within the "Skivsjöslätten" (Rudberg 1954, p. 171 and Pl. 4). This plain is characterized by a few monadnocks with absolute heights of 250–>400 m and relative heights of 50–150 m. The geological map of the Sundö area (Pl. 1) shows that the heights extend in a direction from NW to SE, surrounded by flat, inclined surfaces, e.g. west of Åtmyrberget; or areas with very small formations, e.g. in the middle part of the map. Some of these small formations are too small to be included in the map.

GLACIAL GEOLOGY

Glacial striae. In the western part of the area, approx. 450 m west–northwest of locality 11 (Pl. 1), is a small bedrock outcrop, well polished, with a number of fine striae in N 28°–30° W (Fig. 16). This is the main direction of the latest ice movement in this area.

Approx. 300–500 m south or south–southwest of Åtmyrberget, several small rock drumlins are lying parallel to the main ice movement. On some outcrops very fine striae in N 30° W have been observed, especially on fragments of quartz and pegmatite.

On the southern shore of Åtmyrsjön a bedrock outcrop with a north-facing stoss-side is striated in N 28° W.

In the southeastern part of the area, just south of the road Ottonträsk–Skivsjö, a small rounded bedrock outcrop has striae in N 32°–34° W.

In a preliminary report (H.G. Johansson 1968, p. 206), the different sets of striae at locality 7 (Pl. 1) were described in detail; therefore, only a short summary will be given here. Three different directions of striae were observed on the crest of a ridge-shaped bedrock formation. The age relation between them was N 80°W ⟶ N 31°–32° W ⟶ N 27°–40° E.

These directions also occur, although extremely poor developed, on a small bedrock surface approx. 150 m east–southeast of locality 7. The youngest striae here have an orientation in N 10°–25° E.

Moraines. According to Granlund (1943, the map of Quaternary deposits), the area northwest of Sundö is characterized by drumlins of the inland-type oriented in NW–SE. A more detailed examination shows, however, that most of the moraine ridges occur in an irregular pattern. Ridges with sharp crests and rich in superficial boulders alternate with smooth ridges with a medium or low frequency of superficial boulders. These ridges are typical dead-ice moraines. They can be described as both the Giltjaure- and the Palgejaure-type (G. Lundqvist 1943, pp. 23 ff.).

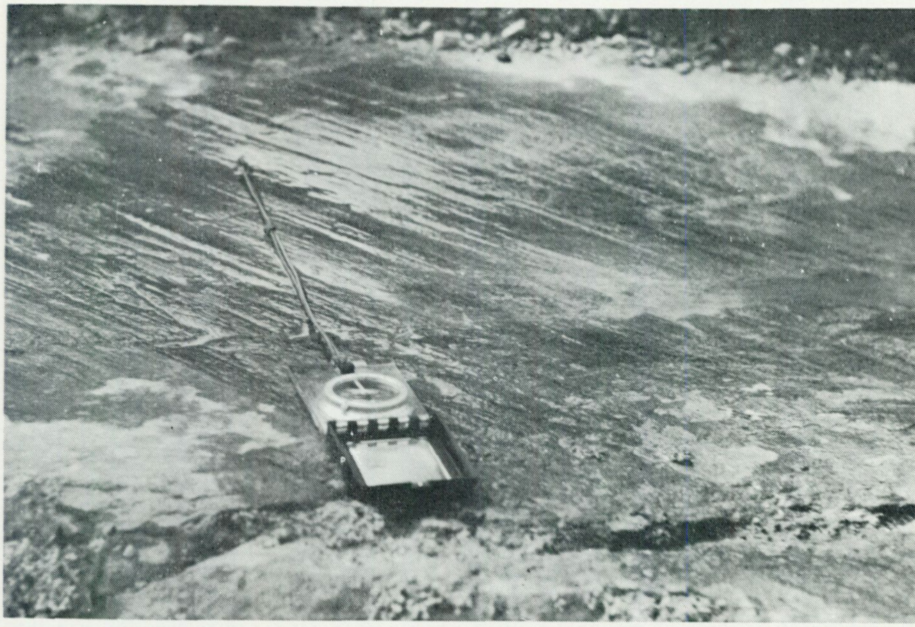

Fig. 16. A small bedrock outcrop with striae from N 28°–30° W, the main ice movement in the Sundö area. The string on the compass towards the south. – Photo H.G.J. 1967.

In the northwestern part of the area, just above the highest shore line, a few, rather small, separate ridges with extremely boulder-rich surfaces occur. These ridges are more straight and regular than the others. They are parallel to the main ice movement from NW. The depressions between the ridges are very narrow and seem to be rather deep. These features point to the fact that the ridges are radial moraines (cf. Granlund 1943, p. 43; see p. 8).

Crag-and-tail ridges, which are so common in the coastal plain, do not exist in this inner part of Västerbotten.

Glaciofluvial deposits. The most important glaciofluvial accumulation in the Sundö area is an esker running from Lill-Ramsjön towards NW and along the eastern slope of Åtmyrberget (Pl. 1). The structure, as well as the texture, in the esker shows great and rapid variation. Very short layers or sheets of gravel, sand and silt, and, contorted layers or other disturbances are common.

The esker-form disappears a short distance southwest of Åtmyrsjön, where the glaciofluvial gravel and sand have been deposited in flat and even fields.

The esker reappears east of Åtmyrberget, where rather thick, coarse-grained sediments have been deposited in the narrow valley. Recent rivulets have cut through the glaciofluvial deposits in this part and destroyed the primary morphological form. The result has, therefore, been several small ridges and very deep ravines. These features, together with some dead-ice cavities, give the whole northeastern part of the glaciofluvial accumulation a very irregular pattern.

Besides this esker, there are only remnants of a small glaciofluvial accumulation in the northwestern part of the Sundö area (Pl. 1). Granlund (1943, Fig. 57 p. 64 and p. 75) described this accumulation as a small delta with its surface 248 m a.s.l. thus, supposing it was situated at the highest shore line (see below).

The highest shore line. The highest shore line in the Sundö area is developed as an erosional shore line, represented partly by a sharp shore cut, partly by an even, wave-built terrace. There is very often a sharp limit between wave-washed and non-washed till. The limit varies in height depending on different exposition (cf. Hörnsten 1964). In the innermost part of the valleys, the highest shore line is poorly developed. It seems to be situated between 246 m and 249 m a.s.l. In the western part of the area there is a very sharp limit at approx. 254 m a.s.l.

In order to get a better and more exact determination of this limit three profiles were levelled on the eastern slope of Åtmyrberget. Samples were taken in each profile and at different levels. The mechanical analyses show very well the difference in the particle-size distribution between non-washed till, wave-washed till, and littoral sediments.

There is a sharp cut at approx. 250 m a.s.l. Below this cut there is a wave-built terrace of gravel, and farther down, there is a gentle slope with finer sediments on the surface. Between 249 m and 251 m a.s.l. is a zone with a high frequency of boulders. The relationship between the morphological features and the particle-size distribution of the surface layer gives a limit for the highest shore line at approx. 251 m a.s.l.

LOCALITY 7

This locality has been described in detail in an earlier paper (H.G. Johansson 1968, p. 206). Locality 7 (Pl. 1) is a moraine ridge built up of two different types of till, lying on a ridge-shaped bedrock surface (striking NW–SE). The upper till is a loose, gravelly till rich in stones (Figs. 17 and 18), and the lower till is a relatively loose, sandy till, rich in lenses, thin layers, and contorted laminae of sediments. It is apparent from the seismic investigations that the upper till has an even thickness of 1–1.5 m over the whole ridge. The lower till is thicker in the eastern and northeastern part than in the rest of the ridge. In this part, the till also seems to be harder, or to have a lower proportion of sediments. The underlying bedrock is well exposed in an outcrop. From a steep bedrock wall and towards northeast the underlying bedrock seems to be rather undulating, with a ridge-shape under the next moraine ridge.

Fig. 17. A section of locality 7. An upper, loose, gravelly till lying on a lower, relatively loose, sandy till rich in sediments. – Photo H.G.J. 1966.

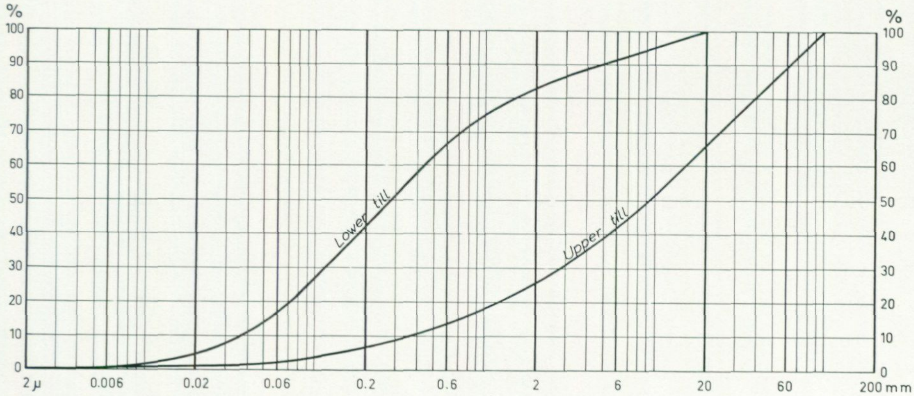

Fig. 18. The composition of the upper and lower till in locality 7.

The fabric was analysed in the two till layers in two vertical sections, perpendicular to each other. The stereodiagrams (H.G. Johansson 1968, pp. 208–209) show particle orientations in the upper, as well as in the lower till, which are somewhat oblique to the youngest ice movement from NNE–NE in this part of the area (cf. above p. 30).

Summarizing the lithological investigations in locality 7, there is a clear dominance of local bedrock fragments, i. e. gneiss and granite. Most of the particles are angular and varihedroid in shape.

LOCALITY 8

A small moraine ridge it situated approx. 150 m southwest of locality 7 (Pl. 1). The ridge extends in WNW–ESE. In its northern slope there is a small pit with the following stratigraphy:

0.6 m fairly loose, gravelly till, rich in stones, with thin layers of sediments. A gradual transition to

>1 m sandy till, rich in thin layers and contorted laminae of sand and silt.

Fig. 19 shows that the moraine ridge seems to be built up exactly as in locality 7, i.e. a coarse-grained till of rather uniform thickness covers a finer till. Also this moraine ridge is accumulated on a bedrock knob.

In a perpendicular section of the exposure, the fabric was studied in the lower sandy till. The sampling area was about 0.5×0.5 m, and one hundred particles with A=20–80 mm were analysed. The diagram (Fig. 20) has a distinct bimodal distribution of the directions, with maxima from NNE and NNW. There is a dominance of particles, which are oriented parallel or slightly oblique to the youngest ice movement. There is also an up-glacier dip. Half the number of the measured particles were flat, and the true dip (D) of these gave a cluster in NNW.

LOCALITY 9

Approx. 100 m west of locality 7 (Pl. 1) is a moraine ridge, 150 m long, 80–90 m wide, and 2–3 m high. It is oriented in NNE–SSW.

There is neither an exposure nor an excavation in the ridge, and in order to get an idea of the stratigraphy and the morphology of the underlying bedrock, two transversal seismic profiles were carried out. The obtained seismic velocities show the same stratigraphical units as in the former localities, with a sediment-rich, fine-grained lower till, overlain by a coarse, upper till. In proximal direction, approx. 25 m north of the road to Örträsk, the velocity of the second layer is rather low (600–700 m/sec.) for a till. This layer may consist either of a sediment or an extremely sediment-rich till. The rather

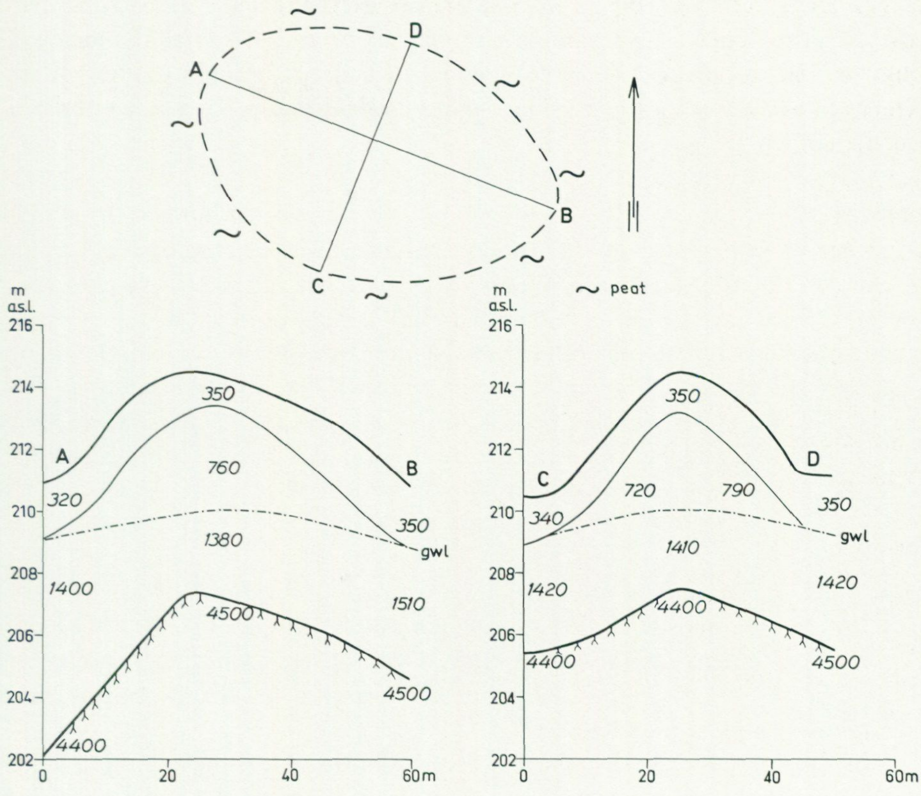

Fig. 19. Seismic profiles of locality 8 in the Sundö area.

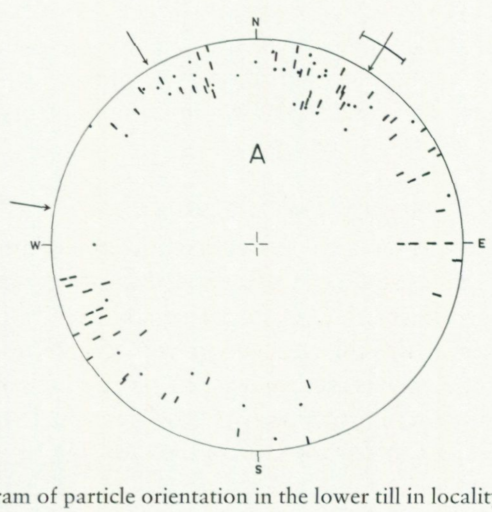

Fig. 20. Stereodiagram of particle orientation in the lower till in locality 8.

small depth to the bedrock, 2–6 m, may also affect the velocities. Southwards, the depth to bedrock increases very rapidly down to 9–10 m as the lower till increases in thickness. The ridge is lying on bedrock, steeply dipping southwards but rather smooth and only slightly undulating in an east–westerly direction.

LOCALITY 10

Another moraine ridge in the Sundö area has been investigated by seismic methods. The ridge has the form of a hemisphere and is, from a morphological point of view, in principle, a mammillary hill. It is surrounded by mires (Pl. 1).

Fig. 21 shows that this ridge has the same stratigraphy as those before mentioned localities although it has an unusual depth to the bedrock. The surface of the underlying bedrock is fairly flat, and dips slightly towards N and E. It is obvious that this hemispherical hummock has no core of bedrock.

LOCALITY 11

Just north of the road, approx. 2.8 km northwest of locality 7 (Pl. 1), is a very low and flat moraine ridge with an orientation of NW–SE. A silty till with thin layers of sediments comprise the ridge. From observations carried out in a little dug pit, it is clear that the upper till, observed in all other localities, is very thin or almost missing here.

The fabric investigations (Fig. 22) in a sampling area, measuring 0.3×0.3 m, show a preferred orientation more or less parallel to the latest ice movement and with an up-glacier dip. A secondary maximum from NNE can also be noticed. The measurements of the true dip (D) for the flat particles give a high frequency and a swarm-like cluster in the northeastern sector.

Almost every analysed particle consists of gneiss or granite with gneiss slightly predominating. The majority of the stones are varihedroid and sharp-angular. According to Zingg's classification system, the distribution is equally proportioned in classes I, III, and IV; only a few stones belong to class II.

SUMMARY AND INTERPRETATION

The main ice movement in the area was directed from NW towards SE. Within a limited part of the area, southeast of Åtmyrberget, a local and younger ice movement, recorded by thin striae, was directed from NNE towards SSW. The orientations of stones in the till correspond with the different directions of ice flow. Southeast of Åtmyrberget, as well as on the higher plateaus farther south in the area, the moraine ridges have been deposited irregularly. A type of dead-ice moraine morphology dominates the area, but towards the western part of the area, regular moraine ridges parallel to the main ice movement

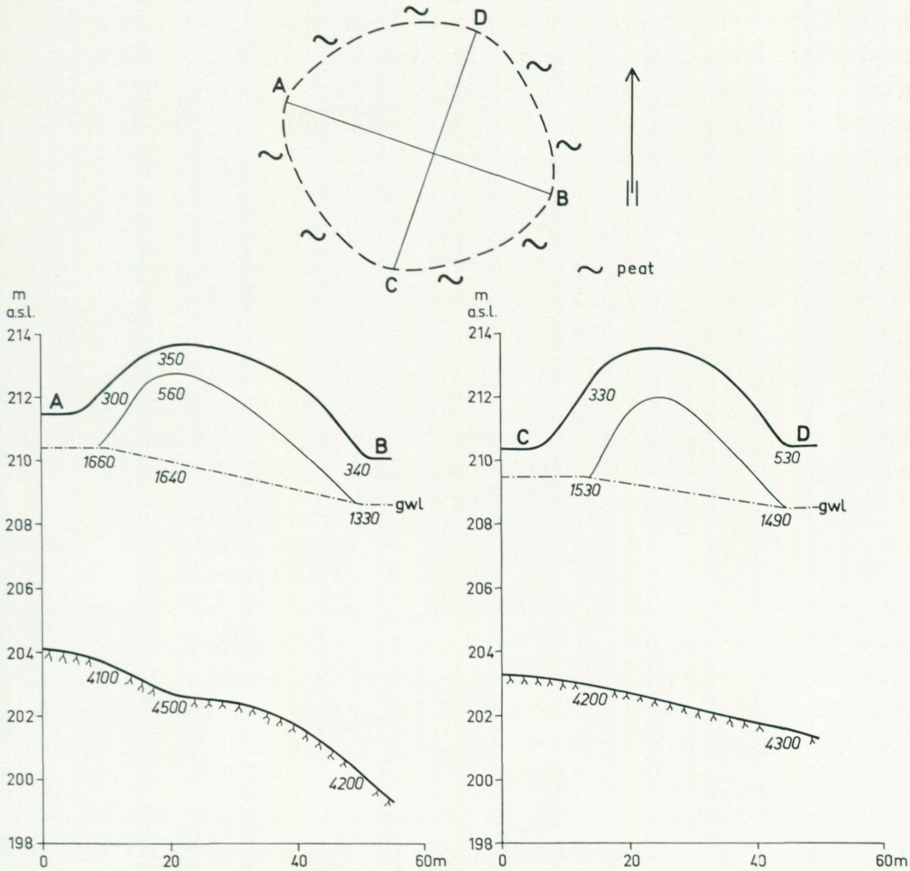

Fig. 21. Seismic profiles of locality 10 in the Sundö area.

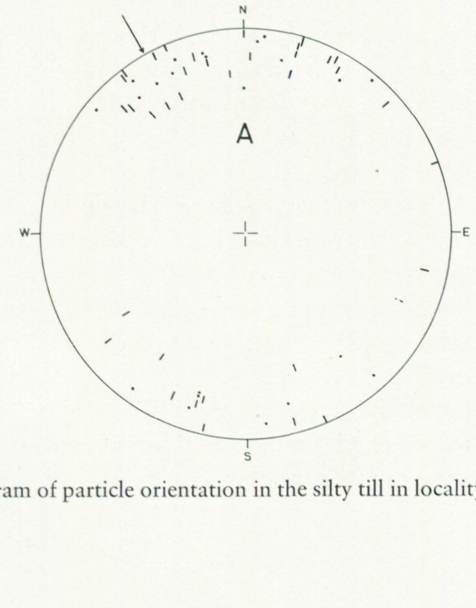

Fig. 22. Stereodiagram of particle orientation in the silty till in locality 11.

occur. There is also an obvious difference in the interior of the ridges in different parts of the area. The dead-ice moraine ridges always have a loose coarse-grained till, underlain by a fine-grained till, rich in sediments. Thus there is a superficial till lying on a basal till. The regular ridges, e.g. locality 11, have no, or only a very thin sheet of superficial till. From the seismic investigations it appears that most of the moraine ridges are built up around a bedrock core, but there are exceptions, e.g. locality 10.

The interpretation of the genesis of the moraine ridges in the Sundö area implies both a subglacial and a superglacial accumulation. There was probably a very complicated deglaciation in this part of the region, mainly due to the transition from subaquatic to supra-aquatic conditions during the land-ice recession (cf. Hoppe 1967, p. 208). The formation of the ridges was primarily initiated by an active ice moving over the undulating bedrock surface. The ice receded rather rapidly (Bergström 1968, p. 57) not by calving in the shallow water, but rather by thinning through ablation. As mentioned above, the main ice movement was from NW, and the sculpturing and erosional activity of the ice resulted in not only striae but also the bedrock drumlins south of Åtmyrberget. In the flat and gently sloping basin in the western part of the area (north of locality 11 in Pl. 1), a basal till was deposited in low moraine ridges, which had the same direction as the ice movement from NW. The orientation of stones in the till (Fig. 22) and the absence of, or the very thin superficial till, indicate a deposition of material by active ice moving from NW during the whole recession period.

Southeast of Åtmyrberget, however, where a younger ice movement has been registered, another theory for the formation of the moraine ridges may be suggested. It has been described earlier in the preliminary report, discussing only locality 7 (H.G. Johansson 1968, pp. 210–211). The remarks from that report, together with the new investigations, give the following synthesis: The formation of the ridges southeast of Åtmyrberget was probably initiated by ice moving over an extremely undulating bedrock surface. In several places a bedrock knob became an obstacle to the ice flow. This feature, in combination with a rather thin ice receding in shallow water or in an supra-aquatical environment, probably made the ice highly crevassed. The narrow and deep valley east of Åtmyrberget acted as a ”bottle neck” for ice moving southwards. The compressing forces within the ice, when passing the concavity, were successively replaced outside (south of) the valley by local differential movements. Southeast of Åtmyrberget and other, smaller hills, the ice fanned out with movements from NNE–NE within a limited area (cf. Granlund 1943, p. 74; G. Lundqvist 1948, p. 27; Virkkala 1960, p. 160). The relatively loose sandy till, rich in sediments lying as a basal till in locality 7 was, thus, deposited subglacially from NE, and the orientations of stones show an oblique alignment with this movement, probably depending on deposition over an obstacle. The supposition that the local ice flow from NE only moved and deposited material within a limited area is confirmed by the fabric analysis from locality 8 (Fig. 20). Despite the very short distance from locality 7, the fabric of the basal till in locality 8 shows a secondary maximum to the main ice movement from NW. The deposition of material in locality 7, as well as in localities 8 and 9, was probably influenced by active ice moving both from NE and NW. The relatively loose matrix and the large quantities of sediments in the basal till indicate a deposition by a rather thin ice.

Most of the ridges in the Sundö area, except for the ridges in the western part, have an upper bed of gravelly till resting on a fine-grained basal till. This favors the idea that the upper till was deposited on the basal till at the very end of the ice retreat phase. The occurrence of this stratigraphy in (1) areas on the lee-side of Åtmyrberget and (2) higher plateaus at or near *HK* (see p. 32) corresponds fairly well with positions favorable for formation of dead-ice moraines according to Ahlmann (1938; cf. J. Lundqvist 1969, p. 26). It is conceivable that the upper till was deposited in crevasses either by an active or a stagnant ice. The till fabric in locality 7 is slightly oblique to the ice movement from NE, and suggests a deposition by an active ice, but on the other hand nothing contradicts an assumption of a successive wasting of the ice through ablation (cf. H.G. Johansson 1968, p. 211).

As mentioned on p. 31 an esker passes through the Sundö area in close contact with the dead-ice moraine terrain in the west (Pl. 1). The esker is probably subglacially formed in a very late phase of the ice retreat in this region (cf. Hoppe 1952, p. 63 and J. Lundqvist 1969, p. 10).

4. The Yttersjö and Ekträsk area with localities 12, 13, 14, and 15

MORPHOLOGY

The investigations in the inner part of Västerbotten have been done mainly northeast of Yttersjö (map sheet 56 Degerfors NV) and northeast of Ekträsk (map sheet 50 Norsjö). Both areas are situated within the region of the Inland plains (Rudberg 1954, p. 171 and Pl. 4). This region is characterized by monadnock plains, a net-work of hummocks and ridges with relative heights of 5–20 m, peat-covered or sediment-filled basins, and many small lakes.

GLACIAL GEOLOGY

Glacial striae. As bedrock outcrops are very rare in these areas, observations of striae are very few. Granlund (1943, the map of Quaternary deposits) observed striae in N 18°–20°W just east of the road at the railway station of Yttersjö. This observation has been verified by the present author.

In Hällnäs, approx. 11.5 km south–southwest of Yttersjö, Granlund observed striae in three different directions, all in sector N to NW (*op.cit.* p. 46). On his map of glacial striae (*op.cit.* p. 24) he also included a direction from NE (cf. p. 41). This locality has not been refound by the present author.

Moraines. The landscape is characterized by relatively high hills with thin till-cover (cf. p. 8) extended in NNW–SSE. Between these hills, in the broad valleys, there are hummocks and moraine ridges lying in an irregular pattern. The longitudinal direction of these small accumulations very seldom corresponds to the presumed main ice movement from NNW.

The material of the hummocks and the ridges seems to vary from one locality to another, from ordinary basal till to glaciofluvial sediment. Frequently, there are transitions between till and sediment even within the same accumulation.

Glaciofluvial deposits. Typical eskers occur only sporadically in this region. A small and, locally, poorly developed esker crosses the road halfway between Yttersjö and Ekträsk (Granlund 1943, the map of Quaternary deposits). This esker can be followed on both sides of the road, but only a short distance towards the south and the north. The material in the esker consists of poorly sorted, stony gravel with occasional thin layers of fine sediments.

The highest shore line. Only approximate determinations of the level of the highest shore line have been made. There has probably been a very weak wave-washing in this part of Västerbotten. The coarse-grained material mantles the hummocks and the ridges almost everywhere and obscures the possible effect of wave-washing in the surface layer. Typical, distinct, wave-washed surface layers are therefore very uncommon. At the cross-road to Sävsjön and to Bastuträsk (map sheet 50 Norsjö), however, the abrasion has formed a wave-cut bench in the southern slope of a rather narrow valley. Near the cross-road it is an elevation point at 254 m a.s.l., which places the highest shore line in this region approximately at this level.

LOCALITY 12

Locality 12 is an exposure in a moraine ridge just east of the road Yttersjö–Ekträsk, approx. 3 km northeast of Yttersjö (map sheet 56 NV). The ridge is oriented in WNW–ESE with a gently descending, northern side and a very steep, southern slope. The ridge consists of fairly hard, sandy till of an ordinary type with normal frequency of boulders and stones. The basal till has in its upper part a fissile structure. Fine sand and silt in lenses, thin layers, contorted lenses and laminae are common. In places, the sediment layers seem to coincide with the arched crest of the ridge. Several small boulders are completely embedded in thin layers of sediment (cf. Virkkala 1952, p. 100; Möller 1960, p. 196). A coarse-grained till, of varying thickness, covers almost the whole ridge, especially noticable on the slopes of the ridge.

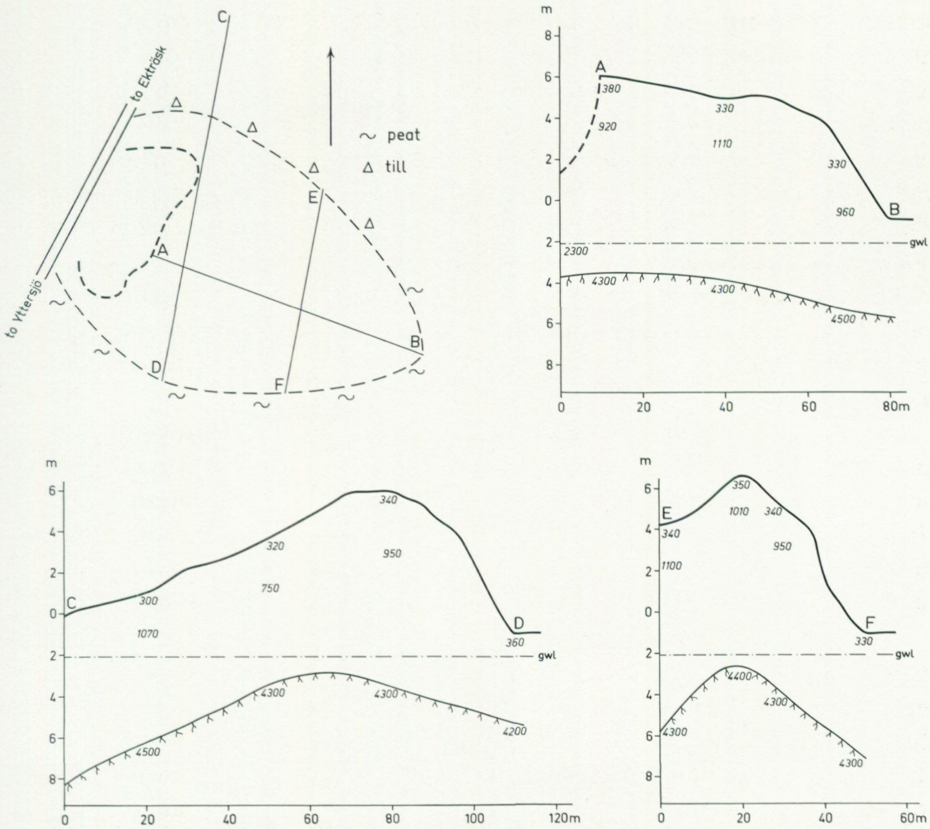

Fig. 23. Seismic profiles of locality 12 in the Yttersjö area.

The seismic investigations (Fig. 23) indicate a rather hard basal till in the ridge. It is possible that the higher velocities in the middle of the ridge indicate a harder till. The underlying bedrock is ridge-shaped, and it coincides fairly well with the orientation and the contour of the moraine ridge.

The fabric was studied approx. 3–4 m under the crest in two vertical sections, perpendicular to each other, and with a sampling area measuring 0.5×0.5 m. The stereodiagram (Fig. 24) shows a distinct tendency of orientation parallel or slightly oblique to the presumed main ice movement from NNW in this region. Analyses of the orientation of long axes of 50 particles have been carried out earlier in the same place by Henriksson (1956). The rose-diagram has a clear maximum in the sector N–N 30° E. There are, however, no details about the position of the analyses (transl. from Swedish ”more than 3 dm depth”), or of particle-size (”analyses of boulders”), etc.

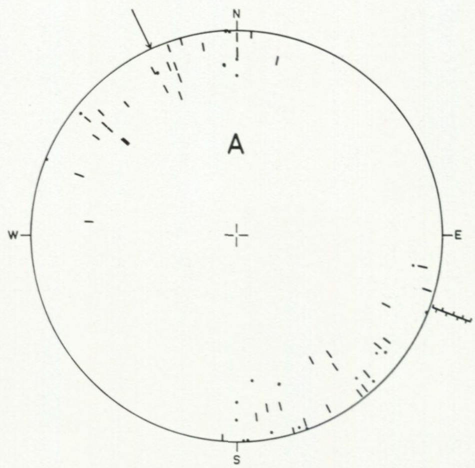

Fig. 24. Stereodiagram of particle orientation in the sandy till in locality 12.

LOCALITY 13

Just east of the road Yttersjö–Ekträsk, approx. 6 km northeast of Yttersjö, a moraine ridge rises 10–15 m above the surrounding mires (Fig. 25). Its horizontal extension is nearly circular with a diameter of 200–250 m. There is a medium frequency of boulders on the surface.

A large excavation, seen in Fig. 25, is situated in the northwestern part of the ridge. Because of debris from the pit walls, the investigations have been restricted to analyses of the particle-size distribution of the basal till, and to studies of the structure, especially in the slopes. The till is compact, with a remarkable high percentage of silt and more than 30 % of stones. Along the slopes, the basal till is covered by coarse-grained till, the thickness of which increases towards the base of the ridge.

Most of the stones lying in the silty matrix are extremely well-rounded. Many of them are also encircled by thin sediment-layers (cf. p. 40). Common features in the basal till are lenses, thin layers, and contorted laminae of fine sand and silt. These features are mixed with a diffuse fissility.

In a fresh section in the southern part of the excavation remarkable disturbances have been observed. Almost vertical, thin layers are intermingled with more or less contorted layers or beds, consisting entirely of water-deposited sediments. In this part, the till is probably a type of Kalix till (in Swedish "Kalix-pinnmo").

Fig. 25. The moraine ridge in locality 13 and the large excavation in its northwestern part. – Photo H.G.J. 1966.

A transversal seismic profile (cross-profile to the ridge) has been placed along the road, and the velocities indicate an approx. 25 m thick basal till in the ridge. The ridge is resting on a bedrock surface steeply descending southwards. The underlying bedrock is, however, ridge-shaped, and approx. 70 m towards the north, the bedrock surface rises and forms a crest between this ridge and the next to the north. The thickness of the till in the interjacent hollow is approx. 9 m.

LOCALITY 14

Along the road, approx. 100 m east–northeast of the above-mentioned locality, the road cuts through a ridge oriented in NW–SE. It is 90–100 m long, approx. 100 m wide and with its highest point 5 m above the surrounding mires.

In the road cut, 1–1.5 m deep, the material consists of more or less well sorted sand. Thin layers of fine sand, in places slightly contorted, give an impression of laminated structure. The material may, thus, be described either as a glaciofluvial sediment or a type of Kalix till (cf. J. Lundqvist 1969, p. 22). In connection with this, it may also be added that the esker described on page 40 runs only a hundred meters farther to the north.

The seismic investigations in this locality reveal the existence of sediments in the ridge (veloc. 450–550 m/sec.). Downward the sediments probably change gradually into hard basal till (veloc. 2 100–2 200 m/sec. below the ground water level). The depth to bedrock, measured from the crest of the ridge, seems to be about 14 m, and this ridge is resting on the northern slope of a bedrock-ridge (see above).

LOCALITY 15

Just above the highest shore line (see p. 40), approx. 2.3 km north–northwest of the Ekträsk railway station, west of the road to Sävsjön (map sheet 50), there is an exposure in a moraine ridge. The ridge is asymmetric and has no distinct longitudinal orientation. The surface has a medium to high frequency of boulders. In the exposure the following section was measured:

0.4 m (along the slope 1 m) a loose gravelly till;
>4 m a fairly hard sandy till with an occasional fissile structure.

Just at the transition from the upper till to the lower till there is a boulder pavement, although not as continuous as in locality 6 (p. 26).

At the depth of 1.5 m in two vertical sections, perpendicular to each other, and with a sampling area measuring 0.5×0.5 m, the fabric was analysed on particles with A=20–100 mm. The preferred orientation is distinctly from NE in a direction transverse to the presumed main ice movement. There are about the same number of particles with up-glacier dip as down-glacier dip. As in every fabric analysis mentioned earlier the gneiss and granite dominate. Varihedroid and sharp-angular particles dominate. An application of Zingg's classification systems gives a remarkably even distribution in all classes.

SUMMARY AND INTERPRETATION

The investigated localities 12–15 are situated in a region close to the level of *HK* (cf. the Sundö area p. 39). The few striae observations show a main ice movement from NNW. The region around Yttersjö and Ekträsk is characterized by an irregular pattern of moraine ridges and some glaciofluvial accumulations. It is a typical hummocky moraine terrain (cf. Hoppe 1952, 1957, pp. 7 ff. and 1959, p. 205). There are great variations in morphology, structure, and texture among the separate ridges. Some of the ridges have extremely steep slopes (25°–30° inclination). The seismic investigations indicate an undulating bedrock surface, but there is not always a conformity between the ridges and the form of the underlying bedrock surface. Most of the ridges are composed either of sandy or silty till, often very hard, with a fissile structure and embedded sediments. In places a type of till similar to the Kalix till occurs. The stones in the basal till seem to be oriented either parallel, slightly oblique, or transverse to the main ice movement from NNW.

There are apparently several similarities between the Yttersjö–Ekträsk area and the Sundö area. In principle, the genesis is also similar. As already pointed out (p. 39) the position of hummocky moraine in a zone close to the level of *HK* favors a subglacial formation in a supra-aquatic environment. The markedly undulating bedrock surface resulted in crevasses extending upwards in the basal part of the ice (cf. Gripp 1929, pp. 225 ff.; Hoppe 1952, pp. 34 ff.; J. Lundqvist 1969, p. 25). The till was subglacially deposited in the crevasses by ice moving from NNW and the orientations of stones confirm the idea of such a deposition. The slightly oblique orientations observed in locality 12 can be interpreted as a continued convergence of movement initiated by the underlying bedrock knob (cf. p. 18). As pointed out above, stones with orientations preferably transverse to the main ice movement, also occur. This fabric was probably created in basal crevasses by the forcing up of material below the heavy ice (Hoppe 1952, Fig. 30; cf. J. Lundqvist 1958, pp. 65 ff.).

Locality 14 between a large moraine ridge and a small but unmistakable esker, has almost all the characteristic features of a Kalix till. It can be interpreted as formed either in an open superficial crevasse or in a basal crevasse close to a melt-water stream (cf. J. Lundqvist 1969, pp. 25–26). The conditions for deposition of sediments were probably more favorable here than at other localities farther away from the melt-water stream (cf. Hoppe 1948, p. 68).

Most of the features point to a subglacial origin of the hummocky moraine in the Yttersjö–Ekträsk area. Even the general configuration of the ridges favors a basal crevasse formation. The extremely steep slopes of the moraine ridges indicate ice-contacts. The sharp morphological features, characteristic for this region, were preserved by the existence of dead-ice. However, the melting of stagnant dead-ice also resulted in coarse-grained till, partly covering the basal till, but mostly deposited in the hollows between the ridges. The thickest layers of superficial till occur upon flat and broad ridges above *HK*. Along the lower parts of the slopes, or at the foot of the steep ridges, there also seems to be a small concentration of such till. A till, lying in this position, has either been primarily accumulated there by sliding on a soaked basal till, or secondarily transported there by frost heaving and solifluction.

In connection with the melting of dead-ice, abundant quantities of water were released. The superficial, coarse-grained layers were probably washed by melt-water, which still more favored the accumultaion of water-deposited sediments, mostly as structures within the upper part of the till, but also as thick layers in the hollows between the ridges.

CONCLUSIONS

The investigated moraine ridges in Västerbotten have revealed that a considerable variety exists in their morphology, structure and texture. In the southern coastal region they are mainly of the crag-and-tail type oriented in the same direction as the main ice movement from N. Only one typical drumlin, an elliptical hill without a bedrock core, has been observed in this region. Towards the northwest and in the zone of the highest shore line, *HK*, the types of moraine ridges change. In the Sundö area they are deposited in an irregular pattern and they are interpreted as a type of dead-ice moraine. In some places there are moraine ridges with an orientation parallel to the main ice movement from NW. In a *HK*-zone farther north, high hills extended in NNW-SSE, with a thin till-cover ("moränlider"), vary with basins or flat areas with hummocky moraine in an irregular pattern.

The internal composition of the different moraine ridges also shows a great variation. The crag-and-tail ridges consist of a hard sandy – fine sandy till. The dead-ice moraines are most often composed of two till beds, a sandy – fine sandy basal till overlain by a loose, gravelly till rich in stones. In the hummocky moraine region, the ridges are composed either of a fairly compact, sandy till, in places with silty matrix, or of a Kalix till.

The investigations of till fabric show an approximate correspondence between the long axis orientation of stones and the direction of the moraine ridges, which mostly coincides with the latest ice movement in the region. The slight divergence between the preferred orientation of the till fabric and the direction of the ridges may depend on an obstacle causing a disturbance of the ice flow during the deposition of till (see below). The lithological investigations and the studies of shape and roundness of the particles have not contributed to the interpretation of the genesis of the moraine ridges. The local bedrock dominates the lithological composition.

The moraine ridges in Västerbotten are related, with few exceptions, to bedrock knobs. In the crag-and-tail ridges in the coastal region, there are bedrock outcrops in the proximal parts of the ridges. These ridges were formed both by erosion and by deposition. The erosional process was syngenetic with the depositional process.

In the Sundö area the moraine ridges were formed mainly by deposition, first by subglacial accumulation of basal till over a bedrock knob initiating basal crevasses in the land-ice. Then, during the retreat of the land-ice, ice-bodies were isolated in certain places, and the melting of these ice-bodies resulted in deposition of coarse-grained till covering the basal till.

Also in the Yttersjö and Ekträsk area an undulating bedrock surface favored a formation of the hummocky moraine in basal crevasses of an active ice. The till fabric also confirms such a formation. However, the till fabric, almost transverse to the supposed direction of the latest ice movement, could probably be due to the pressure of ice between the ridges. The extremely sharp ridges, in combination with a superficial layer of coarse-grained till, were probably formed during dead-ice melting. As distinguished from the type of dead-ice moraine in the Sundö area, the subglacial deposits are very thick and constitute a considerable part of the hummocky moraine in the Yttersjö and Ekträsk area.

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Geological Survey of Sweden, Dec. 1971

Hans G. Johansson

РЕЗЮМЕ́

Моренные гряды и стратиграфия ледниковых отложений в Вестерботтене, Северная Швеция

В ранних исследованиях, посвященных грядам моренного происхождения в области Вестерботтен, они рассматривались как друмлины. В предложенной статье приводятся новые сведения о морфологии, структуре и строении нескольких моренных гряд в этом районе. Проводились гранулометрический, структурный анализы, сейсмические исследования и бурение.

На прибрежной равнине Вестерботтена, ниже самой высокой береговой линии, существуют, главным образом, — овальные и продолговатые гряды, направление которых параллельно последнему продвижению льда с севера на юг. В этой части Вестерботтена наблюдался лишь один настоящий, типичный друмлин, имеющий вид эллиптического холма без скального ядра.

Моренные гряды Вестерботтена, расположенные дальше вглубь страны непосредственно над и под наиболее высокой береговой линией (приблизительно 250—255 м над уровнем моря), рассматривались как образования, связанные с мертвым льдом или холмисто-моренным ландшафтом.

Внутреннее строение различных моренных гряд также весьма разнообразно. Овальные и продолговатые гряды сложены плотной песчаной-тонкопесчаной мореной. В морене, оставленной мертвым льдом, в большинстве случаев имеются два слоя: песчаная — тонкопесчаная основная морена перекрыта слоем рыхлой гравийной морены с большим количеством валунов. Гряды холмисто-моренного ландшафта состоят из относительно плотной, местами алевритистой морены.

В структуре морены обнаруживается примерное соответствие между ориентировкой длинных осей валунов и направлением гряд, которое в большинстве случаев совпадает с направлением наиболее поздней подвижки ледника в этом районе. Однако, поскольку моренные гряды в Вестерботтене, по-видимому, связаны с выступами скального ложа, небольшое расхождение между основной ориентировкой структуры морены и направлением гряд, обнаруженное в нескольких местах, может быть вызвано неровностями скального субстрата. Эти последние, по-видимому, и вызывали нарушения в направлении движения потока льда во время отложения морены.

Овальные и продолговатые гряды сформировались в результате одновременного проявления денудации и аккумуляции их образования. Гряды, относимые к образованиям мертвого льда, первоначально возникли вследствие накопления основной морены и были впоследствии перекрыты грубой абляционной мореной, вытаявшей из изолированных ледяных полей. Гряды холмисто-моренных ландшафтов образовались в базальных трещинах активного льда. Давление льда, находившегося между грядами, также способствовало их формированию.

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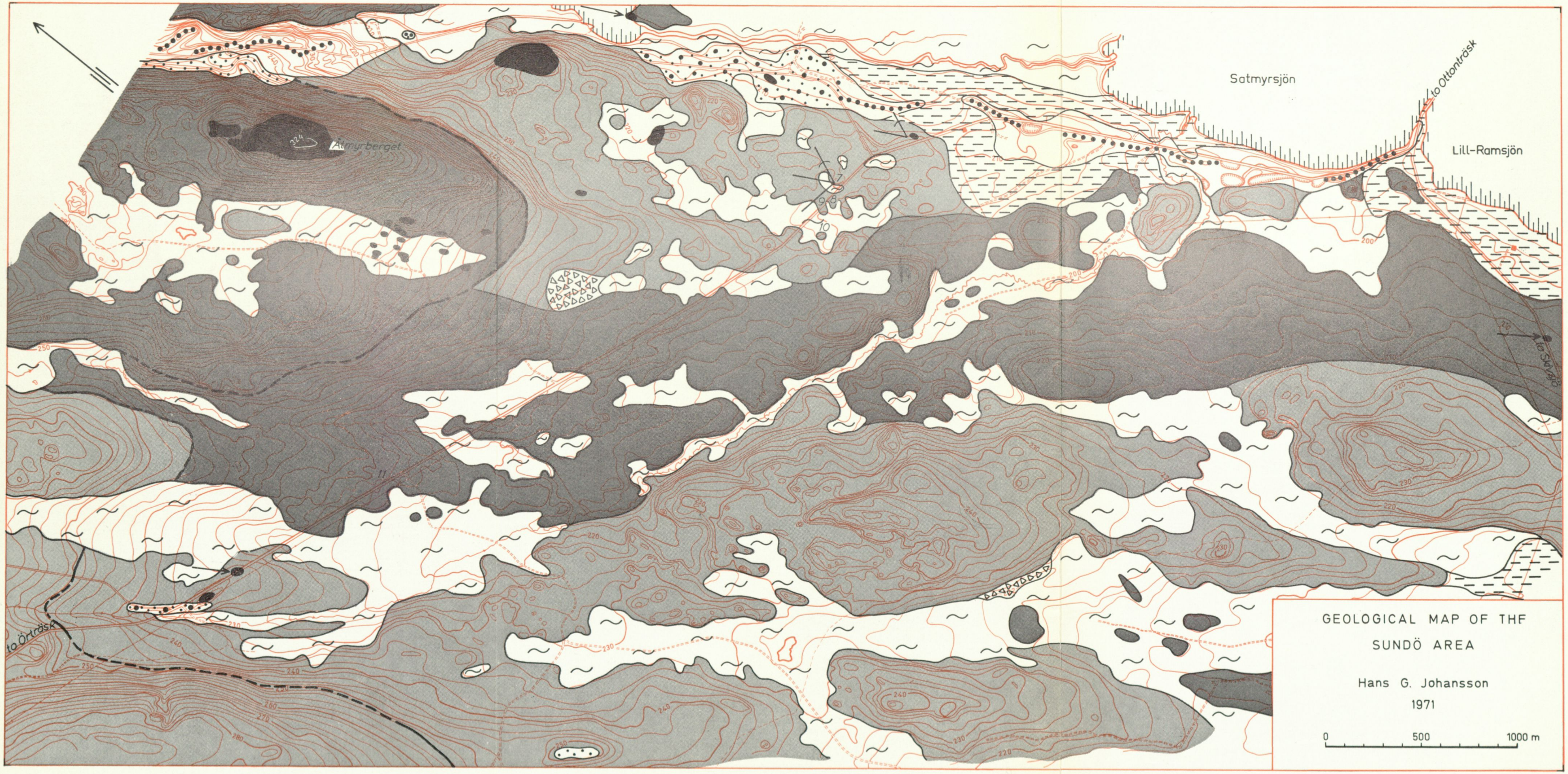

Exposed bedrock
Gravelly till
Sandy-fine sandy till
Esker
Glaciofluvial gravel and sand
Silt
Littoral gravel and sand
Mire
Boulder depression
Glacial striae
Highest shore line (HK)

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