SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 743 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 72 NR 5

HUGO MINELL

GLACIOLOGICAL INTERPRETATIONS OF BOULDER TRAINS FOR THE PURPOSE OF PROSPECTING IN TILL

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ABSTRACT

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The study of glacial geology is of prime importance when prospecting in areas of glaciated terrain. A study of seven mineralizations and their associated boulder trains and geochemical anomalies in central Lappland has shown that the patterns formed by the boulder trains and anomalies in the tills can be interpreted in terms of the behaviour of ice as a flowing medium, the bedrock topography, and the prevailing glacial environment prior to and during deglaciation.

INTRODUCTION

This paper concerns the pattern of boulder trains and geochemical anomalies as well as their genetic origin.

Boulder tracing has been used as a tool in ore prospecting for a long time. As early as 1740, Tilas wrote a publication about the distribution of boulders, but it was not until the twentieth century that serious investigations began to be made. Hausen (1912), G. Lundqvist (1935, 1951, 1963), J. Lundqvist (1952, 1958, 1969), and Fromm (1965) among others investigated the boulder content of tills in relation to the bedrock. Investigations of boulder trains for prospecting purposes were made by a number of people including Sauramo (1924), Högbom (1931), G. Lundqvist (1947), Hyyppä (1948), Grip (1953), Okko and Peltola (1958), Häkli and Kerola (1966), Mutanen (1971), Hyvärinen, Kauranne and Yletyinen (1973).

Boulder tracing for the purpose of prospecting is carried out primarily by geologists and by assistants trained to identify minerals and rock types by sight. Other means of assistance can, however, be used for the identification of sulphide and uranium mineralized boulders. Uranium mineralized boulders can easily be located with the help of a γ-scintillometer, and sulphide blocks by the smell instincts of trained Alsatian dogs. The fine-grained fractions of mineralized material in till can be identified by chemical analysis and by separation of heavy minerals. Anomalous accumulations of uranium mineralized material in till can also be identified by radiometric measurements using a γ-scintillometer or γ-spectrometer either in the air or on the ground. Detailed boulder tracing, radiometric surveying and geochemical sampling are usually carried out within a local co-ordinate system.

The character of the anomalies revealed by these surveys, and the relationships between the anomalies and the bedrock mineralizations can vary considerably. In some cases, the anomalies can lie totally separated from the mineralization by many hundreds of metres. These features can be interpreted in terms of the effects of glaciation on the bedrock, and the behaviour of glacier ice as a flowing medium. The behaviour of active ice in different topographical environments is particularly interesting. A very general description is therefore given of the movement behaviour of glacier ice, in particular extension and compression, as these affect not only changes in speed against the underlying material, but also movements directed downwards (extension) or upwards (compression).

The strength of the underlying bedrock under the pressure of ice is important, as this affects the direct erosion of the bedrock and the character of the moraine. Plucking up of material by the glacier is a pre-requisite for transport and deposition. During transport, the concentration of material in the glacier can be altered by extension or compression. The final process during deglaciation is deposition, which can take place either sub-glacially or supra-glacially with differences in the pattern of deposition as a result.

The purpose of this study has been to investigate all the processes governing the distribution of mineralized material within tills in a variety of environments. Obviously this information can be applied to prospecting in the future. In addition, the information gained through prospecting can be of general glaciological interest. The glaciologist does not normally have access to detailed studies of the distribution of geochemical tracers within tills.

DEVELOPMENT AND EVALUATION OF BOULDER TRAINS

The formation of boulder trains is dependent on a series of factors. The first is the crushing of the rock, which is dependent both on the mechanical properties of the rock (Jahns 1943), but also on the pressure exerted by the overlying ice (Lewis 1954). Differences in pressure are very dependent on variations in the bedrock topography. A strongly undulating topography can cause very considerable pressure variations and shear stresses which may exceed the resistance of the rock and wide scale fracturing can take place (Boulton 1974).

The second factor controlling the formation of the boulder trains is the incorporation of material into the ice, which may take place either by creep "pseudo-plastic flow" or regelation "melting and freezing" (Weertman 1957, 1961, 1964). Loose boulders will be incorporated by creep if the glacier ice is not too thin or pressure too low. The finer fractions are incorporated by regelation unless very temperate or very cold conditions prevail.

The third factor to be considered is transport. If the pressure exerted by the ice is sufficiently high to cause marked friction of the load against the sub-stratum, the load becomes attached to the sub-stratum and the ice passes over by creep or regelation. Where the pressure exerted by the ice is not too high, the amount of transport is rather dependent on velocity. A high velocity of flow can result in such high shear stresses in the material at the base of the glacier that this is transported as a medium, by traction, between the ice and the bedrock (Boulton 1974 a).

A fourth factor is accumulation and deposition, as well as the crushing down and the mixing of the material. A glacier which suddenly stagnates and melts as dead ice would produce a concentrated row of boulders in close proximity to the mineralization, which then thins out and disappears with increasing distance from the mineralization. These conditions are not always fulfilled however, and the pattern of the boulder train can change due to varying conditions within the melting ice. For example, extension of the glacier ice would lead to a boulder train which is more strung out (p. 42) than where the ice has been subjected to compression. A marked enrichment of local material will occur where compression was dominant near the mineralization, because the flow of ice was retarted and the supply of material exceeded removal. Basal melting and refreezing may also be important in controlling the form of the boulder trains. Areas at higher altitudes have not been subjected to compressive fronts (Minell 1978), as a result of which the bedrock may be laid bare. These areas may, however, be covered by basal till probably formed by basal melting (Nobles and Weertman 1971). Strong basal melting can cause mineralized material to be thoroughly mixed, or erosion and incorporation of new material to cease. Thorough mixing and no erosion can also be caused by refreezing.

The intensity of an anomaly or boulder train is also very dependent on the degree of mixing during transport. In areas of considerable accumulation and deposition, one can expect a large amount of mixing. The mineralized material may even be undetected due to a thick overburden of long-transported material (Minell 1978). In areas of strong erosion, a mineralization can supply the till with considerable quantities of mineralized material. If, however, much transport takes place, the content of mineralized material will be somewhat lower than if little transport takes place (pp. 16 and 42). If one looks at the intensity of mineralized material on a regional scale, a mineralization of particular dimensions and in a particular environment should produce a stronger anomaly if it lies near to the ice-shed than further away. The supply of long-transported material is poor near to the ice-shed, and local material is therefore more clearly apparent.

The secondary flow of supraglacial, water-saturated till (Boulton 1968, 1970 a) can also result in a distorted picture of the anomalous distribution. The distortion would be very misleading if till containing mineralized material on a flat, stagnating glacier surface, flowed back towards the mineralization. The mineralized material could then lie proximal to the mineralization which would give a false picture of the true position of the mineralization.

EROSION AND TRANSPORT

The primary stage in erosion, fracturing of the bedrock, was originally regarded as a melt and freeze process, the rock shattering due to the expansion of water freezing in fractures. This should result in a close network of fractures which in turn gives rise to loose boulders (Card 1947). Jahns (1943) observed that a rock will tend to fracture in a particular pattern. Lewis (1954) regarded this systematic fracturing as being due to weakening caused by the release of stored strain during unloading and thinning of the glacier ice. This is an important suggestion, on the basis of which Boulton (1974) has treated erosion of the bedrock both practically and theoretically. Boulton considered the erosional processes of crushing and abrasion in relation to stress conditions and ice velocities.

The failure tendency, after Boulton, $\frac{\text{strength}}{\text{stress}}$ is treated theoretically in a formula where the $\frac{\text{strength}}{\text{stress}}$ ratio (safety factor) in undulating bedrock is:

$$\frac{\tau_o + \left(\varphi_i g h - \frac{10\eta V_i}{\lambda}\right) \tan\phi}{\frac{3{,}13\eta V_i}{\lambda}}$$

τ_o = cohesive strength
φ_i = dencity of ice
g = gravitational acceleration
h = ice thickness
η = viscosity for ice
V_i = glacier sliding velocity
$\tan\phi$ = cofficient of internal friction
λ = wavelength in bedrock

No space exists between the bedrock and the ice.

Failure will occur when the $\frac{\text{strength}}{\text{stress}}$ ratio is less than 1.

The results of failures when using this formula are presented on Fig. 1.

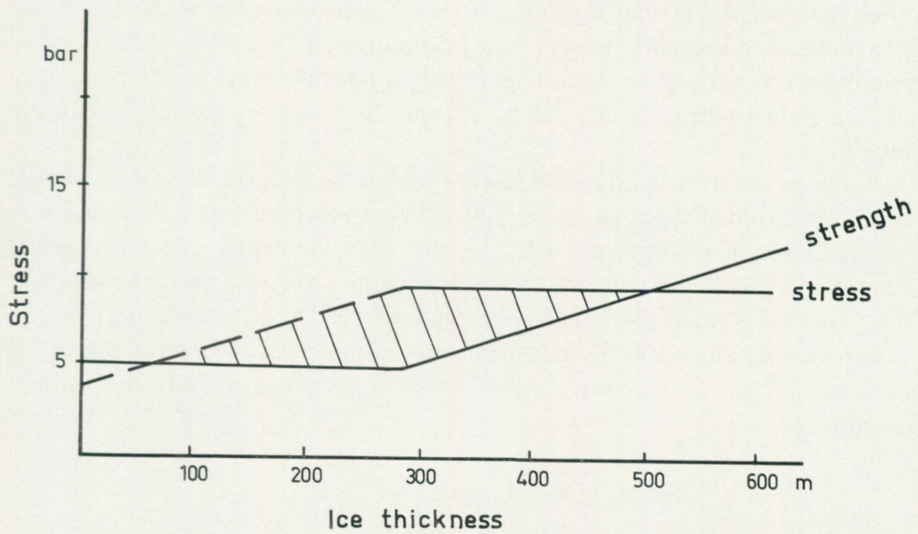


Fig. 1. Diagram after Boulton (1974), showing the conditions for failure of hummocky bedrock with specific wavelength and shape, and specific velocity of ice. The tendency to failure decreases with increasing wavelength and with decreasing ice velocity.

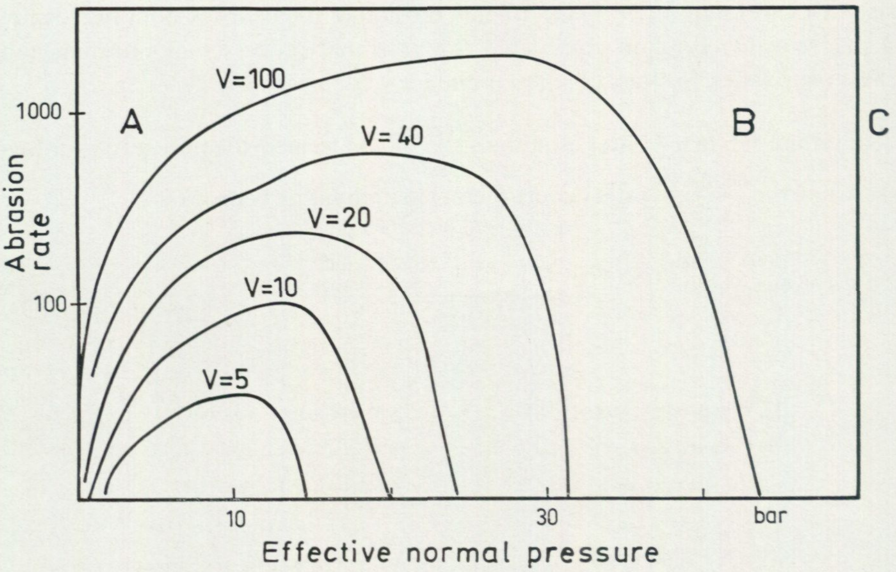


Fig. 2. Diagram after Boulton (1974) showing theoretical rates of abrasion (the vertical axis is abrasion/ $\frac{(k_1c)}{(p)}^{-1}$). In zone A, abrasion increases with increasing ice velocity (V) and increasing normal pressure. In zone B, rates of abrasion fall with increasing pressure, and can fall very abruptly with decreasing velocity. In the area to the right of the diagram (zone C), no abrasion occurs, and transported debris is deposited as lodgement till.

The diagram shows that crushing increases with increased thickness of ice up to a certain maximum, beyond which no more crushing takes place because strength becomes too great. Crushing also does not take place in the peripheral part of a glacier where the ice is thin and the shear stresses are lower than the strength.

Erosion in the form of abrasion, earlier known as the grinding effect, occurs when fragment-loaded ice slides. Boulton (1974) has observed that abrasion is pressure dependent. Abrasion will increase with increasing effective normal pressure and increasing velocity until the pressure reaches a certain maximum value. Above this value, there is no abrasion, regardless of velocity (Fig. 2).

The pressure in bars may be equivalent with the thickness of ice if the pore pressure is zero. The pore pressure (water pressure) decreases the effective normal pressure.

$$N = (\varphi_i g h - \omega_p)$$

φ_i = dencity of ice h = ice thickness

g = gravitational acceleration ω_p = pore pressure

The rate of abrasion (A_b fig 2) is defined as:

$$A_b = \frac{K_1 \; cN}{P} \left[Vi - \left(\frac{N}{L_c} \right)^{1/m} \right]$$

K_1 = the relative hardness of the fragments and bedrock

c = concentration of debris

N = effective normal pressure

P = a plastic property of the rock

Vi = ice velocity

L_c = lodgement index

m = a constant

As an example from the curves on Fig. 2, abrasion at 30 bars is very high at a velocity of 100 m/year, but decreases markedly at a velocity of 30 m/year. Another example is shown when normal pressure is increased for any one ice velocity, the rate of abrasion increases to a peak and then rapidly falls to zero.

MECHANICS OF GLACIER FLOW

A glacier can move in a steady state by laminar flow. Ice is a pseudoplastic medium, however, and is very dependent on stress conditions and time, $E = B\tau^n$ (Glen 1952) where E is the final, steady shear strain rate, τ the shear stress and B and n are constants. Ice is therefore both a rigid and a flowing medium in which stress trajectories can develop resulting in quite complicated flow. Flow can be extending or compressive depending either on the bedrock morphology or whether accumulation or ablation dominates in the area (Nye 1952). In areas with convex terrain or accumulation, extending flow dominates, while compressive flow dominates in areas with concave terrain or ablation (Fig. 3). In extending flow, the forward velocity of the glacier increases as one goes down glacier, which also results in downwards transport of glacier ice. In compressive flow, the velocity decreases resulting in upwards transport of glacier ice. The ice also has a tendency to fracture by shear stresses. The shear planes, called slip-lines by Nye (1952), usually appear in groups with a downwards direction in extending flow but upwards in compressive flow.

It can be assumed that erosion is strong in areas with extending flow producing high velocities and high shear stresses (Minell 1973). Plucked and eroded material in areas of extension is transported parallel to and in contact with the bedrock due to the downwards movement of ice, but in areas of compression, both horizontal and vertical (upwards) components are present in the transport of material. Erosion by abrasion should therefore be more effective in terrain with accelerating and laminar flow, where the material incorporated into the ice is transported parallel to and in contact with the bedrock. Thin layers of till can

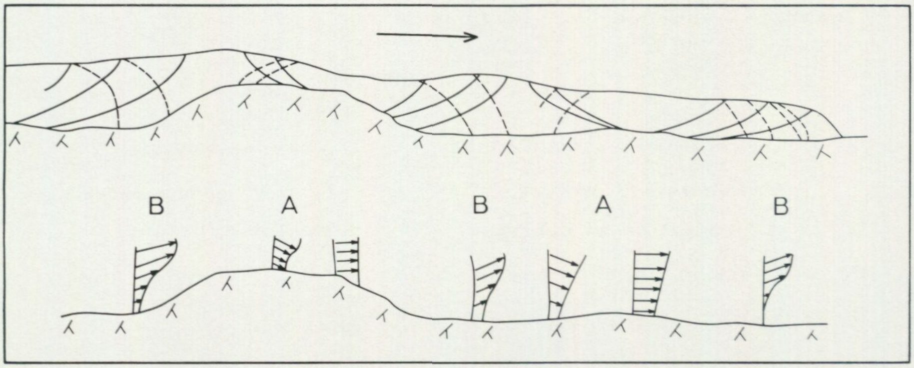


Fig. 3. Longitudinal section through a glacier. A means extending, B compressive flow. The arrow in the upper section shows the direction of glacier flow, and the lines indicate possible slip-line fields. The solid lines show the planes along which the ice has the greatest tendency to produce shear fractures. The lower section shows the relative variations in velocity down glacier within a specific area.

thus be expected in areas where the final movement of ice had a high velocity, or was accelerating due to extending flow. Erosion by abrasion should in most cases be very weak in areas with compressive flow since the velocity is low and all abrading material is plucked up and subjected to a vertical (upwards) transport in combination with horizontal transport.

If the velocity of the glacier ice changes very considerably from one area to another, erosion can take place due to purely thermal processes. Strong erosion can take place, for example, between an area with high velocity, and one with low velocity where the ice may freeze onto the bedrock (Weertman 1961 and Boulton 1972). Within the area of high velocity, large-scale melting of the glacier ice takes place, followed by refreezing when the velocity is reduced. During the process of refreezing, large quantities of moraine material can be incorporated into the ice and transported away (Clapperton 1975).

FACTORS CONTROLLING THE SIZE OF FRAGMENTS

The largest size of boulder which can be transported by ice without further mechanical breakdown, lies between 5 and 25 m, in diameter on the assumption that the rock is homogeneous and strong enough to resist the shear stresses which may act upon it (Menely 1964). However, the regular spacing of joints, schistosity and zones of weakness in the rock generally determine the breakdown of larger erratics to smaller-scale forms. In most cases, the host rocks have a minimum size to which they are shattered before abrasion will become the dominant process of erosion. Homogeneous crystalline rocks and rocks with a massive appearance have widely spaced zones of weakness and therefore produce large boulders, while some of the sedimentary and volcanic rocks are so weak that they produce only cobbles and pebbles as the coarsest fractions.

The first stage in the process of transportation is plucking. Plucking takes place either by plastic flow (Weertman 1957, Boulton 1974) or regelation (Carol 1947, Weertman 1957), and involves the incorporation of particles within the ice. Plastic flow is more effective on larger fragments and regelation (melting-refreezing) on small fragments.

The process of fracturing and crushing continues during transport, mainly due to powerful friction against the bedrock (abrasion), but to a certain extent also between the fragments within the ice. The critical obstacle size is an important factor to be considered here. The critical obstacle size occurs when the velocity around an obstacle or fragment is the same for both plastic flow and regelation. As a result, transport of particles which are larger or smaller than the critical size is slower, because the traction stresses around larger fragments are smaller due to flow around them, and smaller against smaller fragments due to regelation. Fragments of the critical size are therefore abraded more and cause greater abrasion of the bedrock. The critical size is dependent on many factors such as ice-velocity, effective normal pressure, the dispersion and size of particles and so on.

Crushing may take place between particles in large loads, especially in poorly sorted material where small grains may be trapped between large grains and crushed due to stress concentrations where the grain boundaries meet. The small grains are often limited by crystal size or the ”terminal grade” beyond which no further friction occurs. These processes of both abrasion and crushing can explain the high peaks or bimodal distributions of many tills, independent of mixing.

The changing content of local bedrock material in different size fractions has been related to crushing and mixing during transport. Krumbein (1937) and Gillberg (1965) describe the successive crushing of boulders which rapidly reduces their size, and successive mixing with other rock types during transport causing a significant decrease in the frequency of a local rock type (Salisbury 1900, Marcussen 1973, and others).

Dreimanis (1971), Mutanen (1971) and Lindén (1975), among others, found very local occurrences of bedrock represented among the boulders and coarse fractions within tills. Rocks of a new source area make up 30–60 % of the 2–6 cm fraction within a transport distance of 1–2 km in the area. Once the source area has been passed, the content of material representing it decreases to 10 % after more than 4 km of transport. These values are very characteristic for all the coarse fractions (Lindén 1975), and correspond well with numerous investigations from central Lappland (Minell 1978). However, the content of local material can vary very much in different types of till deposits (Gillberg 1955, 1956, 1956 a, Svantesson 1976).

The coarse material in eskers follows a similar pattern, but appears later within the source area, that is, after 4–5 km of transport. The coarsest fractions will be crushed down quite fast while the finer coarse fractions (6 cm) are transported quite considerable distances (Gillberg 1968, Persson 1973). When an esker from an area of Rapakivi granite reaches another source area (after Hellakoski 1930), the Rapakivi granite constitutes 70 % of the esker material, but after 5 km of transport and mixing within the new source area, is reduced to 50 %, and after 10 km to 10 %.

ACCUMULATION

Accumulation of moraine can take place some considerable distance behind the fringes of the glacier ice, or in the peripheral zone itself.

Accumulation in areas situated far behind the fringes of the glacier is due either to stagnation of till-saturated ice where movement is restricted, or to high pressure, where friction between the moraine and bedrock is so high that deposition takes place (Boulton 1974). Pure, unfrozen till can be deposited in areas where temporary melting of the base of the glacier occurs. This melting may be due to high thermal conductivity from the underlying basement, or to high shear stresses against the bedrock (Weertman 1961, Nobles and Weertman 1971). The opposite may also occur, that is, freezing on of till in a cold zone (Schytt 1969) which results in the local removal of material. Within such a zone, however, movement of the basal parts of the glacier is restricted, in places it can be frozen to the bedrock, and stacking of incorporated frozen till probably takes place. This process of accumulation is probably more mechanical than thermal, since the debris-rich ice stagnates because of increasing strength when meeting the cool zone.

A further type of sub-glacial accumulation is the removal of pure till with high pore pressure from an area of high pressure to one of low pressure. Within areas of stagnating ice, this type of accumulation only occurs on a small scale in fractures, whereas in areas of active ice, transport by traction is thought to be possible (Boulton 1974 a). Traction is thought to facilitate the movement of moraine material even if this is not frozen fast within the ice. The distance behind the glacier front to which this process is possible is thought to depend on the thickness of the ice, as this determines pressure against the bedrock and the subsequent sub-glacial deposition of moraine. If a still active glacier ice accelerates towards stagnant ice, strong upwards transport of material can take place along shear planes towards the surface where other processes take over in a water-saturated environment. Within such a zone of compression, sub-glacial folding of the basal moraine probably takes place (Minell 1977 a).

Many of the processes of accumulation just described can take place along the periphery of the glacier ice. In the peripheral areas, however, supraglacial melting and the processes which are related to ice separated from a nearby active ice must also be considered. Large quantities of till can be deposited from a debris-rich ice which is subjected to further accumulation in the concave irregularities on the glacier surface (Boulton 1968, 1970, 1970 a). This till is water-saturated, and can probably be transported for more than a few hundred metres (Boulton 1971).

AREAS INVESTIGATED

The glacial geology of seven areas in southern Norrbotten has been investigated in detail as part of a prospecting programme carried out by the Geological Survey of Sweden (SGU) during recent years. The geographical distribution of the areas concerned is shown on Fig. 4.

NIMTEK

Nimtek, 25 km southeast of Arjeplog, has been investigated thoroughly from an ore prospecting point of view. The main ore minerals are chalcopyrite and pyrite (Cu-mineralization) in a host rock of metamorphosed porphyritic andesitic basalt (Padget 1966).

Nimtek is a lake situated in a slightly concave area at about 500 m a.s.l., with hills only a few kilometres away, Jäknatjavelk to the northeast and Nimtek-

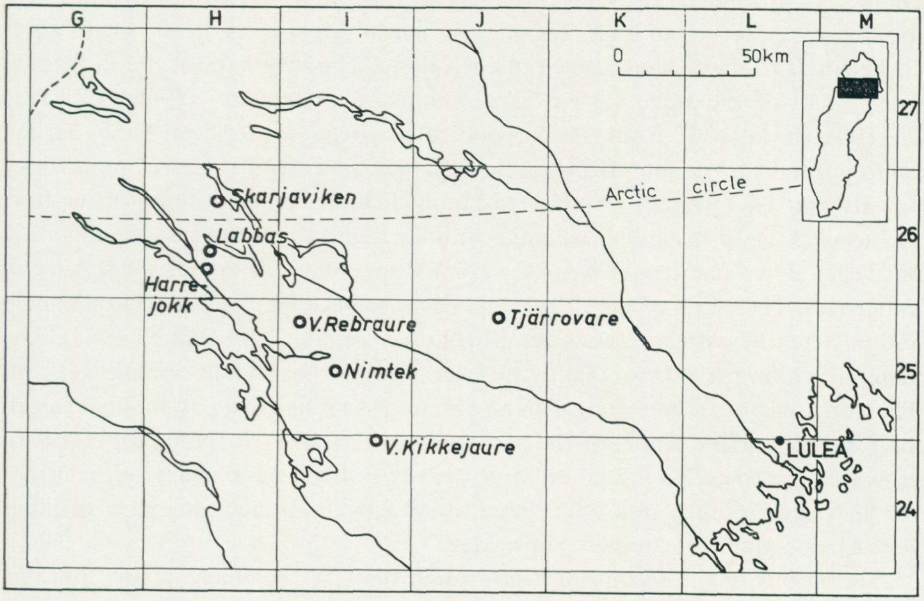


Fig. 4. Map showing the locations of the areas investigated.

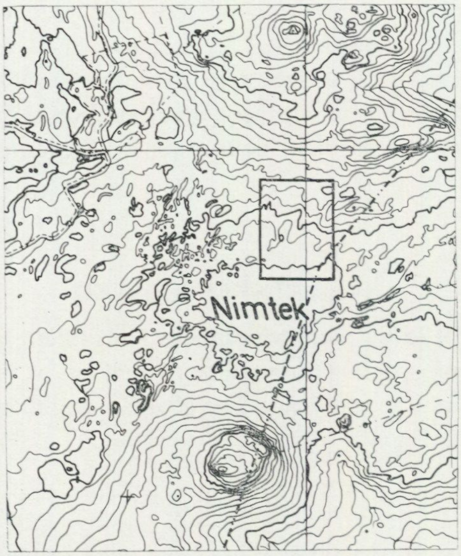


Fig. 5. Topographic map over the Nimtek area (from topographic map sheet 25I). The area investigated in detail lies within the small frame. Scale 1:100 000.

berget to the south, both at an altitude of little more than 650 m. The areas to the northwest and southwest, however, which lie along the axis of ice flow, have altitudes only some 50 m higher than lake Nimtek (Fig. 5). The area around lake Nimtek is covered with very pronounced transverse ridges. The ridges are usually about 10–15 m high, 250 m long and 80 m wide (Fig. 6). Their width corresponds to the distance between each ridge. The long axes of the individual ridges, and of the ridge system as a whole are orientated N20°E, and they therefore deviate 20° from the perpendicular direction of glacier flow. To the south and northeast, the ridges are bounded by areas with ridges of more large dimensions. These ridges are situated perpendicular to the direction of ice flow and usually the forms are barchanlike with the convex part towards the direction of glacier flow. The length can vary from a few hundred metres up to several kilometres. The width of the ridges, and distance between them is approximately 200 m. Their height varies considerably but lies around 10 m (Minell 1978). The material within the ridges is sandy till with normal to abundant boulder content. The form of these transverse ridges are very similar to the so-called Rogen moraine in Jämtland and Härjedalen described in detail by J. Lundqvist (1969 a). However, the so-called Rogen moraine usually shows a basal character, contrary to the ridges in this area. Geochemical investigations and diamond drillings were carried out in one of these large ridges.

Striations in the vicinity are orientated N40°W, but most of the moraine forms, such as drumlins and large transverse ridges, indicate a direction of ice

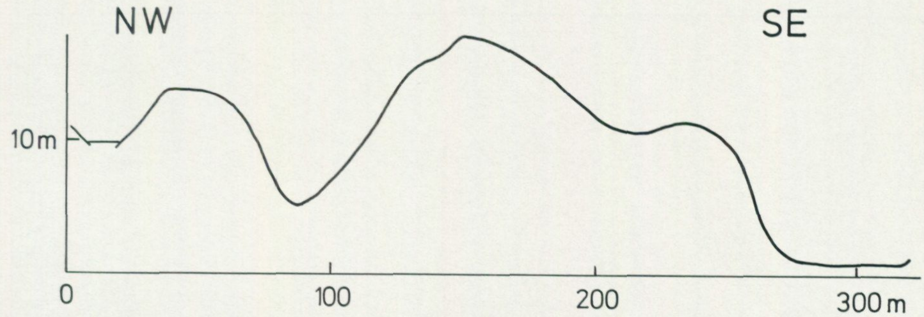


Fig. 6. Profile through two transverse ridges from the Nimtek area. To the left a medium-sized ridge, and to the right a large ridge. Ice flow from left to right.

movement from N30°W. This corresponds quite well with the orientation of the anomalous (geochemical) tills and boulder trains.

The mineralized boulders are all large and angular, most of them being more than 1 m in diameter. The concentration of ore boulders is highest close to the mineralization, and decreases successively along the direction of ice flow. After about 700 m, the boulder train disappears into lake Nimtekjaure. The boulder train is long with its proximal part lying immediately above the mineralization.

Samples for chemical analysis were taken at depths of 0.5 m and 1.5 m (Fig. 7a). The samples from a depth of 1.5 m were taken at closer intervals than those from 0.5 m, thus giving a clearer anomalous picture (Fig. 7b).

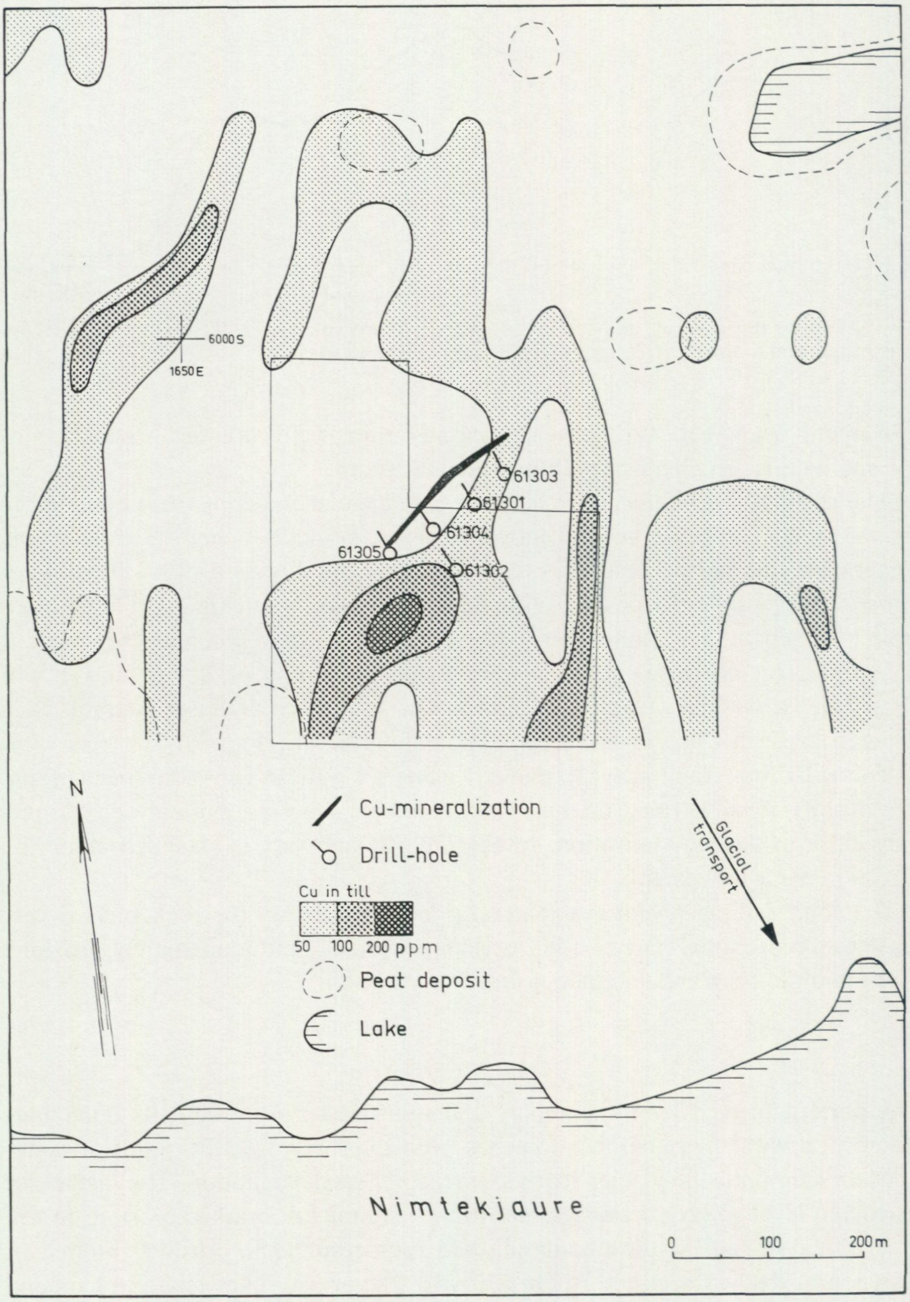
The 0.10 mm fraction was analysed using an optical emission spectograph. The results are illustrated on Fig. 7a and b, and show an anomaly developing very close to the mineralization. In Fig. 7b, the anomaly is extended along the direction of ice movement.

Diamond drilling revealed a mineralization situated on the rock surface very close to the proximal part of a large transverse ridge, and immediately proximal to the boulder train and anomalous area.

INTERPRETATION

The pattern formed by the anomaly and the boulder train, and its immediate connection with the mineralization, has been interpreted as the result of continous erosion until the glacier reached a stage of total stagnation. The glacier ice reached a level where pressure came within the limits of marked erosion. In this area, shear stresses in the undulating bed rock resulted in crushing as well as abrasion of the bed rock (cf. Boulton 1974). The pressure velocity and temperature of the ice were such that material was incorporated by creep and regelation (cf. Weertman 1957, 1961).

While erosion was in progress, the concave topography of the area resulted in compressive flow of the glacier ice, which in turn caused thrusting of the basal


6000 S
1650 E
61303
61301
61304
61305
61302
N
Cu-mineralization
Drill-hole
Cu in till
50 100 200 ppm
Peat deposit
Lake
Glacial transport
Nimtekjaure
0 100 200 m

a

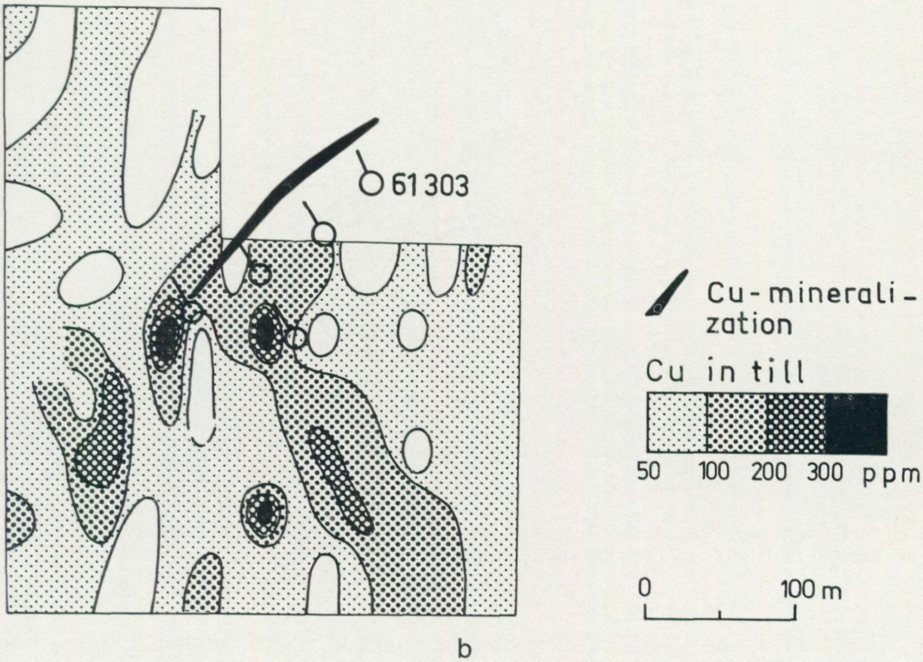


Fig. 7. Distribution of copper in the <0.10 mm fraction of the till, Nimtek. a. At a depth of 0.5 m. b. At a depth of 1.5 m.

till into transverse ridges (Minell 1977). Where compression was very strong and continued for a long time, thrusting penetrated up to the surface of the glacier and till material collected between the thrust planes or in supraglacial crevasses (Minell 1977 a). Erosion continued, due to moderate pressure, until the glacier ice reached a stage of total stagnation.

REBRAURE

The area investigated is situated 45 km west of the northern bay of lake V Rebraure, economic map sheet 25I 8b (Fig. 8).

The investigations have chiefly been made in connection with a uranium mineralization in a bedrock of acid gneisses. The mineralization is associated with an extensive alteration involving Na-metasomatism and the removal of quartz.

There is a slight convexity in the terrain (530 m a.s.l.) within an otherwise concave area (450–500 m a.s.l.). To the south, southwest and northwest, approximately 3 km away, small mountains covering an area of about 3 km and with altitudes of 700–740 m a.s.l. surround the area (Tjuorrevaratj to the south).

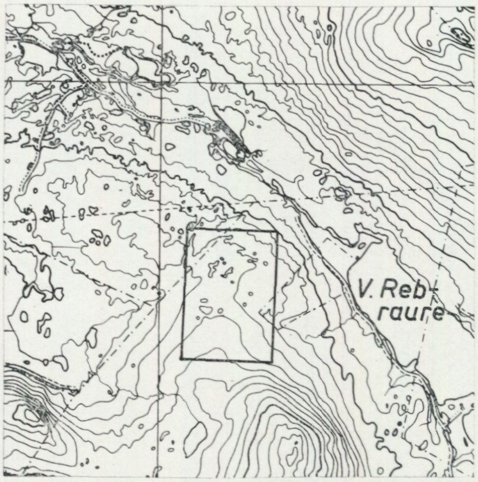


Fig. 8. Topographic map of the Rebraure area (from topographic map sheet 25 I). The area investigated in detail lies within the small frame. Scale 1:100 000.

All the terrain northwest of the mineralization consists of hummocky moraines (Fig. 9). Southeast of the mineralization, the moraine is more gently undulating. A few km to the northwest, the hummocky moraine is silty with a low boulder content. Closer to the proximal part of the convex area, the till is coarse and rich in boulders, and beyond the most convex part (where the mineralization occurs), the boulder content decreases and the till becomes more silty.

The till is generally 3–5 m thick with a maximum thickness of 8 m and a minimum of 2 m. The final movement of ice came from N40–50°W.

The boulder train consists mostly of the metasomatic rock type, but in some cases with fissure mineralizations. The boulders are not uniform in size as with other examples mentioned. Variations between 30 and 100 cm are common, and in some cases boulders up to 170–200 cm are present. The boulder train is 1 km long but only 35–40 m wide (Fig. 10). This figure relates to the densest part of the train which is oriented N43°W. Dispersed groups of boulders are found at 1 and 1.3 km intervals along the extension of the boulder train and 60–70 m to the sides.

Diamond drillings revealed strongly anomalous bedrock 40–50 m from the first boulders in the proximal part of the boulder train (Fig. 10).

INTERPRETATION

This well-defined boulder train lying in close connection with the source, has been interpreted as the result of relatively constant erosion of the bedrock: Erosion could continue for a long period because of the presence of a convex

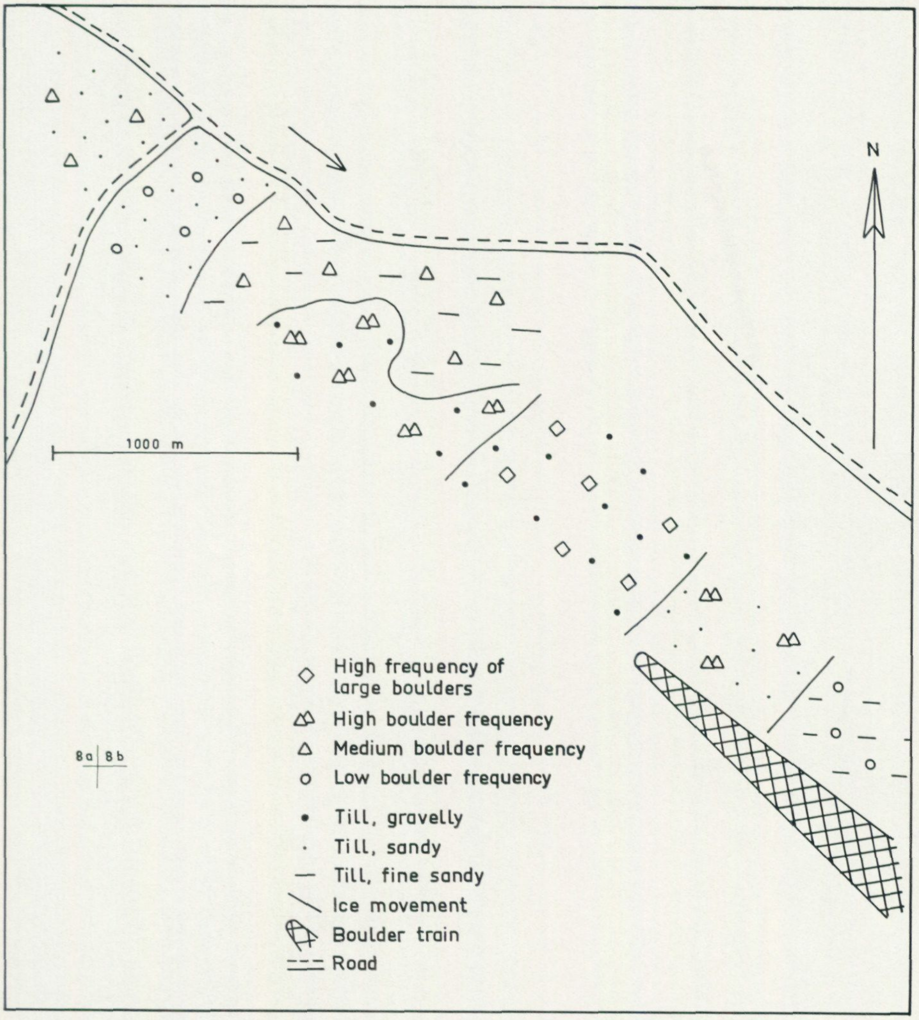


Fig. 9. Map showing the distribution of tills at the proximal end of the boulder train, Rebraure.

feature in an otherwise largely concave and open terrain. On the lee side of this convexity, where the mineralization is situated, suitable pressure for marked erosion of the undulating bedrock was reached at an early stage because of the high position. The velocity, and consequently the shear stresses against the bottom were high, facilitating the takeup and transport of material (cf. Boulton 1974). Erosion and transport continued at this altitude until the glacier stagnated.

Compressive flow on the proximal side of the convexity and the boulder train caused strong upward movement of material to the glacier surface; such material usually having a large locally-derived content. When the ice stagnated and melted

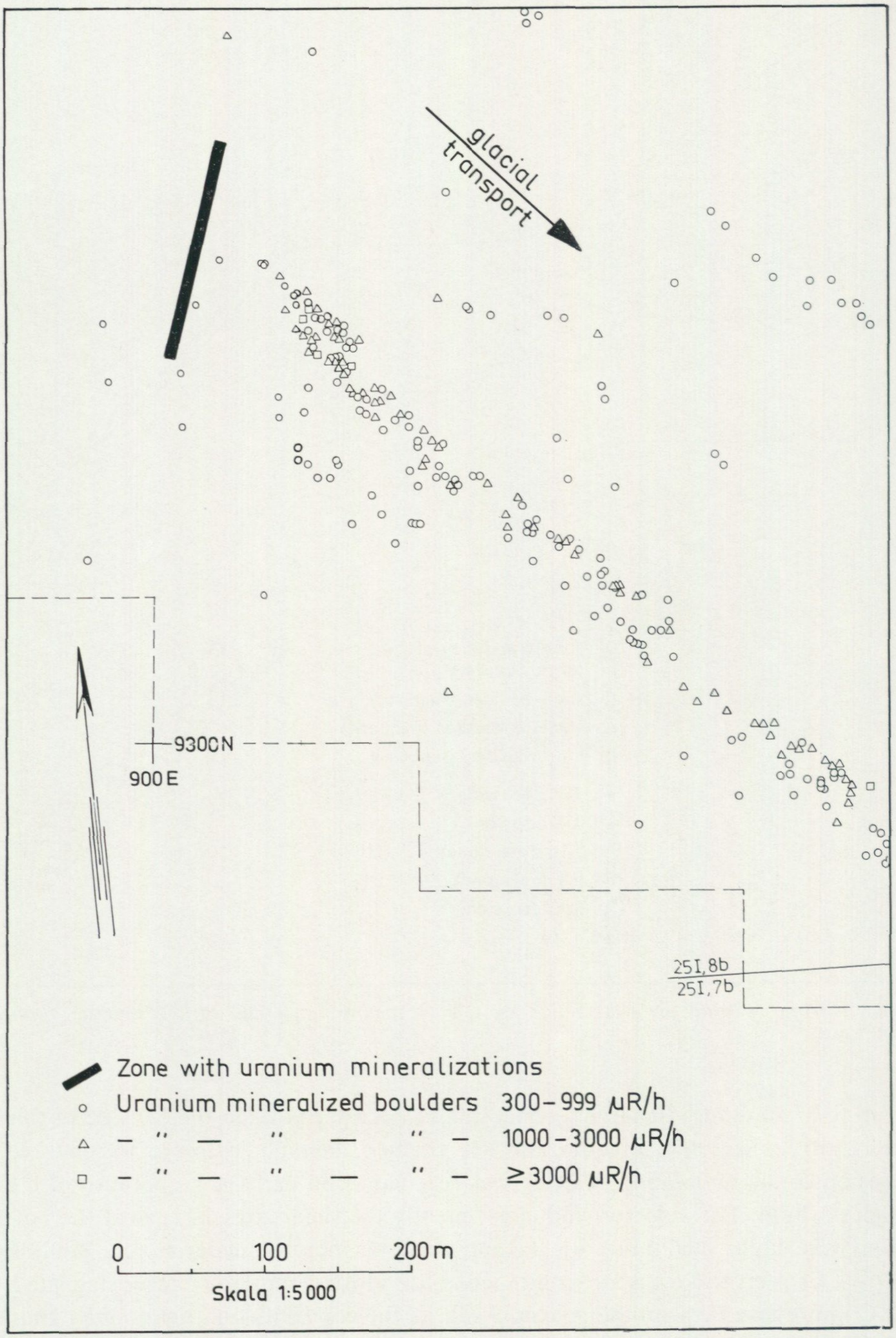


Fig. 10. Map produced from detailed boulder tracing, showing the densest part of the boulder train, Rebraure.

away, crevasses and surface irregularities resulted in the deposition of hummocky moraine. The compression did not affect the mineralization, and is thus a good indication of the absence of mineralized rock in the area of hummocky moraine.

SKARJAVIKEN

The area is situated on the western shore of lake Tjeggelvas, 200 km southwest of Kiruna (Fig. 11). The bedrock, of Precambrian age, consists of acid volcanic rocks in which a zone of Mo-mineralizations is disseminated. This prospect is situated where the glaciated terrain opens out, at an altitude of approximately 455 m. Ardnastjåkkå (611 m a.s.l.) is situated about 3 km to the northwest (proximally), and Gibnotjåkkå (717 m a.s.l.) to the southeast (distally).

The till in the test area is of a coarse type rich in local material. Large angular boulders lie on the surface of the till, and boulder size decreases downwards into a lodgement-like till. The glacial morphology is that of slightly undulating hummocky moraine as in the surrounding areas.

No outcrops of bedrock occur within the area investigated. The final movement of ice came from N60°W as indicated by the orientation of pebbles and striations. This direction coincides quite well with the elongation of the boulder train and the anomalous area of till.

Diamond drillings revealed that the head of the boulder train lies 200 m from the mineralization in the bedrock along the direction of ice movement (Fig. 12). The mineralized boulders occur in a limited area forming a boulder train about

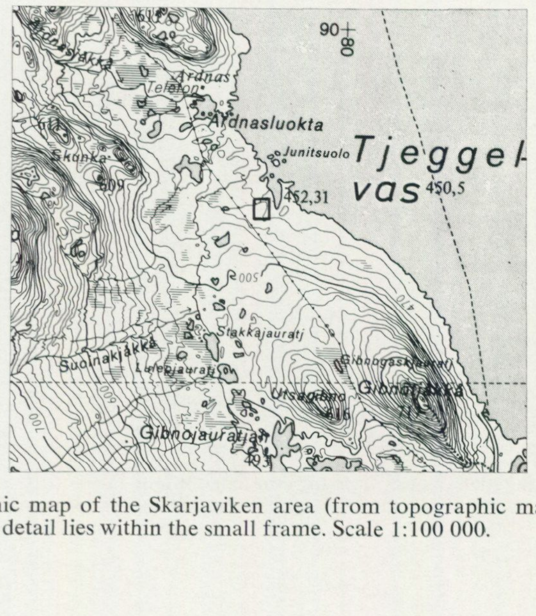


Fig. 11. Topographic map of the Skarjaviken area (from topographic map sheet 26H). The area investigated in detail lies within the small frame. Scale 1:100 000.

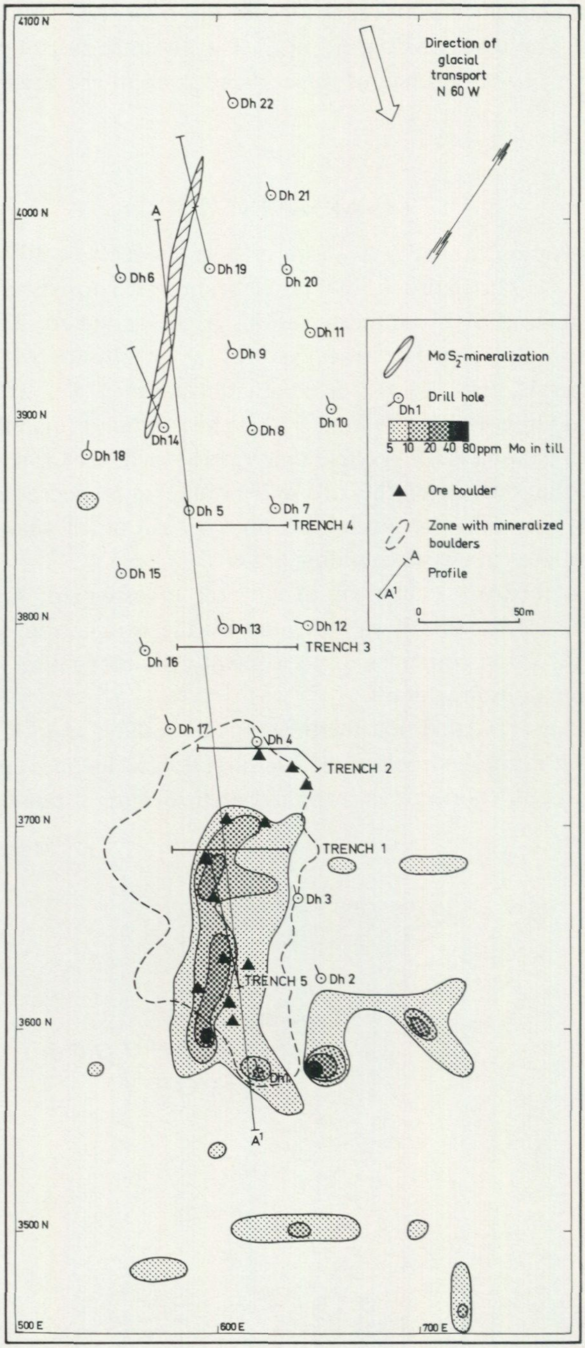


Fig. 12. Map showing the distribution of molybdenum in the <0.10 mm fraction of till samples from a depth of 0.5 m, and the distribution of molybdenum-mineralized boulders, Skarjaviken.

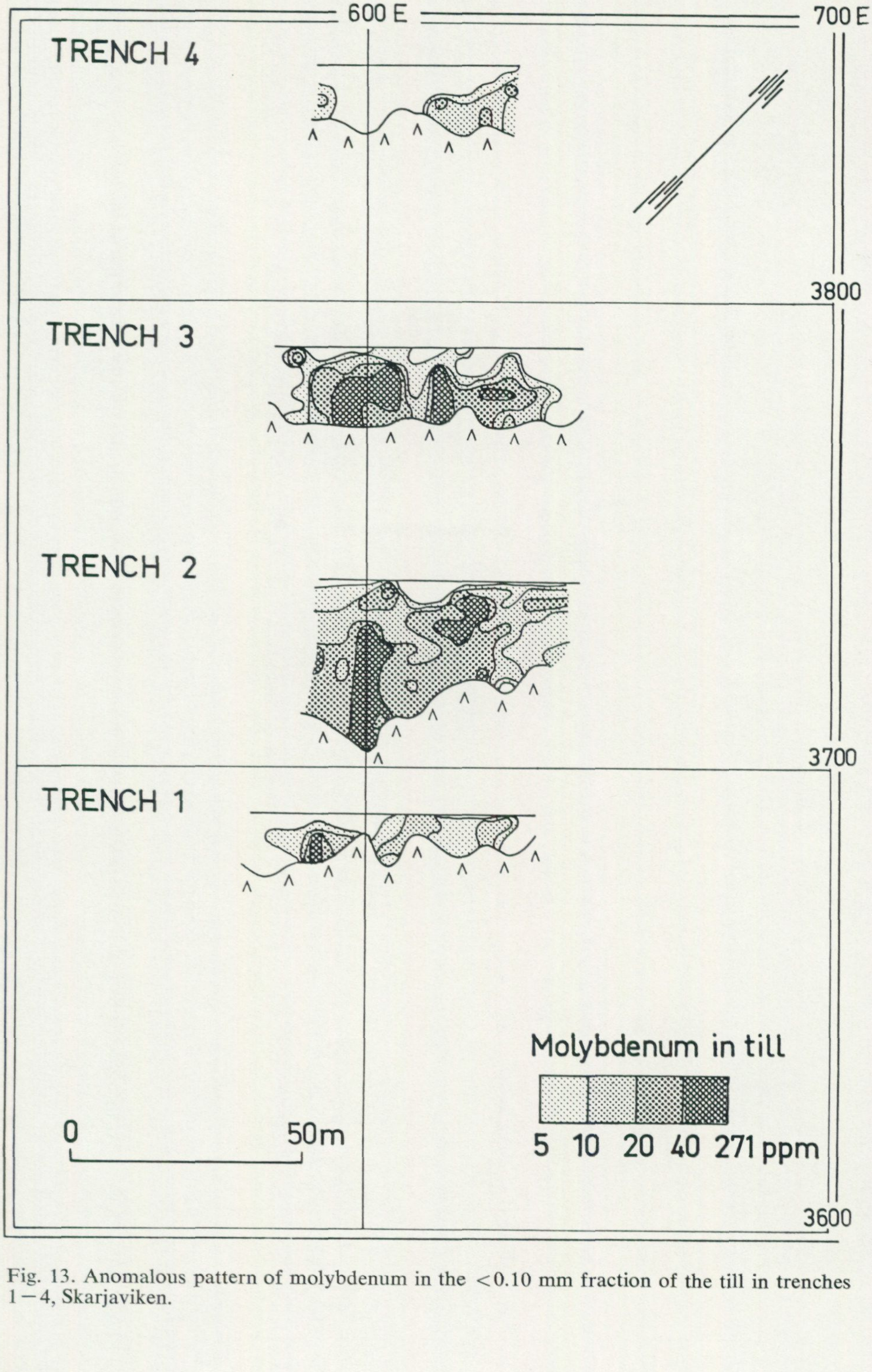


Fig. 13. Anomalous pattern of molybdenum in the <0.10 mm fraction of the till in trenches 1 – 4, Skarjaviken.

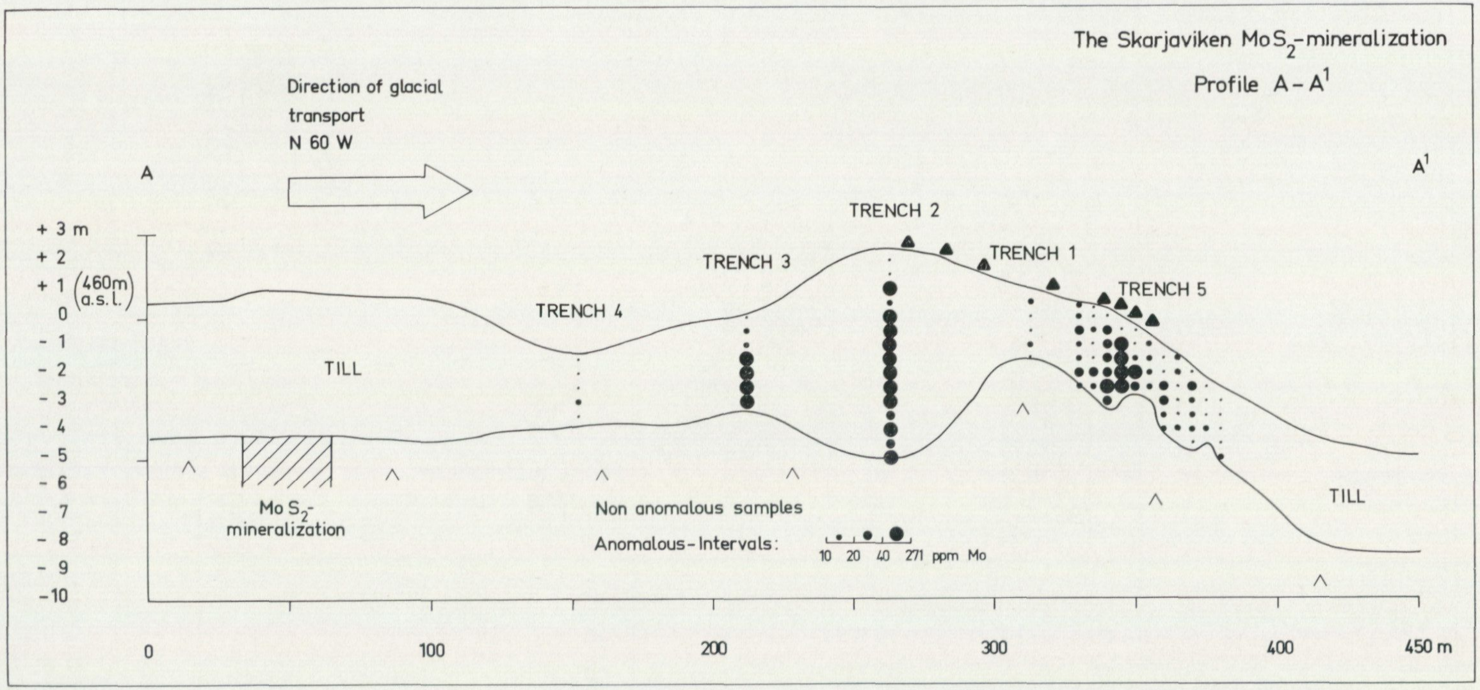


Fig. 14. Profile A – A¹ through the Skarjaviken area showing the distribution of molybdenum in the <0.10 mm fraction of the till.

150 m long. The dominant size of the boulders is 30–50 cm diameter in the lodgement (basal) till, but boulders up to 80–130 cm in size are found on the surface.

Samples for geochemical analysis were collected from the C-horizon and from top to bottom of trenches dug at right angles to the direction of ice movement (Ek and Toverud 1976). The trenches were dug on the proximal side of the boulder train (Fig. 12).

Total chemical analysis of the till samples was carried out using a direct-reading optical emission spectograph equipped with a tape machine. The results of the analyses show a close correlation with the distribution of the ore boulders. The highest values were obtained from the trench lying immediately proximal to the boulder train. (Figs. 13 and 14). The frequency of mineralized boulders was highest in this trench. The Mo-anomaly was weaker and no mineralized boulders were present in the two trenches to the northwest (Fig. 14).

INTERPRETATION

The distinct gap between the mineralization and the boulder train and anomalous clusters is the result of material transport after erosion and abrasion had ceased: A distinct boulder train of abraded material was created during deglaciation, when pressure release allowed marked erosion in the bedrock. Erosion took place primarily by plucking of fragments with low strength from the bedrock, but also by abrasion of loosened fragments against the bedrock. Erosion was most pronounced behind the glacier front where the shear stresses were highest. Erosion, incorporation of material and abrasion gradually decreased, however, as the glacier approached stagnation because of diminishing pressure and shear stresses (Boulton 1974), and a reduction in creep and regelation (Weertman 1961). High water pressure at this stage would also reduce the shear stresses. Material suspended in the ice, however, was still transported even after erosion had ceased, resulting in a distinct gap between the mineralization and the anomalous boulders and finer fractions.

KIKKEJAURE

The area investigated is situated only a few hundred metres south of the northwestern part of lake V Kikkejaure, economic map sheet 24I 9i (Fig. 15).

The investigations have chiefly been made in connection with a uranium mineralization in a bedrock of granite and metavolcanic rocks. The mineralization is associated with an extensive alteration involving Na-metasomatism and the removal of quartz.

The area is one of gentle hilly topography, with the individual hills being 1–3 km in diameter and 450–650 m high. Prospecting was carried out in

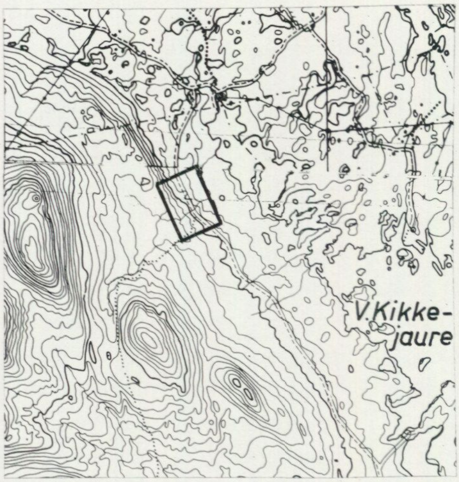


Fig. 15. Topographic map of the Kikkejaure area (from topographic map sheet 24I). The area investigated in detail lies within the small frame. Scale 1:100 000.

a 6 km wide valley between two of the hills, Norr-Döttern (660 m a. s. l.) and Strittjomvare (500 m a.s.l.).

The valley, or basin, containing lake V Kikkejaure is partly filled with large perpendicular ridges, the convex-sloping sides of which stretch against the ice flow. The width of the ridges is about 200 m (Minell 1978). The till is sandy to fine sandy in composition and in some cases there are lenses of sorted material. The boulder content is usually normal to rich. These ridges probably belong to the so-called Rogen moraine described by Lundqvist (1969 a). In the northwestern part of the area which was systematically investigated, sediments and tills from a lateral ice lake produced a kame landscape.

To the south, slightly undulating hummocky moraine predominates. The till is of the boulder-rich type with a predominance of local pebbles and granules. There is no evidence of foliation because of the scarcity of silt horizons, but layers which have been crushed and mixed to a greater or lesser extent indicate that the till was transported very close to the bedrock within the ice. Lenses of sand and silt occur in the upper parts of the till indicating secondary flow during melting of the glacier. Geochemical investigations and diamond drilling were carried out in this hummocky moraine. The till has a thickness of 2–6 m. Pebble orientation studies revealed preferred orientation of N45°W and N5°W which coincide quite well with striations of N45°W on Norr-Döttern, 3 km to the northwest, and Järntjärnsdalen 4 km to the south. The boulder train as a whole is oriented N20°W although the longest single unit within the train is oriented N40°W (Fig. 16). The boulder train consists of uranium mineralized, quartz-poor and calcite-rich rocks. The dominant size of boulders is 15×40 cm,

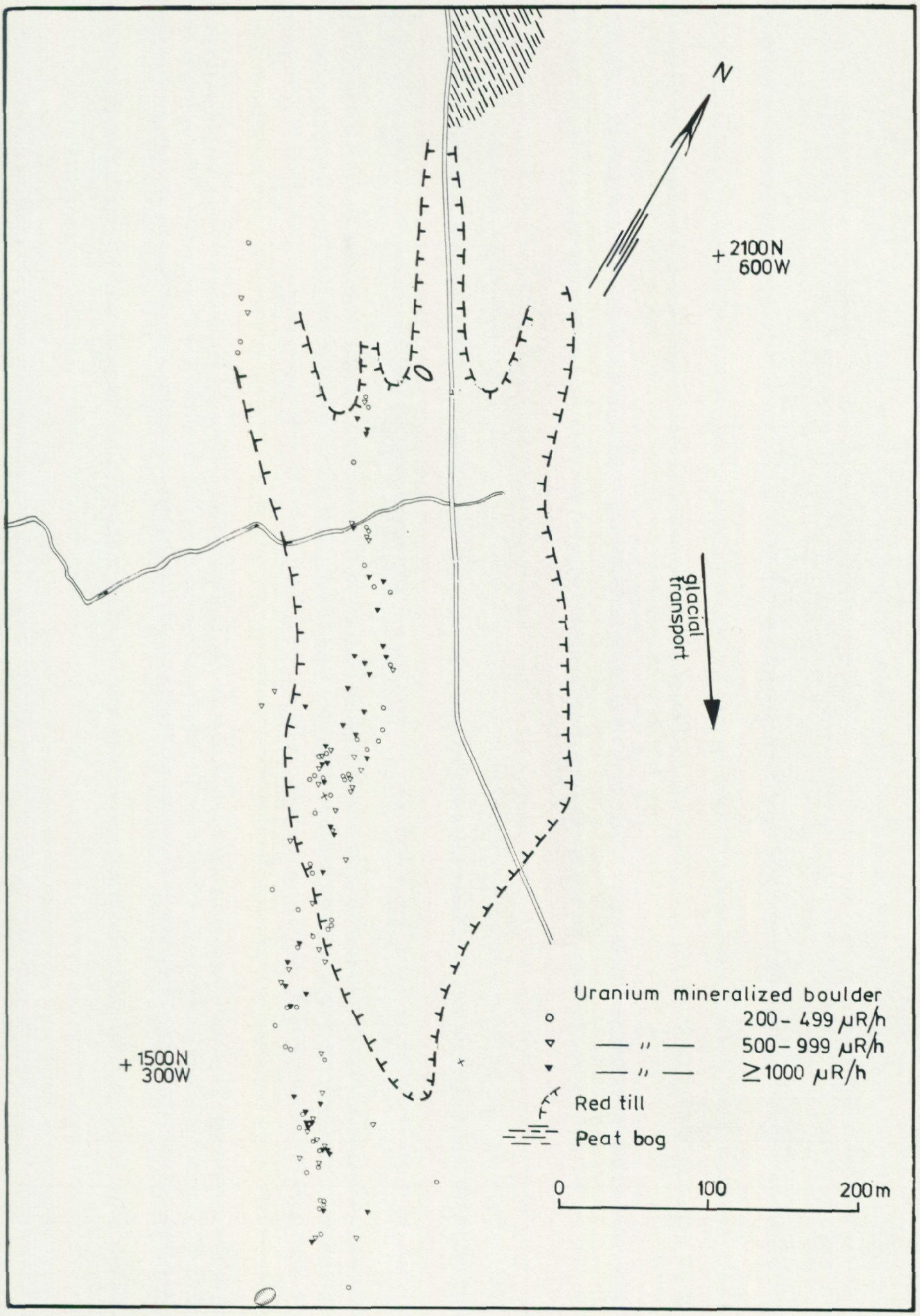


Fig. 16. Map showing the boulder train and the distribution of the red till, Kikkejaure.

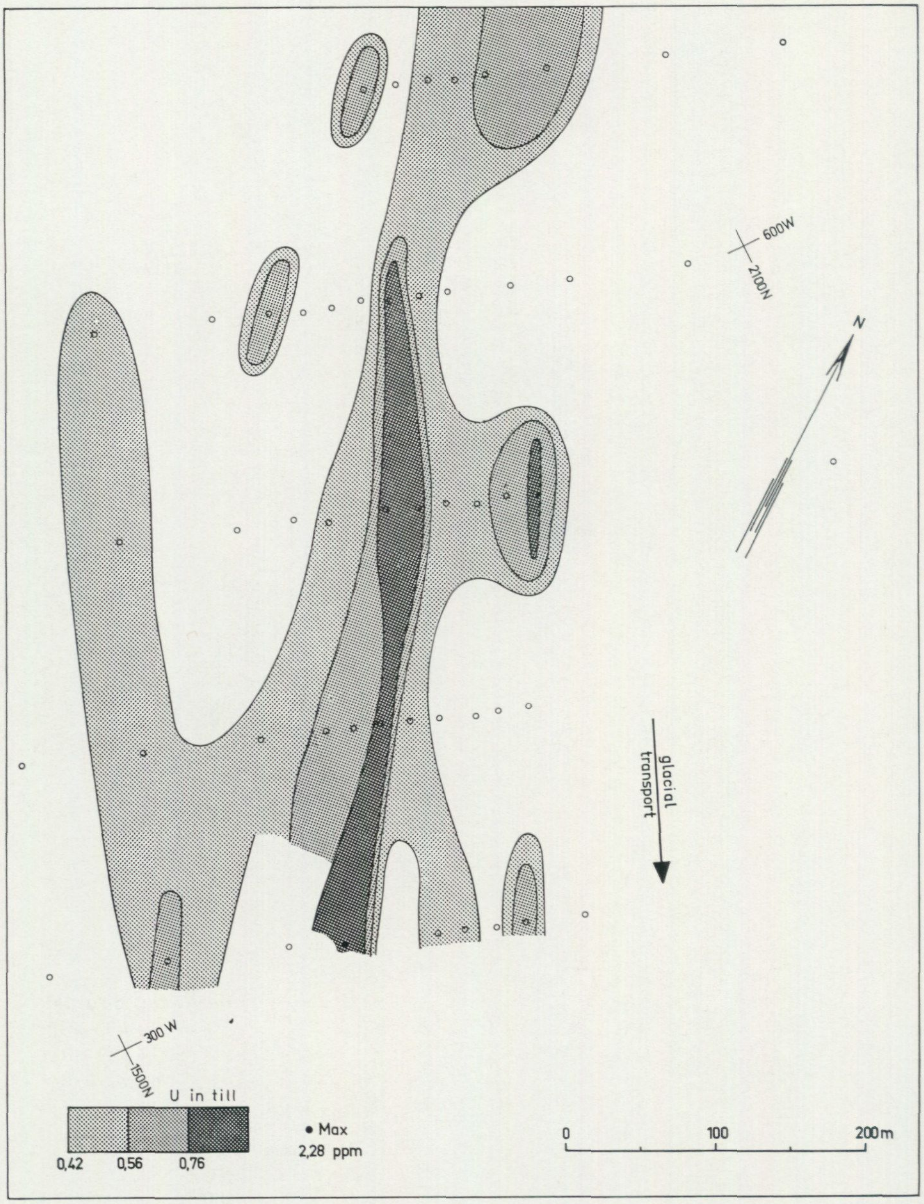


Fig. 17. Anomalous pattern of uranium in the 5−20 mm fraction of the till at a depth of 0.5 m, Kikkejaure.

with a few at about 10 cm. A small group of boulders with dimensions of about 80×180 cm was found but no larger ones. The large boulders are usually weakly mineralized.

The true extent of the boulder train is difficult to determine, because of isolated boulders and boulder groups or small trains lying at some distance from the main train. The main train, however, has a distinct length of 600 m. The widest part is not more than 40 m (Fig. 16).

The boulder train is associated with a red till (Fig. 16). The red till consists of very local material from a strongly deformed and metamorphosed zone with which the mineralization is associated. Calcite and hematite are found in addition to uranium. The presence of calcite facilitates weathering and crushing of the rock, giving it a very weak character, and the hematite gives a reddish colour to the material. The red till together with the reddish inactive boulders and the active boulders have been mapped. A comparison between their distribution and that of the uranium mineralized boulders shows that the reddish boulders are always found with the red till whereas the greyish metamorphosed boulders and the uranium mineralized boulders are found far beyond the area with the red till (Fig. 16). In some places within the area of red till, the mineralized boulders lie on a greyish till which overlies the red till.

Diamond drillings have revealed mineralized bedrock lying 200–300 m from the densest, proximal part of the boulder train. The bedrock between the uranium mineralization and the boulder train consists of the crushed and weathered type.

Many pits were dug over a wide area covering the main part of the boulder train and the area between the train and the mineralization. Samples were taken from the pits, and the bottoms of the pits were measured with a γ-scinillometer. The samples have been treated by Bååth (in preparation). The results of the analyses show a continuity of the anomaly for a further 300 m upstream. The anomaly is related to particles in the 5–20 mm size fraction (Fig. 17).

INTERPRETATION

In this example, the different distances between the source and, on the one hand the boulders, and on the other the clastic anomalies, have been interpreted as the result of two stages of erosion. Initially, pressure and shear stresses were sufficient to erode and take up all the loose material into the ice for further transport. This stage occurred quite late during deglaciation and therefore produced a boulder train with limited extent. When the pressure and shear stresses diminished, large loosened and broken fragments were no longer produced (cf. Boulton 1974) and the low rate of creep inhibited further incorporation of the larger fragments. Small fragments, however, were still incorporated by regelation (cf. Weertman 1961) in an environment where abrasion and erosion of fragments with low shear strength still took place.

Transport without erosion of large fragments produced a gap between the boulder train and source. The diminishing abrasion and erosion of small fragments produced decreasing anomalies but these lie closer to the source than the boulders.

LABBAS

The area investigated is situated 3 km south of the westernmost part of lake Labbas, economic map sheet 26H 3e (Fig. 18).

The investigation has been made in connection with a pitchblende mineralization in a bedrock of gneisses and granites intruded by greenstones and pegmatites. The mineralized zone has been affected by Na-metasomatism with the supply of minerals such as calcite and hematite and the removal of quartz. The area concerned is slightly concave (520 m a.s.l.) lying between a small mountain to the northwest (Ardnasvare, approx. 700 m a.s.l.) and a mountain plateau to the southeast (Tjaveljägge, approx 600 m a.s.l). The distance between the investigated area and the mountains to the northwest and southeast is only a few kilometres.

The terrain is slightly undulating with abundant swamps and springs. Tills of both basal and ablation character are present with a combined thickness of 2–5 m. Undulating moraines are found in the adjacent areas, while quite thick deposits of tills forming a plateau-like hummocky moraine are found on the plateau to the southeast.

No outcrops with striations have been found in the vicinity, but the boulder train is clearly oriented N30°W. This direction coincides quite well with directions obtained for the latest ice movement in the vicinity.

The boulder train consists of the uranium mineralized, metamorphosed syenitic rock. The boulders are usually about 15×50 cm in size with very few outside this size range. The boulder train can be followed for 1300 m. Interruptions are common but are due to swamps in the terrain. The width of the boulder train varies from 70 to 140 m.

Four trenches were dug at 200 and 35 m intervals (Fig. 19). The terrain in the area of the middle two trenches has a slightly convex topography. The two northwestern trenches (which lie proximal to the mineralization) gave no results, and the first (proximal) boulder was found in the highest part of the third trench. The lower part of this trench consisted of a fine sandy basal till containing Caledonian material (Fig. 20). Many boulders were found in the fourth trench in a mixed basal till with material from both Caledonian rocks and the local crystalline rock type. Boulders first appeared on the surface between the third and

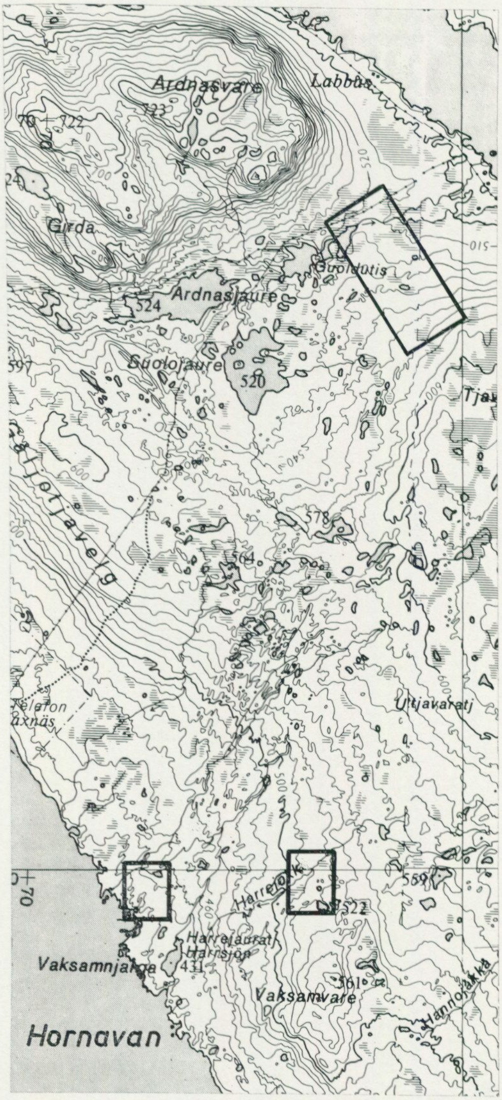


Fig. 18. Topographic map of the Labbas (N) and Harrejokk (S) areas (from topographic map sheet 26 H). The areas investigated in detail lie within the small frames. Scale 1:100 000.

fourth trenches (Fig. 19). Diamond drillings revealed that the mineralization lay approximately 60 m upstream from the first surface boulder (Fig. 19).

Till samples were taken systematically from all four trenches. The <0.10 mm fraction of the samples was analysed by X-ray fluorescens (XRF). The results revealed anomalies in only a few places at the bottom of trench 3 (Fig. 21). Trench 4 gave no results due to the difficulty of taking samples in very swampy conditions.

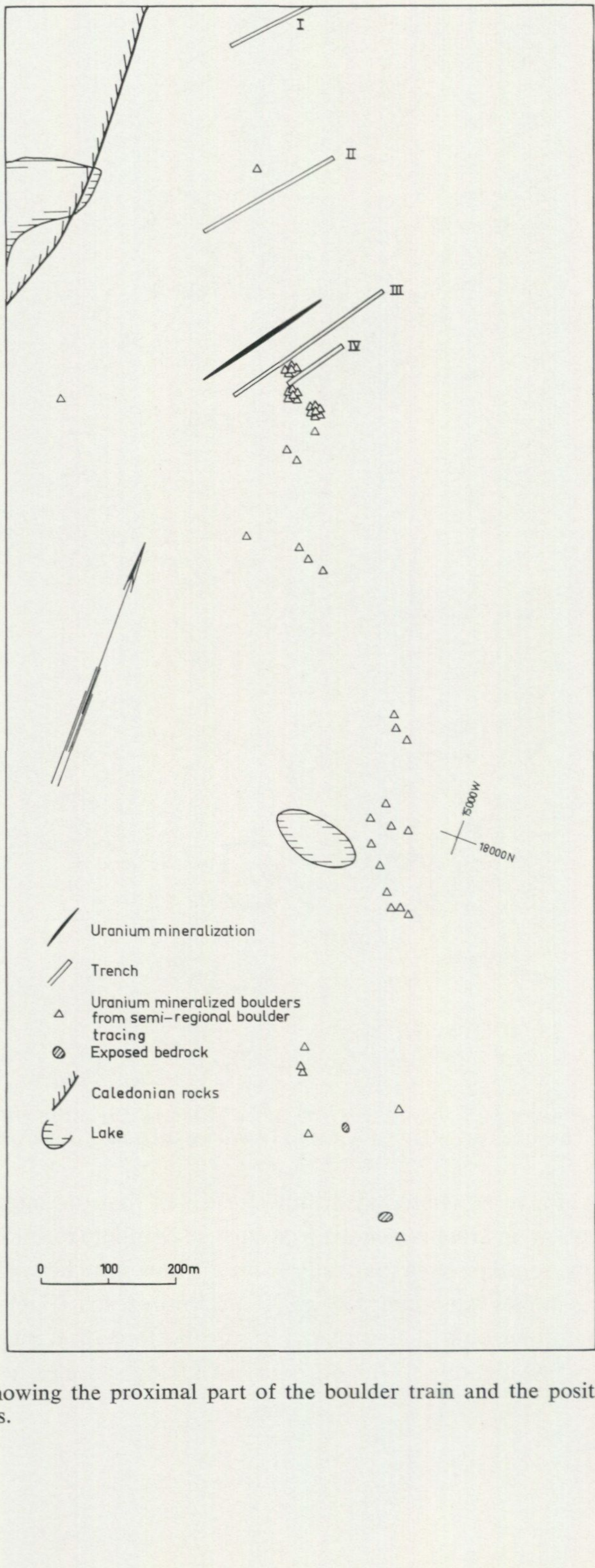


Fig. 19. Map showing the proximal part of the boulder train and the positions of the four trenches, Labbas.

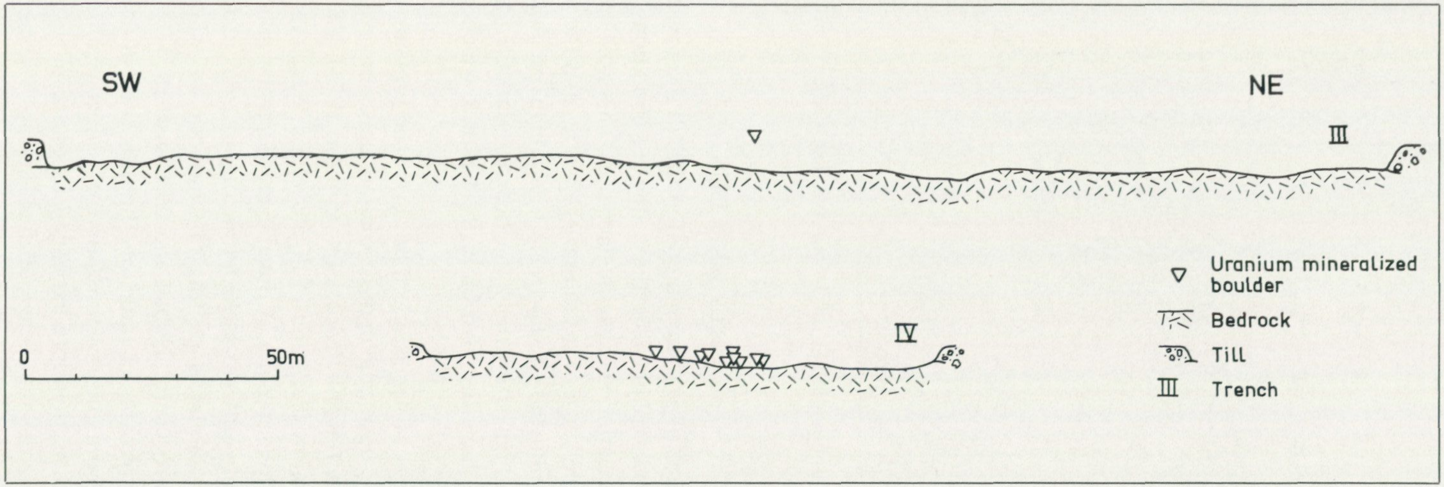


Fig. 20. Distribution of uranium-mineralized boulders in trenches III and IV, Labbas.

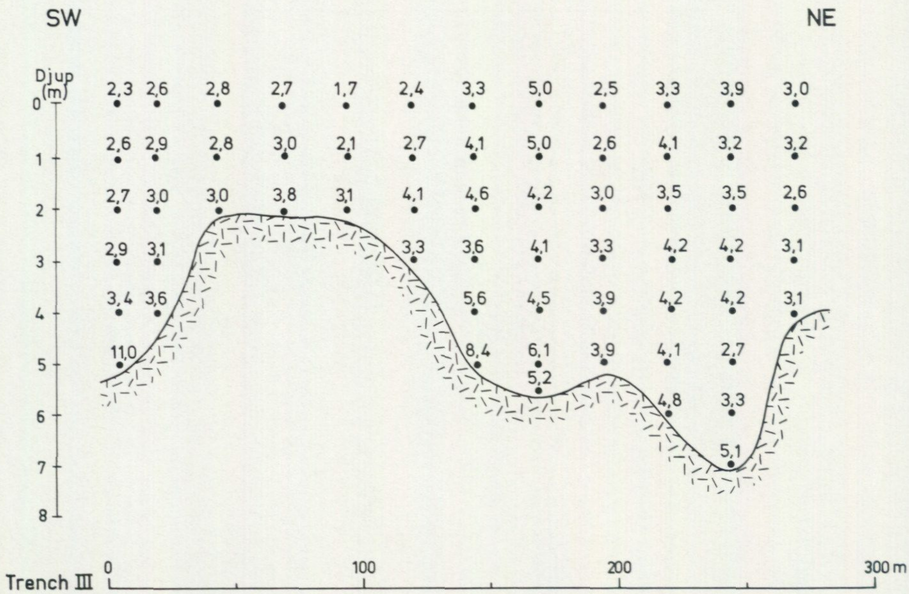


Fig. 21. Distribution of uranium in the <0.10 mm fraction of the till in trench III, Labbas.

INTERPRETATION

The sudden appearance of granitic material in the till so close to the Caledonian rocks can probably be explained by the following conditions during the stages of both maximum glaciation and late deglaciation. This area lay in the vicinity of the ice-shed during the stage of maximum glaciation, and the supply of material was therefore small. Further downstream, very high pressure exerted by the thick ice resulted in high strength in the bedrock and till (cf. Boulton 1974). The glacier may well have been frozen to the bedrock which would also inhibit erosion and transport (Schytt 1974).

During the late stage of deglaciation, however, the pressure exerted by the ice in the area was low, resulting in less friction between fragments and lower strength in the till material and bedrock (cf. Boulton 1974). The ice was then able to incorporate material by creep and/or regelation (cf. Weertman 1961), and transport it out to the peripheral parts of the glacier. Here, the material was accumulated either by stacking and supra-glacial melting in areas of restricted flow and compression, or by sub-glacial melting in temperate ice where friction contributed to the melting process (cf. Nobles and Weertman 1971).

The pattern formed by this example, of a boulder train of uranium mineralized boulders separated from the mineralization by till consisting mainly of Caledonian rock material, is therefore explained as the result of transport without further erosion during the final stage of deglaciation. The mineralized material was incorporated by the ice during a fairly late stage of deglaciation, but immediately prior to stagnation, transport only continued, producing a window between the boulder train and the source which is covered by the long-transported Caledonian material. A few anomalous values were found in the basal layers of the long-transported till (Fig. 21). These are interpreted as the result of slight abrasion caused by small topographical variations. The mineralized boulder found in the upper part of the third trench was probably picked up at a very late stage.

HARREJOKK

The area investigated is situated very close to the northeastern shore of lake Hornavan, economic map sheet 26H 1e (Fig. 18).

Extensive investigations have been made in this area in connection with mineralizations of pitchblende. The mineralizations occur in Na-metasomatised zones in a host rock of gneiss and granites intruded by greenstones.

The terrain is slightly concave (430–460 m a.s.l.) with a mountain situated 7 km away to the northwest and a smaller mountain, Vaxamvare (500–560 m a.s.l.) only a few kilometres to the southeast (Fig. 18).

The glacial geology of the area consists mainly of moraine ridges (Minell 1977). The till is 2–6 m thick and has the character of an ablation till with local rock types dominating. Hummocky moraines are dominant in the surrounding areas. In the northern and northeastern massifs, quite thick deposits (15–20 m) of tills have formed, resulting in a more plateau-like hummocky moraine.

Striations indicate that the final movement of ice came from N20–25°W which coincides with the orientation of the boulder train. The oldest striations encountered are oriented N60°W. Pebble orientation studies proved negative due to the ablation character of the till.

The boulder trains consist of uranium mineralized rock of syenitic composition. The dominant boulder size is about 20×70 cm. Larger boulders occur but are mostly limited to a size of 1–2 m. A bimodal distribution of boulders is therefore apparent with a high peak at 20–70 cm and a very small peak at around 1–2 m. The larger boulders are usually of a nonmetamorphosed rock type. The boulder trains (Figs. 22 and 23) are of limited extent with lengths of 300 to 400 m for the most concentrated parts. Widths are about 20 m and never exceed 25 m.

Diamond drillings revealed that the first boulders lay 250–300 m downstream from the mineralizations. No other type of till or lake deposit is found between the boulder trains and the mineralizations to explain these gaps.

Till samples from the sides and proximal part of the first boulder train (W Harrejokk, Fig. 22) have been analysed. Different fractions from different depths were analysed with respect to uranium and thorium (Figs. 24–26). The uranium

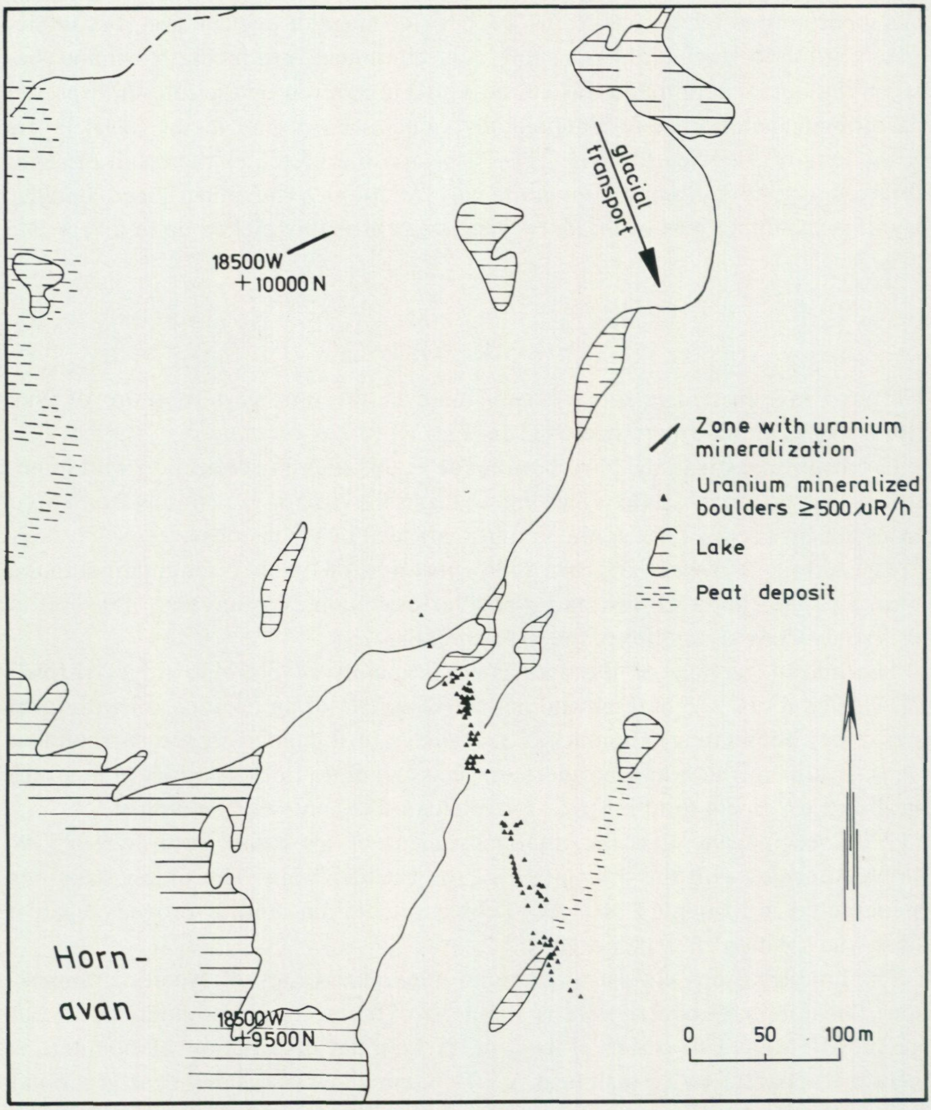


Fig. 22. Map showing the uranium-mineralized boulder train from W Harrejokk. The mineralization in the bedrock is marked with a line.

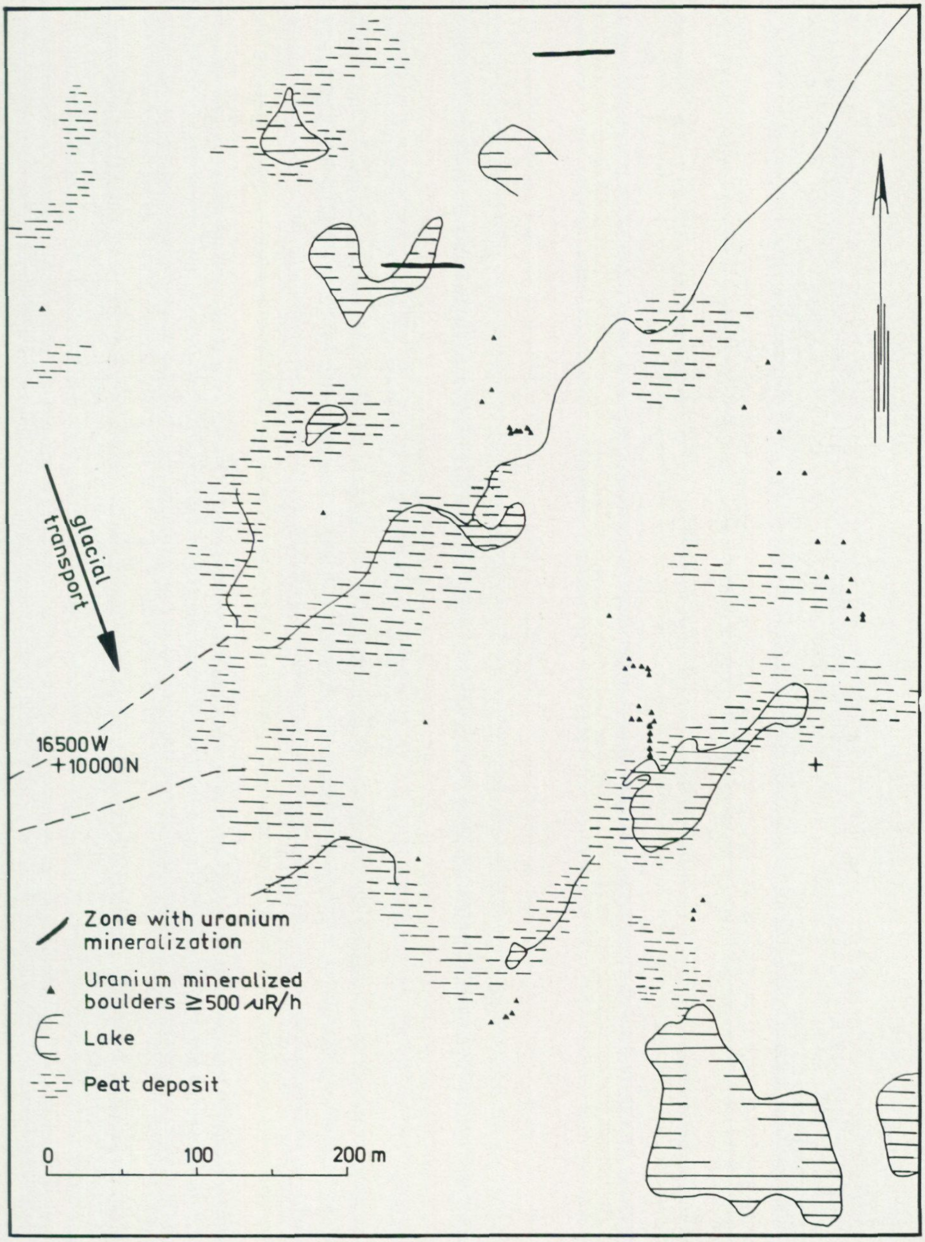


Fig. 23. Map showing three uranium-mineralized boulder trains from E Harrejokk. The bedrock mineralizations are marked with lines.

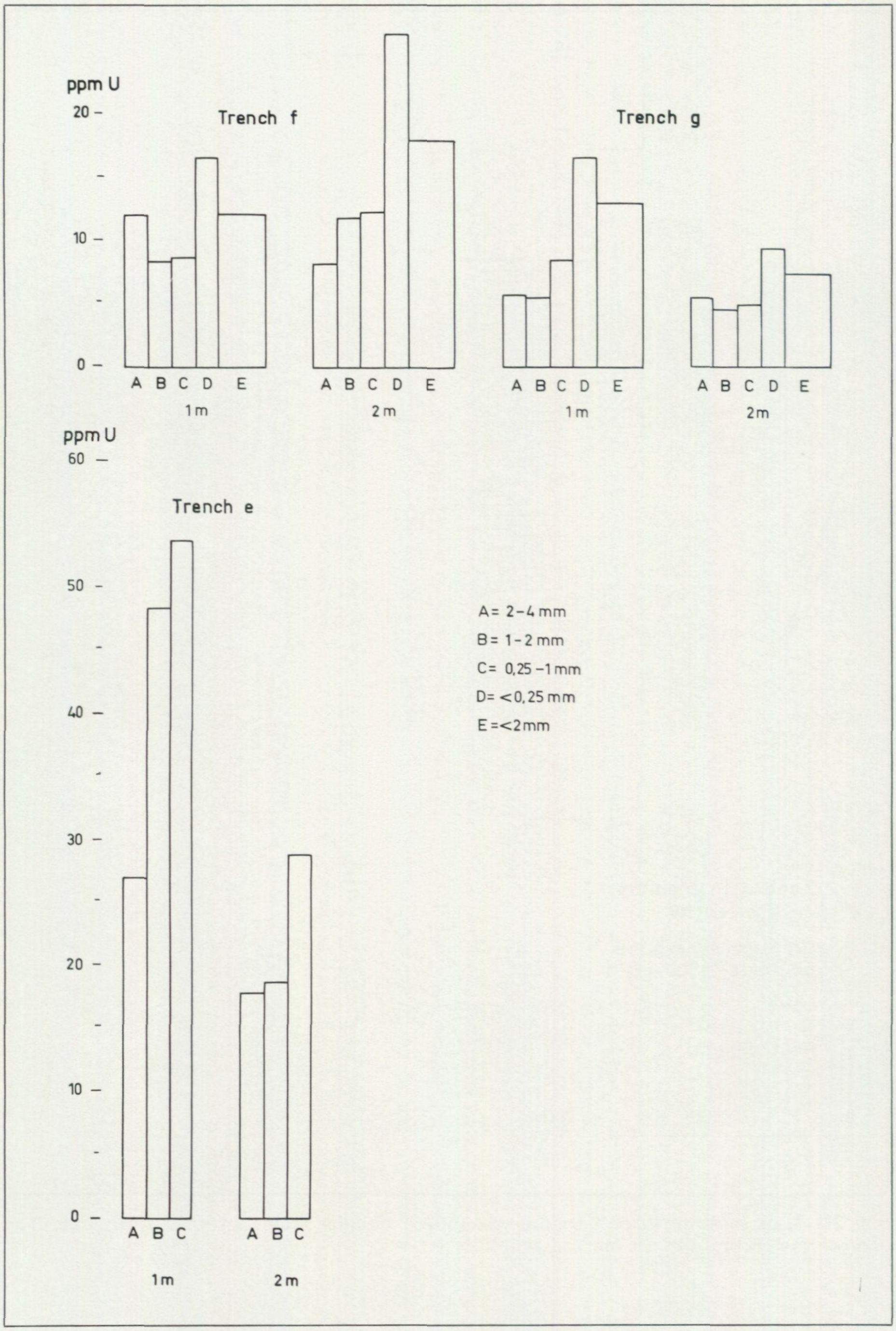


Fig. 24. Diagram illustrating the distribution of uranium in different till fractions from the immediate vicinity of the boulder train, W Harrejokk.

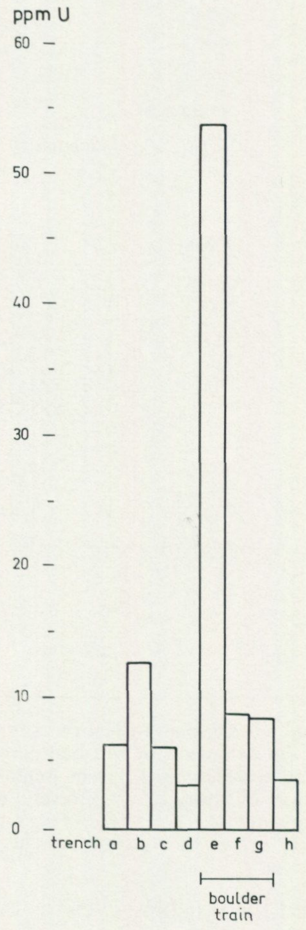


Fig. 25. Results of uranium analyses of the 0.25 – 1 mm fraction from till samples taken at a depth of 1 m along the boulder train and its extension to both NW and SE, W Harrejokk.

was analysed at AB Atomenergi by delayed neutron activation. The thorium was analysed by Industrins vatten och luftvårds AB by wet chemical analysis. The results of these analyses show a close correlation between the ore boulder train and some small clastic anomalies lying at distances of up to 70 m to the sides of the distal part of the boulder train. Approximately 100 m upstream from the proximal part of the boulder train, one clear anomaly is visible.

There is a strong tendency to find higher uranium and thorium contents in the fine fractions of the till independent of pit depth. The crushing of the uraninite

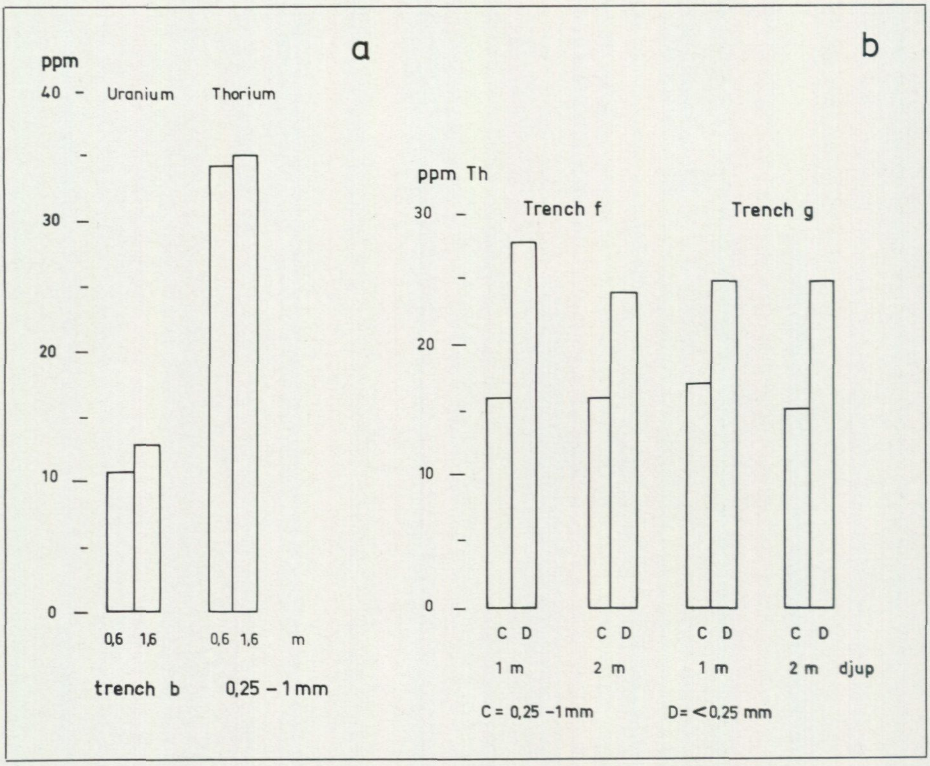


Fig. 26. Results of analyses from till samples with high contents of thorium, W Harrejokk. The samples were taken along the extension of the boulder train to the NW. a. trench b, distribution of both uranium and thorium at different depths in the 0.25 – 1 mm fraction. b. trenches f and g, distribution of thorium at different depths in the <0.25 mm and 0.25 – 1 mm fractions.

aggregates probably followed the crushing cycle as described by Dreimanis and Vagners (1971), that is, rapid disintegration to a certain crystal or aggregate size.

The Harrejokk area is interpreted in the same way as the Skarjaviken and Labbas areas.

TJÄRROVARE

The area is located about 120 km northwest of Luleå. The investigations have been carried out in connection with a chromite-mineralized ultramafic intrusion with an olivine-pyroxene-hornblende composition. The surrounding bedrock consists mainly of gneiss with intrusions of pegmatite-bearing red granite. The dolerite dike shown on the map is deduced from small outcrops and from gravimetric and magnetic measurements.

The prospect lies parallel to the eastern side of mount Tjärrovare (Fig. 27).

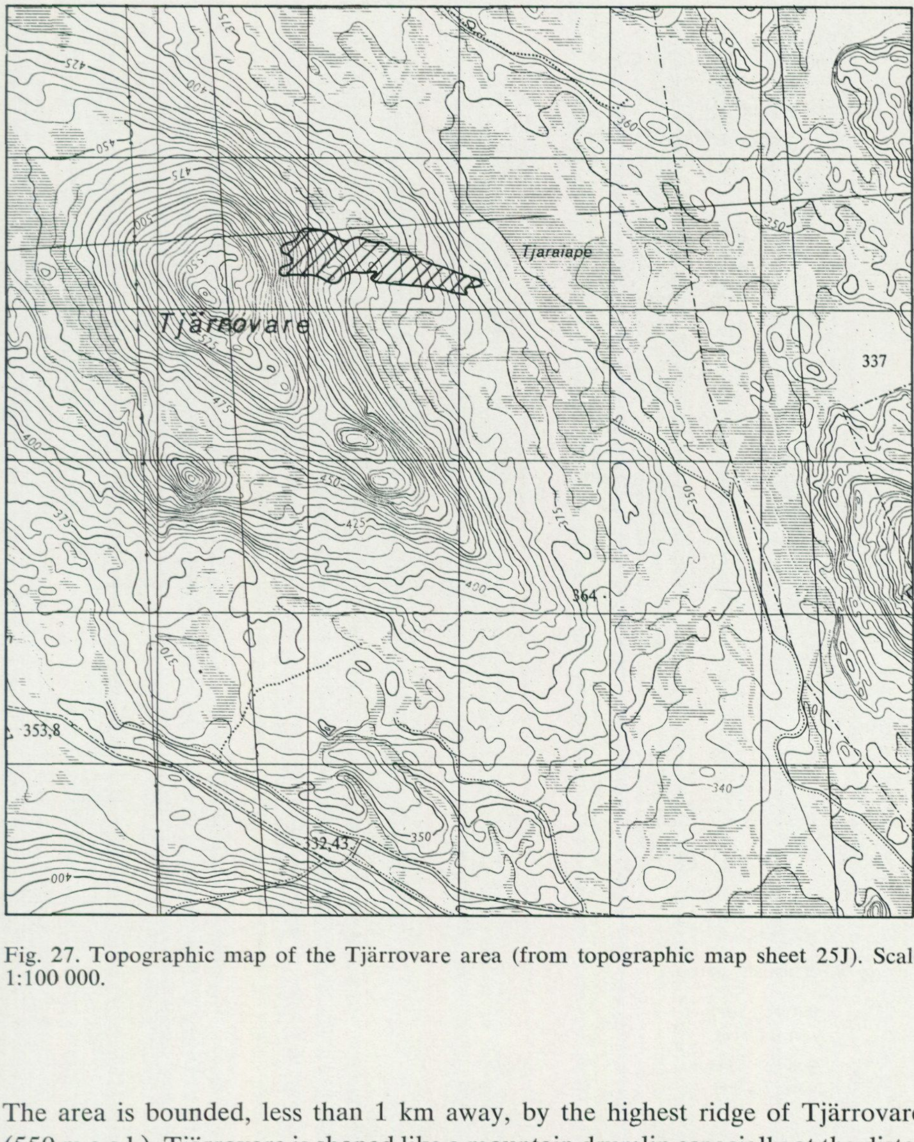


Fig. 27. Topographic map of the Tjärrovare area (from topographic map sheet 25J). Scale 1:100 000.

The area is bounded, less than 1 km away, by the highest ridge of Tjärrovare (550 m a.s.l.). Tjärrovare is shaped like a mountain drumlin especially at the distal end at 400–500 m a.s.l. The terrain east of the area investigated is quite flat with drumlins and drumlinised moraines at the foot of, and parallel to Tjärrovare. Different types of hummocky moraines are found to the southeast at the end of the mountain drumlin and further east.

The till in the northern and central parts of the area investigated consists of a basal till with a thickness of 2–8 m. The boulder and pebble content of this till is fairly normal. The till, however, becomes coarser to the southeast with a higher content of boulders, and the moraine morphology becomes more disrup-

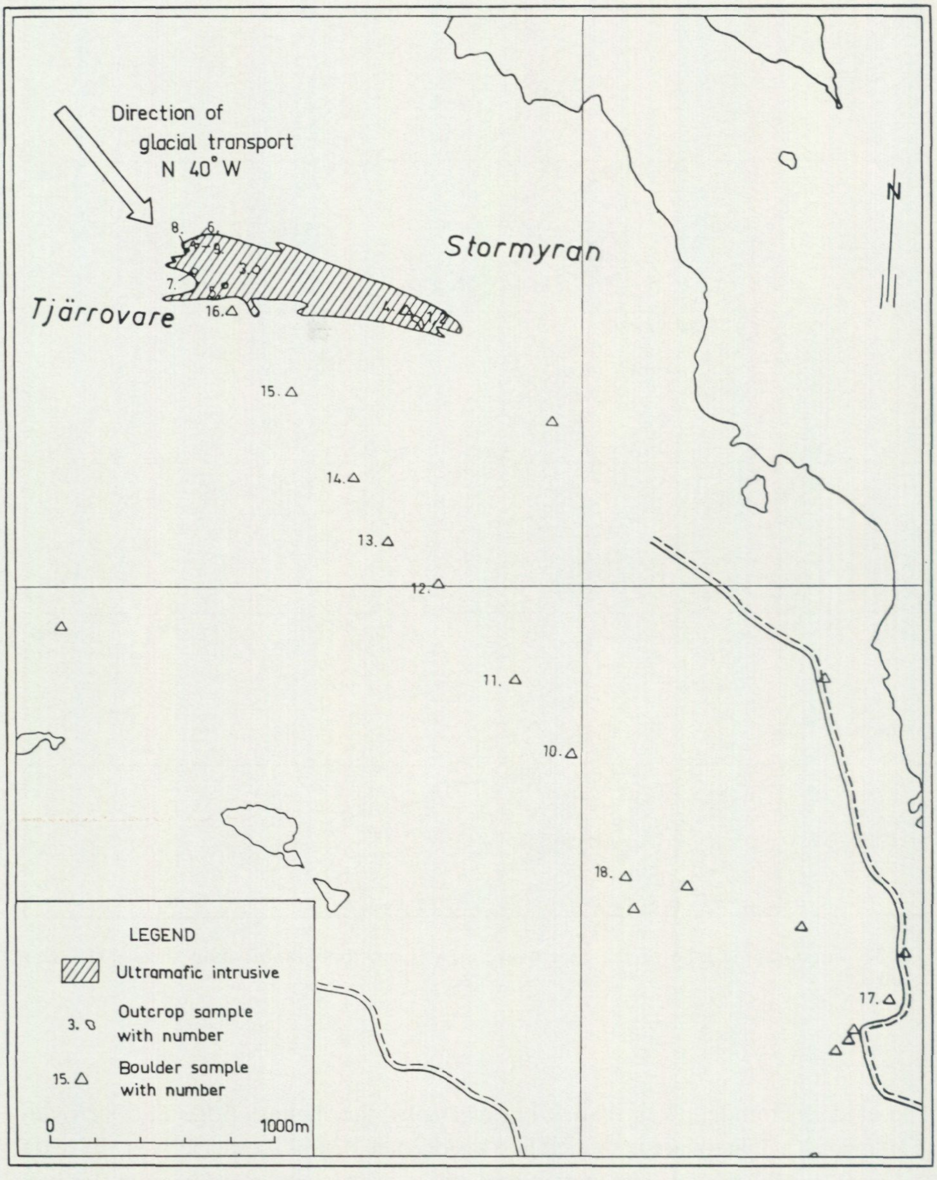


Fig. 28. Map showing the outcrop and boulder train at Tjärrovare.

ted. The final movement of ice, as indicated by striations and the orientation of drumlins, was from N40°W which coincides quite well with the orientations of the boulder train and anomalous tills.

Boulders of the mineralized rock are moderate to small in size with a minimal amount of rounding. The boulder train is more or less homogeneous, with the first boulder lying close to the mineralization, followed by boulders at intervals of about 200 m (Fig. 28). The densest part of the boulder train seems to lie at the distal end.

Till samples were taken systematically over a large area east of Tjärrovare. The samples were analysed with respect to the <0.10 mm fraction, using a direct-reading optical emission spectograph equipped with a tape machine. The results show a chromium anomaly, probably of clastic origin, with an extension of more than 4 km (Figs. 29 and 30). The anomaly has more or less constant values and is about 150 m wide for 2000 m downstream from the western part of the ultramafic intrusion. Further downstream, the anomaly is more widespread and more intensive over the whole of this area which is about 200 m wide and 1500 m long. At the distal end of the anomalous tail, the width of the anomaly begins to decrease, although small anomalies begin to appear further east which coincide with a prolongation downstream of the ultramafic massif (Fig. 29).

A study was carried out to determine the amount of chromium, silica-bound and/or oxygen-bound (Cr_2O_3, Cr-bearing magnetite mineralization) in the anomalous province. This study was carried out by statistical multielement analysis of soil samples (Ek and Elmlid 1976). The analysis includes R-mode Factor analysis and Trend-surface analysis of factor scores, which means a grouping of the metal distribution based upon a rotation of the correlation matrix of the chemical data (Cameron 1967). The results (Figs. 31 and 32) show that mafic silica minerals (with Cr) increase in the area at about 2.5 km from the intrusion where the clastic anomaly is most intensive but beginning to diminish. The magnetite and chromite minerals, however, are most abundant immediately above the ultramafic massif and decrease successively.

The problem here is not only the form of the anomaly, but also why the eastern ultramafic massif has not produced any apparent clastic anomaly.

INTERPRETATION

The increase of clastic material and coarse fragments at a great distance from the mineralization has been interpreted as a consequence of erosion and transport in ice with laminar flow towards the periphery of the glacier. Erosion was strong at high altitudes, but limited at low altitudes by high pressure. Transport was quite considerable due to the free flow of the ice. Free flow was the result of the convex position of the area which probably caused extending flow within the glacier ice (cf. Minell 1978). The ice probably had a high velocity, and the

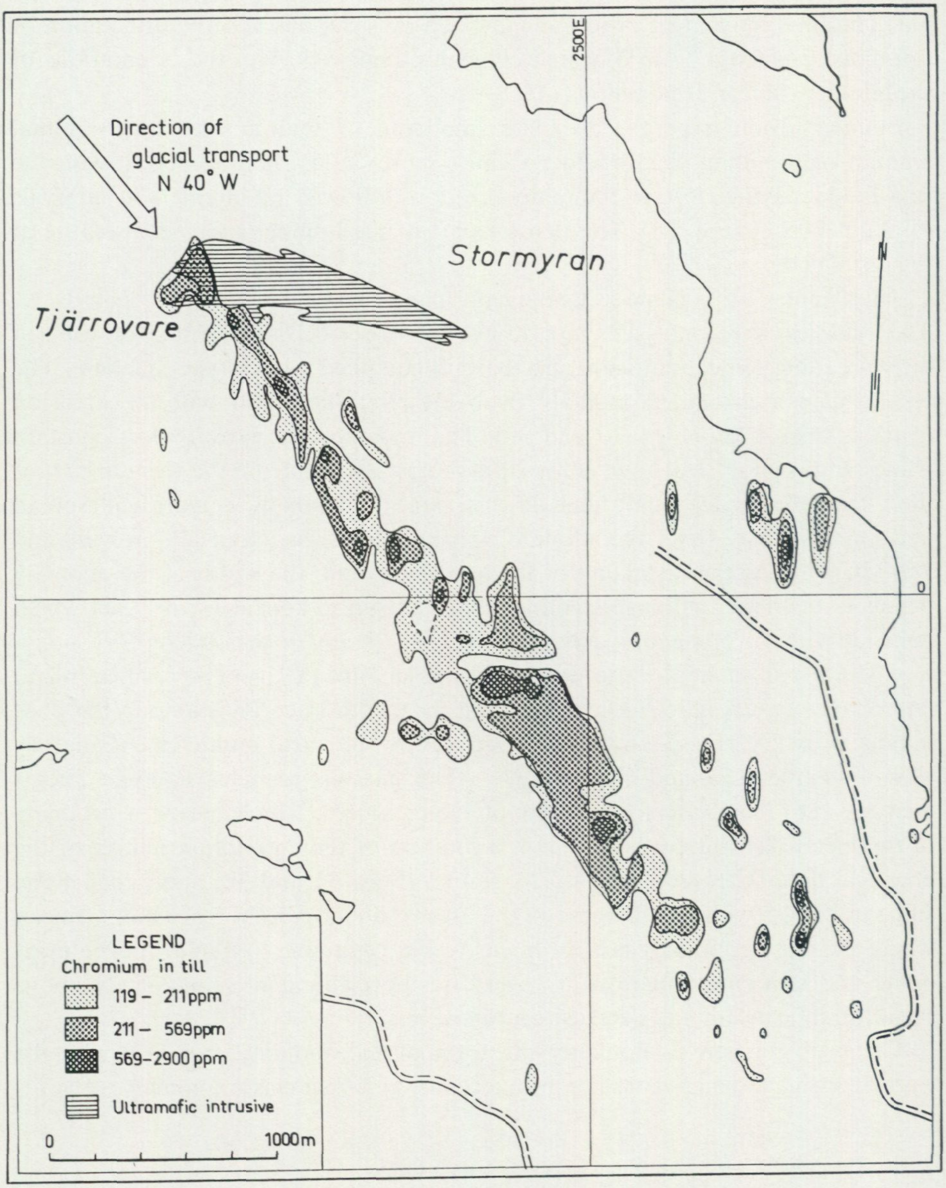


Fig. 29. Distribution of chromium in the <0.10 mm fraction of till samples from a depth of 0.5 m, Tjärrovare.

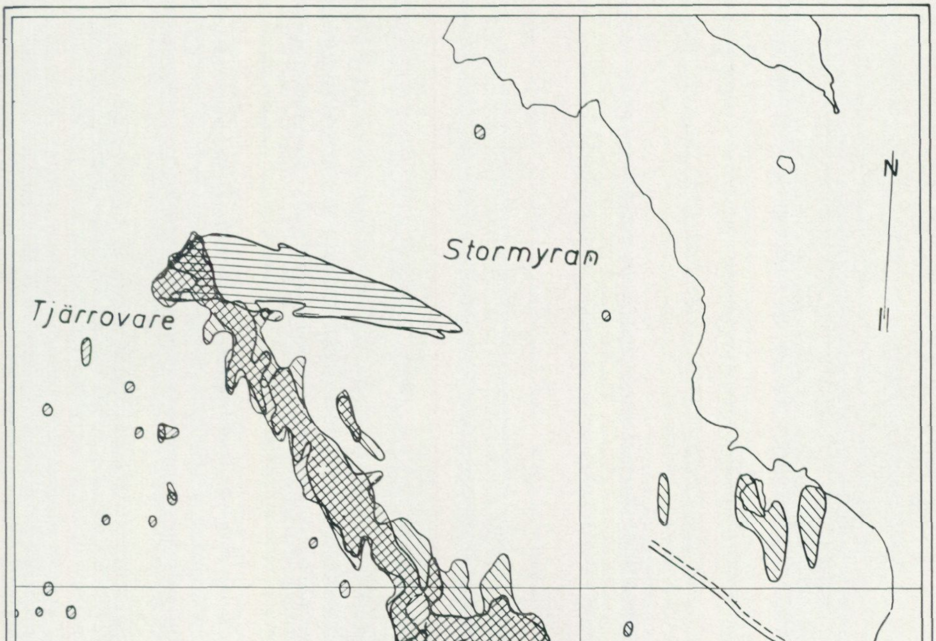


Fig. 30. Distribution of chromium and magnesium in the <0.10 mm fraction of till samples from a depth of 0.5 m, Tjärrovare.

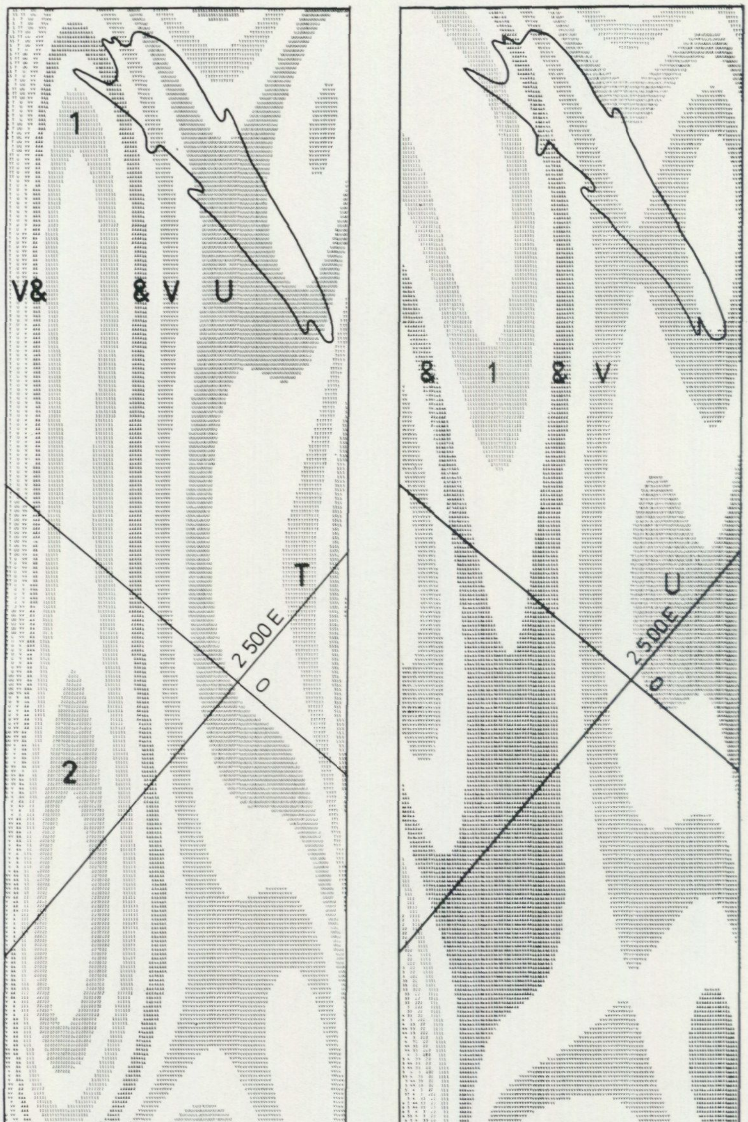


Fig. 31 (left). Fourth degree trend surface of factor scores – factor 1 (Mg, Ca, Cr, Co, V), 30.8 % fit, that is, a levelling of the variations within contour interval 0.20. The surface explains 30,8 % of the total variation of factor. 1. Each factor is divided within different intervals, each width having unit of 0.20 (contour interval). The association of Mg, Ca, Cr, Co, and V tends to be higher and has a greater content with increasing trend ⟶ 1,2,3... but decreases with ⟶ V,U,T ...

Fig. 32 (right). Fifth degree trend surface of factor scores – factor 3 (Ti, V, Fe, Cr), 11.2 % fit, that is, a levelling of the variations within contour interval 0.20. The surface explains 11.2 % of the total variation of factor 3. Each factor is divided within different intervals, each width having unit of 0.20 (contour interval). The association of Ti, V, Fe, and Cr tends to be higher and has a greater content with increasing trend ⟶ 1,2,3... but decreases with ⟶ V,U,T ...

resulting high shear stresses at the base of the glacier enabled material to be transported there (Minell 1973). Only in the lee and distal parts of Tjärrovare was the glacier ice compressed and material transported upwards, (cf. Minell 1978) mixed and accumulated, resulting in the clusters of distinct anomalies. The till is therefore rather thick in this area of compression, whereas only very thin layers of till developed over the most convex parts of Tjärrovare.

SUMMARY

PROBLEM

The results of systematic boulder tracing and geochemical analyses, when plotted on maps, reveal boulder trains and clastic anomalies of varying character. The material used has been collected during the prospecting programme which SGU has carried out in recent years in southern Norrbotten. The purpose of this investigation is to determine the relationship between the boulder trains /clastic anomalies and the mineralizations.

METHOD

The problem is a very considerable one, which this investigation has attempted to solve theoretically using an elementary knowledge of glaciology and of the mechanical processes of erosion at the sole of a glacier. In the cases studied, the glacier ice flowed over a variety of surfaces including bedrock, melt-out till and stagnant frozen moraine.

MATERIAL

Information collected in the field from systematic boulder tracing and the results of geochemical sampling are presented for seven different areas.

Two areas, Nimtek and Rebraure, lie between the ice-shed and the highest shore line in concave terrain with strongly disrupted moraine morphology. The moraines have marked contents of local rock material. The mineralized boulders, in both cases, lie in direct connection with the mineralizations. Geochemical sampling has also revealed strong anomalies immediately adjacent to the mineralizations.

Four areas, Skarjaviken, Labbas and Harrejokk which lie immediately east of the ice-shed, and Kikkejaure, between the ice-shed and the highest shore line, also lie in concave areas with variable moraine morphology and with marked contents of local bedrock material in the moraines. The clearly developed boulder trains, however, lie at distances from 50 to several hundred metres from

the mineralizations. Trenches dug in Skarjaviken and Labbas have also shown that the geochemical anomalies are separated from the mineralizations by distances of over 40 m in Labbas, and over 200 m in Skarjaviken. In Harrejokk, the boulder trains are not only separated from the mineralizations, but are also clearly restricted in length to approximately 300 m. The boulder train in Kikkejaure also has a distinct length of approximately 300 m, and is separated from the mineralization by several hundred metres. The clastic anomalies, however, lie much closer to the mineralization, although they decrease in intensity on the surface close to the mineralization.

One area, Tjärrovare, between the ice-shed and the highest shore line, is situated in convex terrain with an even and relatively thin cover of till. The content of local bedrock material is low. The boulders first begin to appear quite close to the mineralization, but are not concentrated. The boulders are thought to lie closer together in some places along the boulder train, but these concentrations lie several kilometres from the sub-glacial outcrop. The important feature here is that the boulder content seems to increase rather than decrease with increasing distance from the mineralization. This increase is also clearly apparent for the clastic anomalies, which are relatively weak and narrow close to the mineralization, but become broader and more intensive at a distance of 3 km. The anomalies disappear at a distance of 4 km from the mineralization.

RESULTS AND INTERPRETATION

Nimtek and Rebraure, with boulder trains which lie in direct contact with the mineralizations, have been interpreted as the result of compressive flow in a central position within a glacier. Compression was due to contact between a still dynamic, active ice and stagnant ice in a concave basin. The low speed and overall retardation and stagnation of the active ice caused relatively strong upwards transport of locally eroded material while removal of this material was negligible and the supply of long-transported material was very low. Erosion of the bedrock was very strong due to the relatively high pressure conditions which prevailed. The boulder trains, particularly in Rebraure, indicate that strong crushing of the bedrock took place because the prevailing pressure conditions resulted in shear stresses which exceeded the resistance of the fractured bedrock. The chemical anomalies in Nimtek also show that abrasion took place, due to appropriate pressure and velocity against the bedrock, until transport completely ceased. Both the coarse boulder material and the fine clastic material could be incorporated in the ice and transported because the existing pressure favoured both creep and regelation.

Skarjaviken, Labbas, Harrejokk and Kikkejaure, with clear windows between the boulder trains and mineralizations, and in certain cases also between the chemical anomalies and mineralizations, have been interpreted as the result of compressive flow in relatively thin glacier ice. Erosion and incorporation of material ceased while transport continued. The prevailing low pressure did not allow the development of shear stresses which would exceed the resistance of the bedrock. Poor pseudoplastic conditions prevented the incorporation of the coarse material into the ice. Boulders already incorporated, however, could be transported. The low pressure, in some cases, also inhibited abrasion of the underlying bedrock. The pore pressure in this environment probably had a marked effect on the low pressure, resulting not only in very weak abrasion while transport continued, but also limiting further incorporation of material by regelation. Material already incorporated, and possibly material with high pore pressure, could therefore be transported away from the source. In Kikkejaure, where the chemical anomalies lie fairly close to the mineralization but the boulder train is clearly separated, continued abrasion and incorporation of the fine fractions within the ice must have taken place while the coarse boulders could no longer be eroded and incorporated.

Tjärrovare, with its boulder train and chemical anomalies increasing in intensity at a considerable distance from the sub-glacial outcrop, is interpreted as the result of extending flow in the glacier ice, or at least high velocity relative to the underlying surface. Erosion, incorporation and transport of material were relatively constant. The high velocity resulted in a high level of transport, so that the moraine on the most convex parts of the area is thin. In the distal part of Tjärrovare, where compressive flow became dominant, material could be transported up and accumulated, and it is here that the anomalous material from the mineralization becomes apparent. The glacier ice eventually stagnated without affecting the convex terrain by any further processes.

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SGU = Sveriges geologiska undersökning

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The author wishes to draw attention to the following newly published book which makes an important contribution to this field of study:

SUGDEN, D. E., and JOHN, B. S., 1976: Glaciers and Landscape. A geomorphological approach. — Edward Arnold, London, 376 pp.

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