THE STRATIGRAPHY AND GENESIS OF STOSS- AND LEE-SIDE MORAINES

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Abstract. The surface forms and the inner construction of glacial deposits situated on the stoss- and lee-sides of rocks in western Sweden are described. In these positions, also deeply weathered rock material has been found, overlain by till.

The stoss-side moraines in front of steep rock walls, mostly greatly but sometimes incompletely glacier-eroded, are characterized by a hard ground till with foliation structures, slickensides and joints. In some places, tectonized sediments may be overlain by this hard ground till.

The stratigraphy of the lee-side moraines is more complex. Below the steep lee-side precipices that may be incompletely glacier-eroded and are instead more or less abraded by water, stratified sediments of silt, sand and gravel with down-glacier dip are overlain by ground till. This is intercalated by thin sand strata and lenses, and the boulders and stones lie in stable positions.

These formations are supposed to have originated beneath the inland ice in hollows and caves in the bedrock. As the ice grew thinner and thinner during the deglaciation, it gradually became incapable of fitting into its basement. Into the subglacial openings, debris was carried by running meltwater and till was successively detached from the basal layers of the moving inland ice.

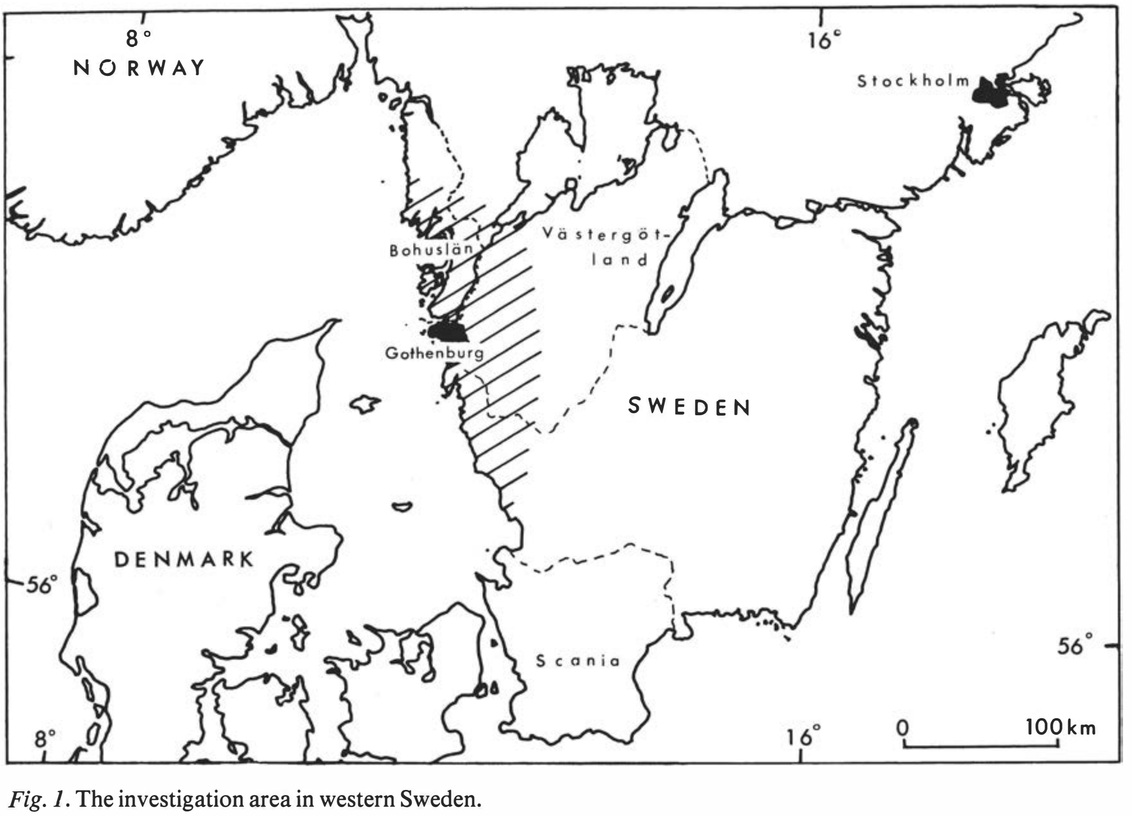


Fig. 1. The investigation area in western Sweden.

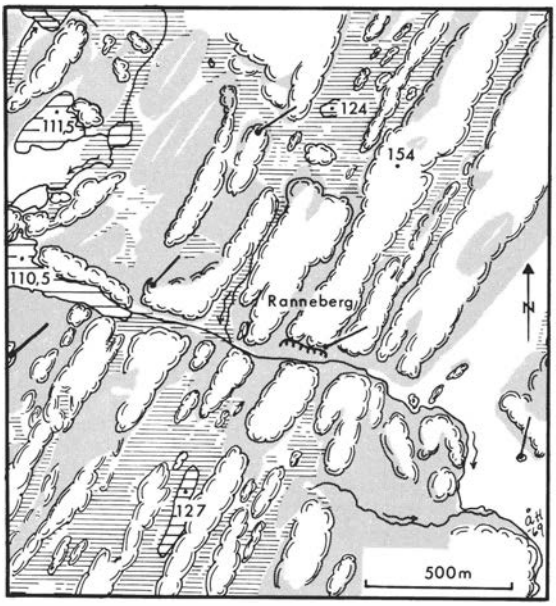


Fig. 2. Map of a landscape in southern central Bohuslän with stoss- and lee-side moraines and even drumlins. The bedrock consists of gneisses striking NNE.—SSW. and lies naked in wide areas. The valleys are to a great extent occupied by peat (= hatched areas) and lakes. The arrows denote the direction of the movement of the inland ice. At Ranneberg there is a gravel pit in a lee-side moraine. Here the ice has flowed plastically towards the lee position below the steep lee slope of the rock ridge. A deeply down-cut joint valley runs perpendicular to the direction of the strike. Cf. Fig. 5.

DEFINITION

The definition of stoss- and lee-side moraines is based on the positions of morainic deposits on the stoss sides and lee sides of obstacles to the ice movement. This movement has been determined with fairly great certainty in western Sweden, where the field studies of the glacial deposits in question have mainly been performed (Fig. 1). The obstacles consist of steep rock surfaces turned towards or away from the glacial flow. They may be of very different sizes, from small slabs to mighty convex vaulted *roches moutonnées* and whole rock valley sides.

The bedrock predominates in the topography of western Sweden and the glacial drift is normally very sparse. In some areas, however, there is a thicker cover of moraine. Then the stoss- and lee-side moraines give the landscape a striated or drumlinoid character. They may also gradually pass over into real drumlins.

SURVEY OF THE LITERATURE

The concept of "lee moraine" was introduced by Björsjö (1949, pp. 66—77) on the basis of studies carried out in the southern part of Bohuslän in western Sweden. Before that, Hessland (1943, pp. 18—22) had described related phenomena with hydrodynamically enriched coarse sediments of glacial origin along steep lee slopes in joint valleys in the northern part of Bohuslän.

From the vicinity of Stockholm in central Sweden, Möller (1960) has given a detailed description of stoss- and lee-side moraines which he thinks are better termed "moraines with sediment lenses". Möller was the first to discuss in detail the genesis of these morainic formations.

Gillberg (1943, p. 443; 1955, pp. 510—511) called attention to the stoss-side moraines and their transition into drumlins in his investigations of the southwestern part of Västergötland, which has a fairly thick moraine cover.

B.G. Andersen (1954; 1960, pp. 64—65), who has mapped the glacial deposits in Sørlandet (southern Norway), has called attention to the smoothing out of a rough rock terrain by stoss-side moraines, which are thus thickest in the lower (steepest) parts of the mountain sides.

In a series of sketches, Hellaakoski (1934, pp. 13—14) has presented the different types of drumlins in the Saima region in southeastern Finland. The types developed in connection with an increasing supply of drift from drumlin embryos on the lee sides of *roches moutonnées* into fully developed drumlins with rock cores.

In an earlier work, I have given descriptions of some localities with stoss- and lee-side moraines in western Sweden and discussed their origin (Hillefors, 1969, pp. 124—142). In this connection I have called attention to deeply weathered rocks in stoss- and lee-side positions. These phenomena are strange in a landscape which is otherwise predominantly characterized by glacial erosion and deposition. During survey studies in the southernmost part of Norway, I also found deeply weathered rocks below a thin till cover, i.e. stoss- and lee-side moraines. In this paper I have discussed more systematically the genesis of these features.

In North America and England, stoss- and lee-side deposits of glacial origin were described at an early date and were termed "precrag" accumulations (Chamberlin, 1888, p. 197), crags and tails or knobs and tails. The drumlinoid character appears in the term rocdrumlin (Fairchild, 1907, p. 393), which, however, designates the actual glacial eroding effect upon rocks and not the depositional activity of the ice.

OCCURRENCE

From the survey of the relevant literature, it can be seen that stoss- and lee-side moraines–often together with fully developed drumlins–occur in Sørlandet in southern Norway, in western Sweden, in the vicinty of Stockholm, in southeastern Finland, Scotland, Nova Scotia, etc. They are certainly frequent also in other areas but have not been closely studied. They appear both above and below the marine limit, like other glacially determined water levels, for example, ice lakes.

Here it may be appropriate to remark that the stoss- and lee-side deposits hardly seem to occur in Denmark, northern Germany or Poland, i.e. in fairly flat areas. Thus, as stated in the definition, quite rough, rocky or mountainous relief is a prerequisite for the formation of stoss- and lee-side positions, in order to obtain the form needed for these morainic features to originate. Drumlins, however, occur in both flat and rough terrains and this shows how complicated and manifold the depositional processes of the inland ices have been.

SURFACE FORMS

The *stoss-side moraines* form half-moon-shaped collars or borders in front of the steep stoss sides of rocks and mountains. In their most developed variety, they form a toe-cap-like, stoss-side drumlin. They may gradually pass over into large, vaulted, real drumlins in front of high rocks or mountains (Fig. 2). The ground surface is often characterized by boulders, most of which are firmly rooted deep in the concrete-hard till.

The *lee-side moraines* also form cone-like accumulations or borders below glacially plucked, steep, rocky slopes. They may also develop into lee-side drumlins in terrains rich in till. The ground surface is characterized by boulders lying loose, many of which were surely produced by frost bursting in postglacial times.

These morainic features are thus rather insignificant. But in areas, that are as poor in moraine as western Sweden, the lee-side moraines have played an economic role as gravel resources. For road construction, they provide a material that is self-draining and yet coherent. I have had the advantage of being able to study several gravel pits in lee-side moraines. The stoss-side moraines are mainly revealed by road cuttings.

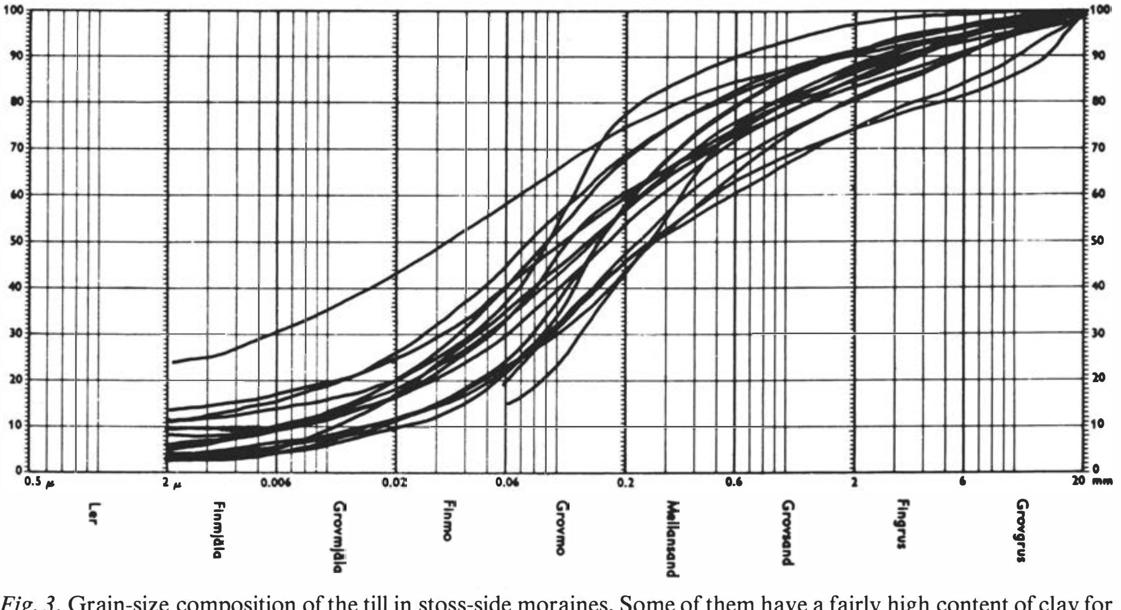


Fig. 3. Grain-size composition of the till in stoss-side moraines. Some of them have a fairly high content of clay for tills of crystalline Archaean rocks. Some samples have a little higher content of fine sand than others. The ice may have incorporated sandy sediments that were intermingled with crushed "normal" till. One samples shows an exceptional content of fines. This may be a special kind of till (cf. the paper by J. Lundqvist in this volume).

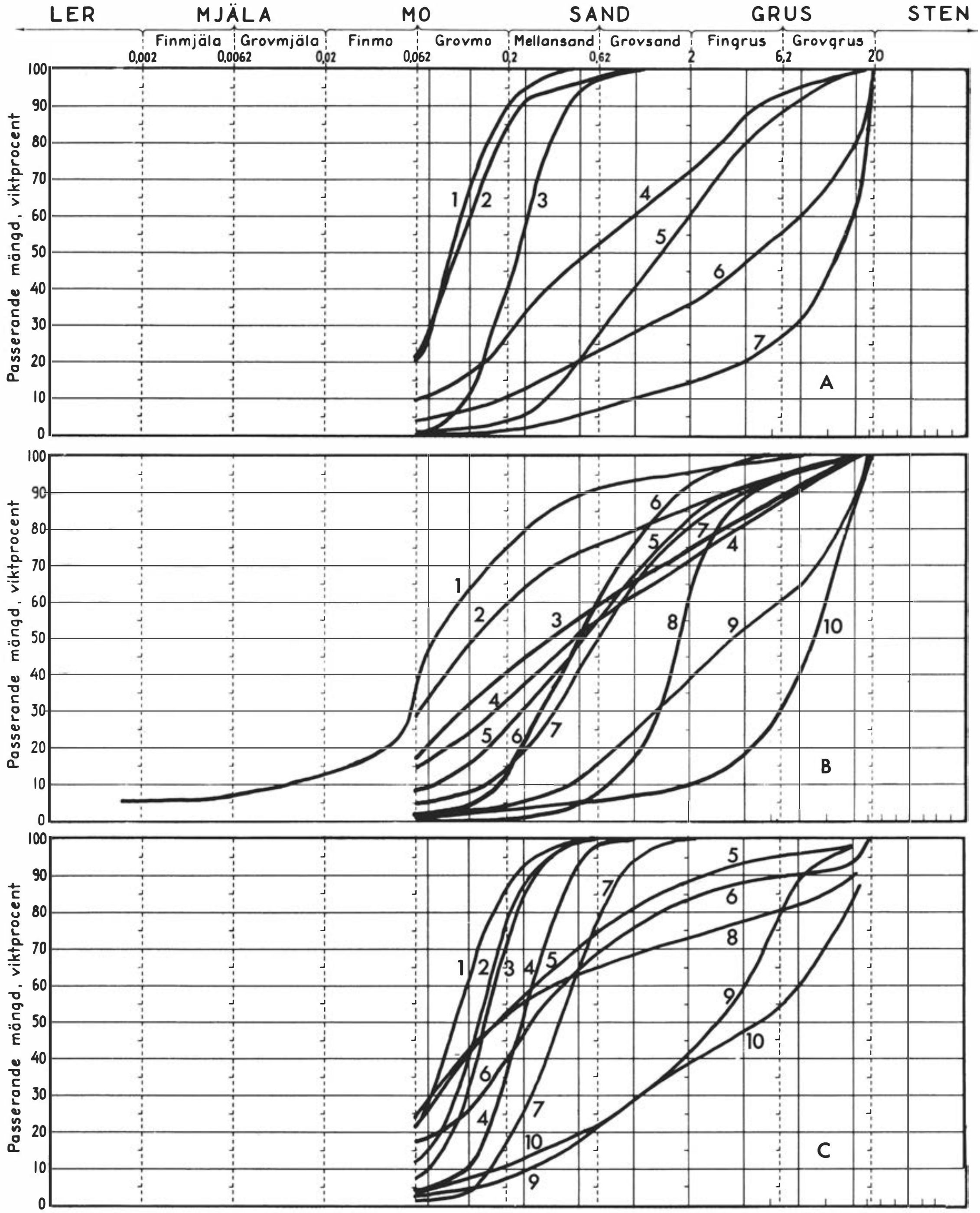


Fig. 4. Grain-size composition of different beds in three lee-side moraines: A, Västersjön in southern central Bohuslän; B, Mölnebo on the island of Tjörn in western Bohuslän, and C, Jättegrytsgatan in Örgryte, Gothenburg.

Well-sorted sediments and normal ground till occur, as do transitions between sediments and till, which may have been formed by basal till being washed by meltwater. The content of clay is mostly low, i.e. some 5 %.

STRATIGRAPHY

The stratigraphy of the stoss- and lee-side moraines has been studied at many localities and during different phases of exploitation, which has revealed their inner construction. Samples from till beds and sediments have been analysed according to the grain-size composition (Figs. 3 and 4). Some till-fabric analyses have also been performed (Fig. 5).

The *stoss-side moraines* show from the top downwards:

(*a*) Ablation till at levels above the marine limit; below this the till is wave-washed.

(*b*) Ground till, foliated, compact and with shear planes; in some places tectonized involutions or layers of sand appear within or below the till (Fig. 6).

(*c*) In some places a thin (3–10 mm) stratum of sandy, unsorted silt, firmly fastened to the rock surface, which is polished and scored by the ice (Fig. 7). This stratum may be lacking or have a discontinuous extension on the stoss sides. It may also be replaced or completed by thin, glacier-polished flakes of lime, filling out small (1–2 mm deep) unevennesses of the greatly glacier-eroded rock surface.

(*d*) In some places, deeply weathered or incompletely glacier-eroded rock, apparently in the most sheltered positions (Fig. 8).

The *lee-side moraines* show from the top downwards:

(*a*) Ablation till or wave-washed till (cf. above) (Figs. 9 and 10).

(*b*) Ground till, often fairly rich in boulders and stones that are stably layered in a sandy-silty matrix. The till is often stratified and contains lenses and thin lamina of sand and gravel. With an often very sharp contact, it is underlain by the sediments in (*c*) below.

(*c*) Sediments with layers of fine sand, sand and gravel, dipping steeply (40–60°) down-glacier or distally close to the rock precipice and dipping more gently (10–15°) further out towards the periphery of the cone deposit. Boulders and stones are common and appear unexpectedly in the stratified sediments (Fig. 11); even slabs and flakes of ground till may occur within beds of water-borne debris.

(*d*) Rock surface, partly glacially polished and scored—after being plucked—and partly abraded by running water; in some places deeply weathered rock has been preserved in the most sheltered positions and covered by till, as was the case below the stoss-side moraines. As yet, no section has been found showing till and sediments together, covering deeply weathered rock, only till-covered, deeply weathered rocks in lee-side positions. In some places, sheets or nodules of lime like "wall-paper" have been observed on lee precipices (Fig. 12).

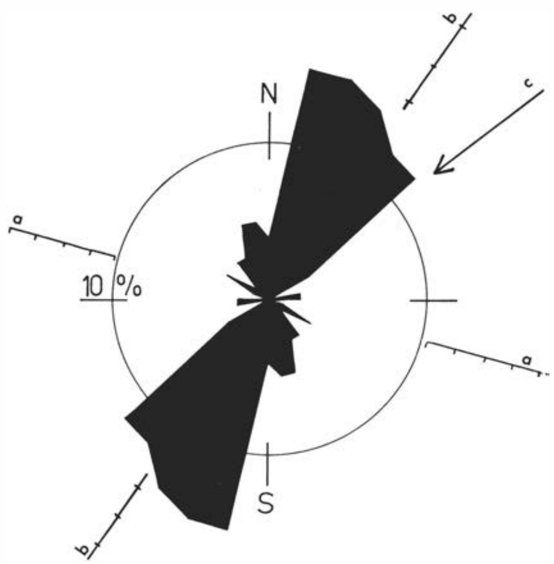


Fig. 5. Diagram of the orientation of long axes of rod- and blade-shaped till stones (100 measurements), Ranneberg (cf. Figs. 2 and 9). *b-b,* the direction of the structure valleys; *a-a,* the direction of the joint valley; *c,* the direction of the ice movement on the rock under the till. The ice accurately floowed the structures of the rock during the deposition of the till. Before that, it was able to glide into the lee positions.

GENESIS

The genesis of stoss- and lee-side moraines may be subdivided into stages that yield transitions into each other with or without sharp limits (Fig. 13, *a–d*).

The *first stage* comprises the glacial erosion of the bedrock, which includes the problem of why and how the deeply weathered rock masses were preserved in stoss- and lee-side positions.

The gneisses, granites, and greenstones have been transformed by the weathering into loose, clayey masses, several metres thick in joint zones. The content of kaolinite in these masses—determined by X-ray diffraction—indicates that the weathering probably took place in a humid climate and in an environment characterized by a low pH value. Though the content of clay minerals in several samples is rather low, this may be due to the fact that the weathered rock masses

Fig. 6. Stoss-side moraine resting upon an incompletely glacier-abraded rock surface. The till is foliated and shows joints and shear planes. The content of clay in the till closest to the rock was here 14 %, a very high value probably due to deeply weathered, clayey, rock material being incorporated into the till and to heavy comminution of rock particles. In the middle of the till cover, the clay content here was 5 %, a quite normal value. Peppared, Mölndal, to the S. of Gothenburg.

Fig. 7. An almost vertical stoss-side moraine, transverse to the ice movement and voered by a fine-grained (fine sand and silt), very hard till. This forms a plate crust that flakes off from the rock surface.

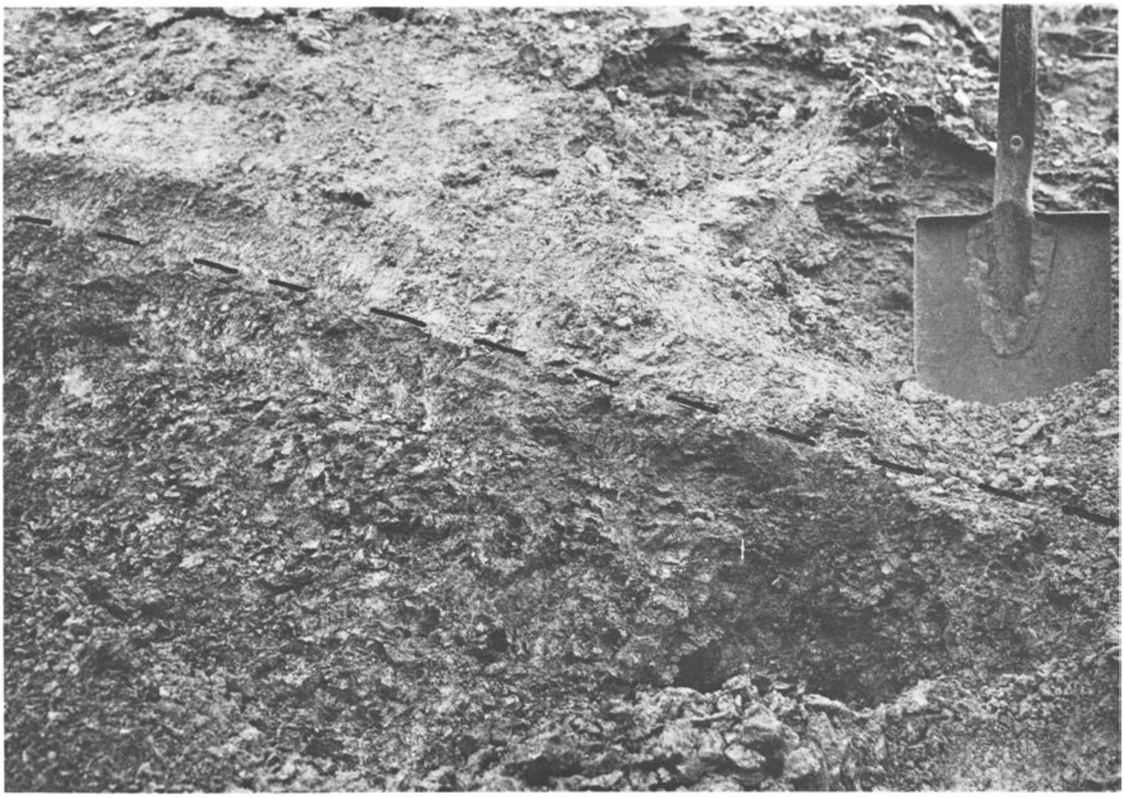


Fig. 8. Stoss-side till with a foliated structure (behind the spade) resting upon deeply weathered rock. A hatched line marks the contact.

Fig. 9. Lee-side moraine at Ranneberg (cf. Fig. 2). View towards the NNW., i.e. obliquely to the structures of the gneiss and the direction of the ice movement. The steep lee slope is 60 m high. Rock surfaces, ground and plucked by the ice, appear in the gravel pit. In the middle, a moraine that seems to be layered through the arrangement of the boulders and stones in rows. In this part of the pit, the orientation of the stone axes was analysed (cf. Fig. 5). To the left, a section of the lee moraine parallel to the ice movement (cf. Fig. 10).

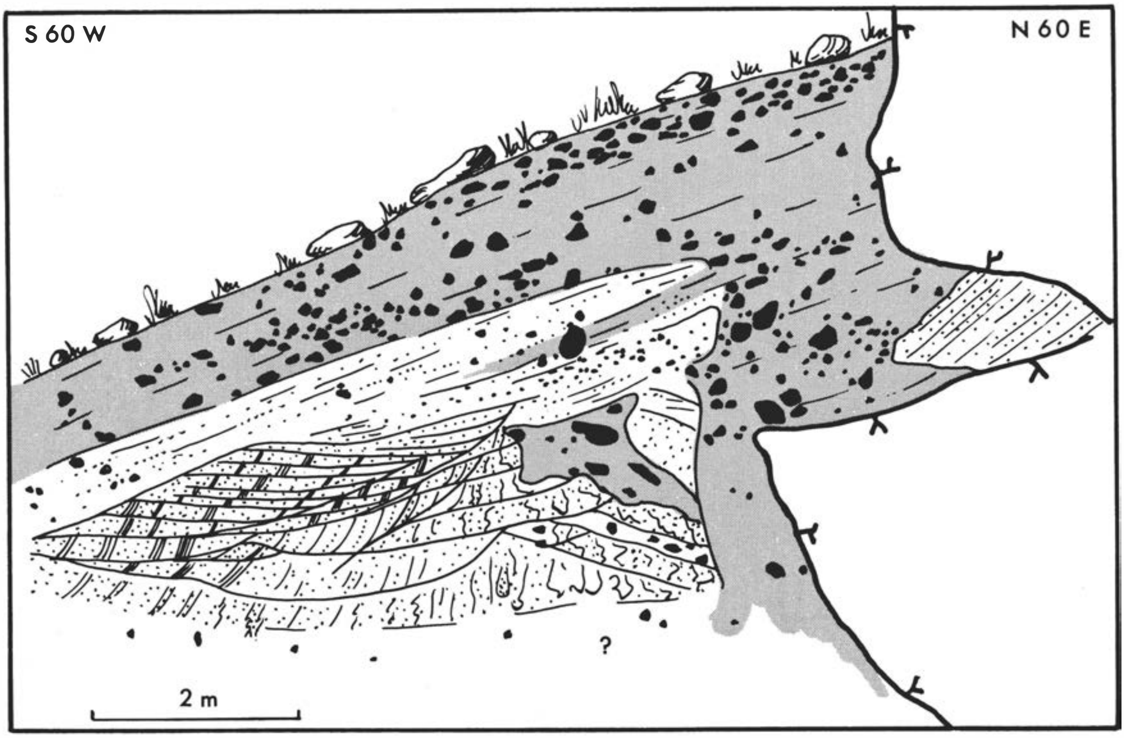


Fig. 10. The stratigraphy of the lee-side moraine at Ranneberg (cf. Figs. 2 and 9). The grey tone denotes till or till-like material. The lee slope of the rock is to the right. In a pocket in this lies a lens of stratified fine sand. The sediments have slid down out into the valley to the left. A lens of till has thereby been carried away. The sediments appear down at the bottom of the valley and lie also in direct contact with the lee slope deeper down, as was revealed by further cuttings.

Both the till and the sediments were often transformed into a conglomerate, cemented by iron compounds from the ground water, which, of course, exerts great pressure in these positions.

hitherto found represent the least transformed parts of the weathered bedrock, while the more transformed parts have been carried away. The till and the glacial clays do not contain any noteworthy quantities of clay minerals. Thus they have not been derived from weathered earth masses of clayey character. Instead they have originated by glacial crushing and abrasion, together with glacial and periglacial frost bursting.

The deep weathering of the bedrock in western Sweden can hardly have developed during an interstadial or even an interglacial. Firstly, these periods seem to have been too short, and, secondly, they did not have a climate that was very favourable to chemical weathering. The actual field conditions that reveal the postglacial weathering do not support such a dating of the processes (cf. Hillefors, 1969, pp. 80–83). The weathering thus seems to have taken place in preglacial times and is probably of exogenous origin. It may be contemporaneous with the weathering of the Archaean bedrock in the northern part of Skåne in southern Sweden, where it is of pre-Cretaceous age. However, endogenous origin is not out of the question, in cases in which the weathered material has been found in heavily jointed bedrock.

Each inland ice obeys the same laws of movement. The stoss- and lee-side positions did not change very much during the Quaternary glaciations, as the different inland ices seem to have moved in mainly the same direction, i.e. from the N.E. in western Sweden, as regards the radiation centre of the Scandinavian inland-ices and the distribution of indicator boulders in different drift beds in Denmark and Germany, for example, even if one takes into account the spreading of such debris by icebergs. As the loose, weathered, rock masses in stoss- and lee-side positions have survived the overriding of the last and apparently the most effective glaciers of the Würm inland ice, they probably survived even older inland ices. Though at least some of these ices had greater extensions than the last, they did not differ very much in thickness. This fact was of import-

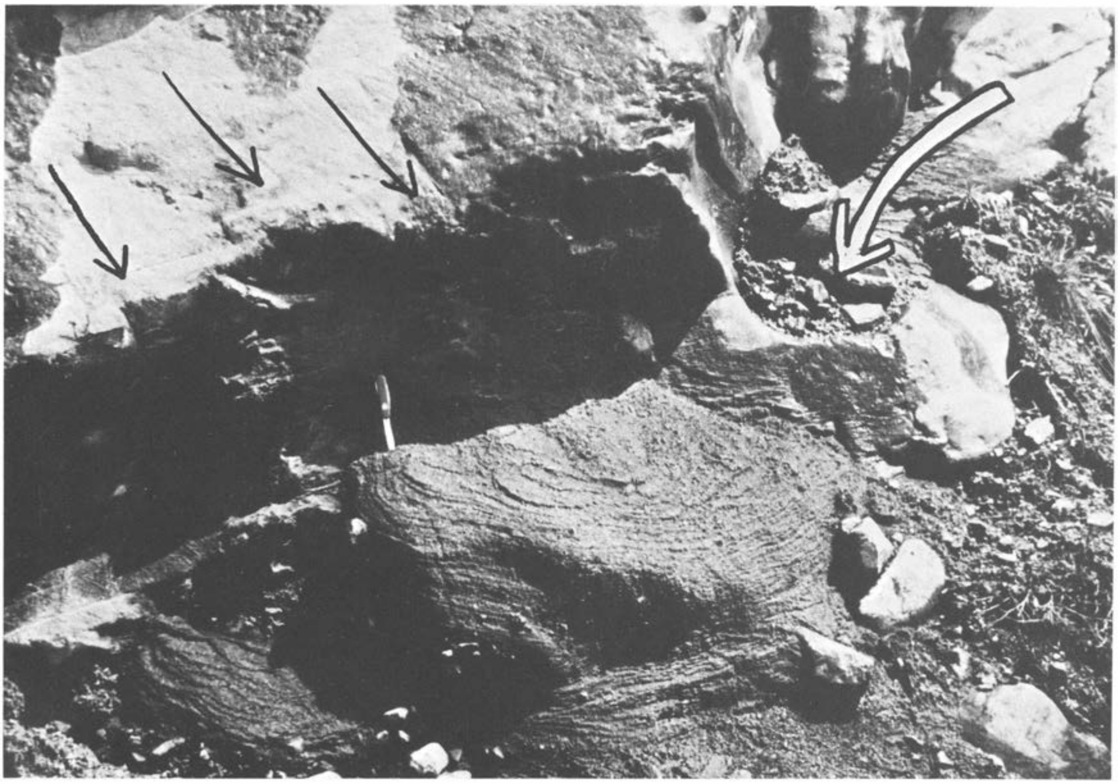


Fig. 11. Stratified sand, made hard as cement by iron compounds and situated below an overhanging rock. This has been plucked by the ice-shadowed surface against which the clasp-knife leans and was somewhat abraded by running water before the deposition of the sand took place. The very sloping rock surface on the top is striated (black arrows) and ground water oozes over it. Below the overhanging rock and behind the sand, an incomplete – or destroyed – giant kettle is visible (white arrow).

ance in connection with the glacial erosion and thus with the preservation of the weathered rock masses. The overdeepened fjords, however, seem to have been mainly excavated by the greater inland ices before the Würm glaciation, as interstadial marine clay, overlying fluvioglacial sand and gravel, rests upon the bedrock in the fjord-like Göta River valley in the vicinity of Gothenburg (Miller, 1964). The relationship with southwestern Norway is fairly close (cf. Mangerud, 1970).

The glacial meltwater erosion and the fluvial sheet erosion in a periglacial environment may have diminished the thickness of the preglacial, weathered rock covers considerably. But this erosion, of course, affected the more exposed parts first and foremost. The bottoms and especially the lower parts of the sides of the joint valleys were also sheltered from the erosion by running water as they were probably covered by fluviatile deposits alluvial fans when the first inland ice advanced. This began to remove the loose weathered soils and to uncover the hard crystalline bedrock. Each of the following inland ices had then to incorporate and carry away older glacial soils before it could attack the bedrock, which was gradually accommodated to the ice flowage. Thus, the probably preglacially weathered rock cover was gradually diminished by each glacial flow.

The glacial striation on the stoss- and lee-side precipices shows in detail how the ice flowed. It was not able to penetrate into the most sheltered places. Here, instead, meltwater polished the surfaces and washed away loose rock debris. Some rocky lee slopes indicate by their raw surfaces that the ice plucked away pieces. But then the ice was not able and/or had not time to abrade the newly exposed rock surfaces before it disappeared.

The theoretical explanation of the behaviour of the inland ice in the ice/substratum interface is given by the laws of ice flow (Glen, 1952 and 1955, and Nye, 1952, 1959 and 1965). Nye and Martin (1968) have made

Fig. 12. Lee side of a *roche moutonnée* with a crust of limestone. The coin, 24 mm in diametre, lies upon the ice-scored rock surface, here almost horizontal. The limestone was striated by the inland ice in its upper parts after its deposition or precipitation. In its lower parts and upon a somewhat steeper lee slope, its nodulous original structure has been preserved. This indicates that the crystallization took place from drops, probably around sand grains, in subglacial openings. The crusts of limestone can thus be paralleled with lee-side sediments. Västra Frölunda, Gothenburg.

important observations of the glacial erosion, which are particularly appropriate here to explain the preservation of the weathered rock masses and the striation of the stoss and lee-sides (Fig. 14).

The abrading meltwater flowed subglacially and under high pressure and in increasing quantities as the melting proceeded. It polished the surfaces, cut out grooves and excavated giant kettles in sequences and series. The kettles are especially frequent in the lee-side corners of rocks (*lähörnläge,* according to Johnsson, 1956, p. 161). Here also well-abraded and rounded stones and gravel deposits are found and they may have served as grinding tools, together with sand and silt (cf. Fig. 11). However, the giant kettles may have been formed first and foremost during a later stage of the deglaciation (cf. below).

In the stoss-side positions, plastically sculptured glacial forms, such as curved, polished and finely striated grooves and channels, oval troughs and the like, are to be found (cf. Johnsson, 1956, pp. 140–144; R. Dahl, 1965, pp. 122–124). The rock surface is normally also polished and smoothed by the ice, which was very deformable or "plastic". Diverging striation systems of up to 180° have also been noted. According to Nye and Martin's theory of the geometry of the slip-line field of the ice, such breaks in the relief may have been lodgements for immovable bodies of ice, overridden by moving ice. This phenomenon has actually been observed at a glacier terminus by Boulton (1970, p. 243). Thus a related hypothesis by G. Lundqvist (1940, p. 38) to explain the occurrence of different types of tills in central Sweden has been corroborated. Instead of subglacial "dead ice-bodies", remnants of deeply weathered rocks or older Quaternary deposits may have lain out of the reach of the eroding inland ice. Hitherto, however, no such beds or involutions of evidently much greater age than the normal accumulations have been found in the stoss- and lee-side moraines. Along the western bank of the Göta River valley, however, some drumlins, the so-called Dösebacka formations, have a very complicated stratigraphy, representing different glacial and interstadial stages of the Würm glaciation (Hillefors, 1969, pp. 34—93).

The *second stage* comprises the incipient deposition along stoss and lee-sides. In the stoss-side positions, the pressure of the inland ice on steep rocks caused the ice to melt when certain critical threshold values were reached. Out of the pressure meltwater, lime might be precipitated on the rock surfaces and remain protected in small cavities. But these thin coatings may also have been rapidly eroded or dissolved. This process is discussed in more detail by Kers (1964) and Samuelsson (1963).

When the ice melts in front of a steep rock wall, some heavily crushed debris may be freed from the grasp of the ice. The meltwater is pressed partly downwards and partly down-glacier or distally. But in the last case it could not disappear in any other way than around stoss-side corners. Together with the grains of clay, silt and fine sand expelled from the basal ice layers when they melted and produced the water, it cut grooves, throughs, channels and other p-forms, which perhaps in a later stage were glacially striated, widened and otherwise re-shaped or even destroyed. The fine-grained debris may finally have been deposited, forming a hard crust on the steep stoss sides and on boulders and stones.

Such crusts are not now found in lee-side positions. Here, instead, some of the pressure meltwater that was produced on the stoss sides was forced to run in a distal direction by the moving ice and, as the pressure here decreased, it re-gelated and then caused frost bursting. Some other parts, as already mentioned, sickered downwards through open joints in the bedrock. But, with the increasing ablation, the re-gelating process gradually diminished. This meant that small meltwater streams also appeared at the lee-sides. Contemporaneously, comminuted debris was released too and might be deposited beneath the gliding inland ice through small openings, where it formed the first sediment lamina of the lee-side moraines.

The existence of subglacial hollows and caves behind steep lee-side slopes is, of course, essential in this connection for the formation of the lee-side deposits, particularly their sediment cores. These hollows and caves will therefore be discussed in somewhat more detail.

Theakstone (1966) has described subglacial hollows in Østerdalsisen, which is part of the Svartisen ice cap in northern Norway. Here, tunnel-like caves under the glacier are formed as the glacier slides over a series of rock steps, equal to the lee-side precipies. Also Kamb and LaChapelle (1964) have observed how the basal layers of a glacier separated from the rock floor over a distance of about 10 m down steep bedrock slopes. Other glacier caves have been reported by Drake and Ford (1970) and Petersen and McKenzie (1968). Theoretically, Nye and Martin (1968) explain the existence of subglacial hollows and caves—both on stoss and on lee sides—by an enlargement of the radius of the cycloid slip-line field, caused chiefly by the decreasing ice thickness, which in its turn diminishes the friction and thus the temperature of the ice. In a simplified way, it may be said that the ice loses its ability to adapt itself to its substratum. Of course, it is the same glacial mechanism at work as in the case of the preservation of the deeply weathered rock masses from glacial erosion. The crusts of lime on lee-side rock surfaces also directly indicate the existence of subglacial openings by the micro-sculpture.

As these subglacial hollows and caves were opened by an "interaction" of the bedrock topography and the physics of the flowing ice, they must have been fairly stationary, a prerequisite for the formation of lee-side moraines and also for stoss-side moraines. But with small changes in the direction of ice flow, the ice thickness and the bedrock topography, they have been closed or changed in size, meaning that deposition by sickering meltwater must have interchanged with ice erosion, i.e. the carrying away of formerly deposited debris and even plucking and striating of the bedrock.

But evidently the ice grew thinner and thinner. The slip-line field then gradually changed, meaning that the cycloids had larger and larger radii. In the stoss-side positions, heavily crhused and comminuted basal till then was detached from the ice. The shear planes, foliation and die structures, joint planes and slickensides reflect the changing conditions when the stoss-side moraines were formed. Their compactness must be due to the fact that the pressure meltwater from the inland ice and possibly also from ice lenses within the till dissipated through the deposits and that a heavy, moving inland ice passed over them. The stoss-side moraines are thus built up of greatly over-consolidated till.

During this gradual deposition, the moving ice rested upon the convex shields and summits of the *roches moutonnées,* which were greatly striated, older striae revealing a more plastic, deformable ice and younger striae indicating a rigid ice with straighter trajectories (cf. Fig. 5).

Boulton (1970) has given a detailed description of stoss-side moraines *in statu nascendi* below glaciers in Vestspitsbergen. The foliation structure of the till shows

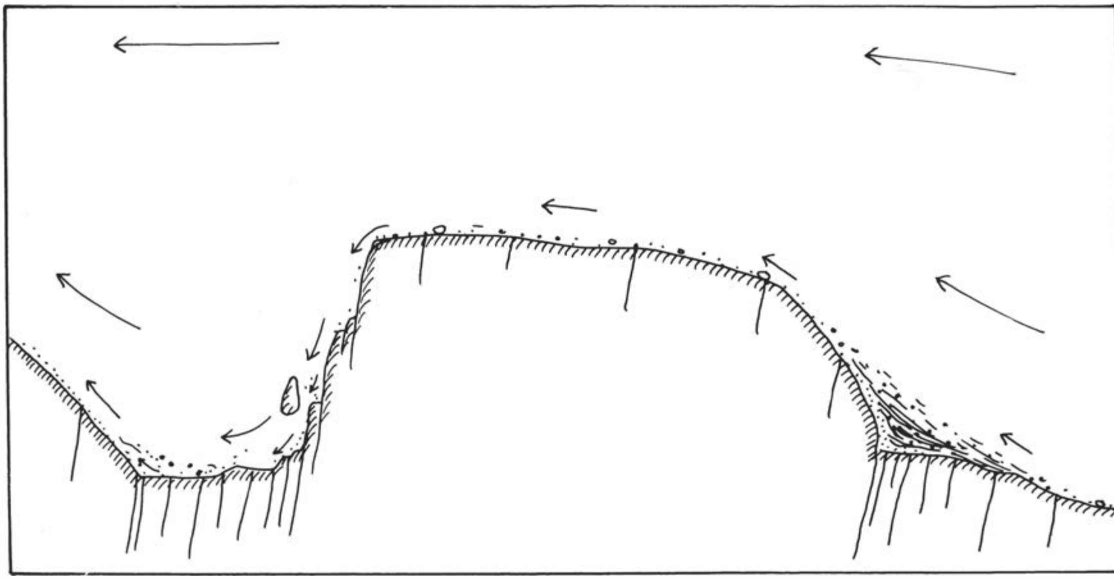
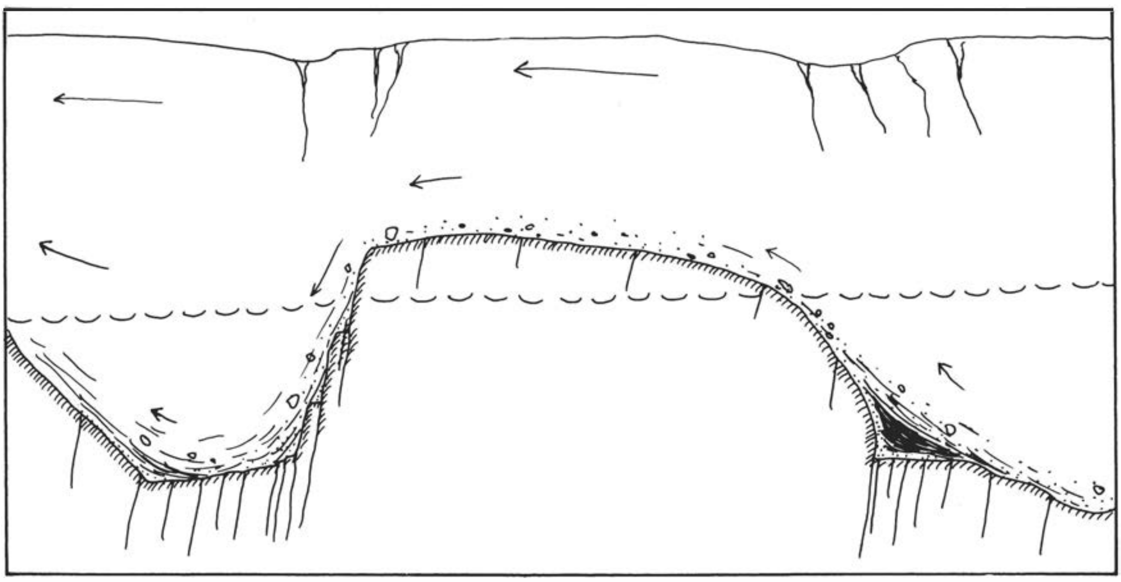
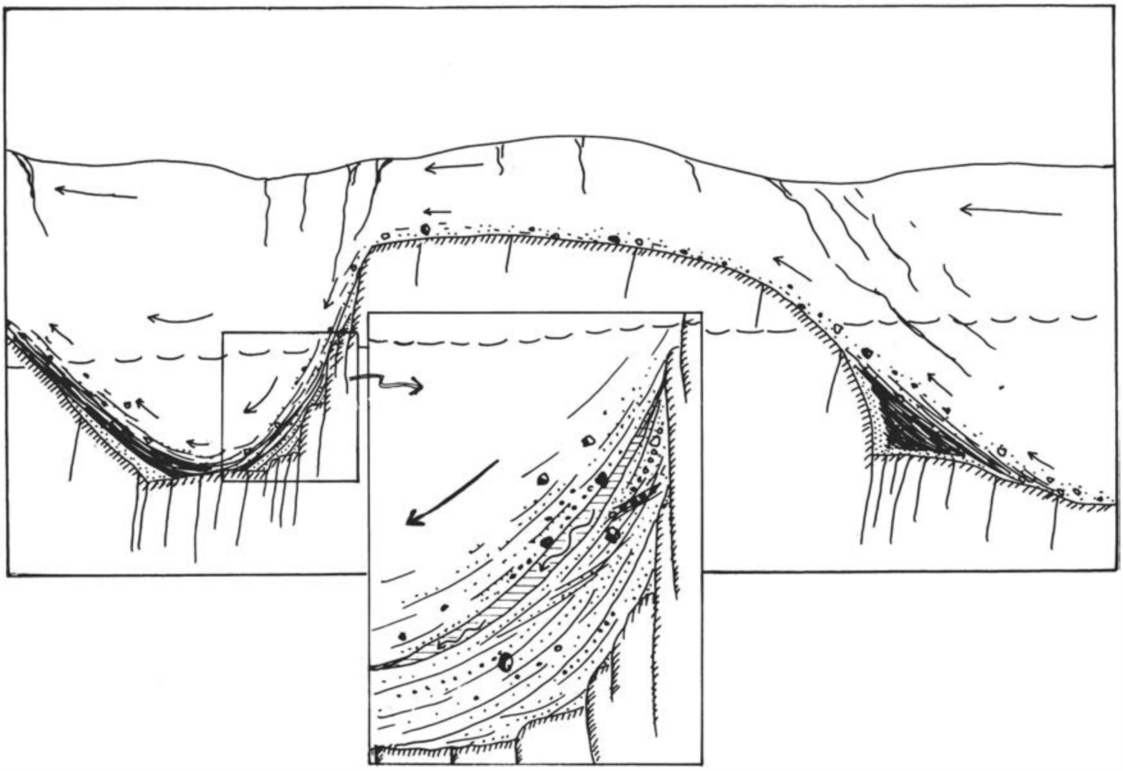


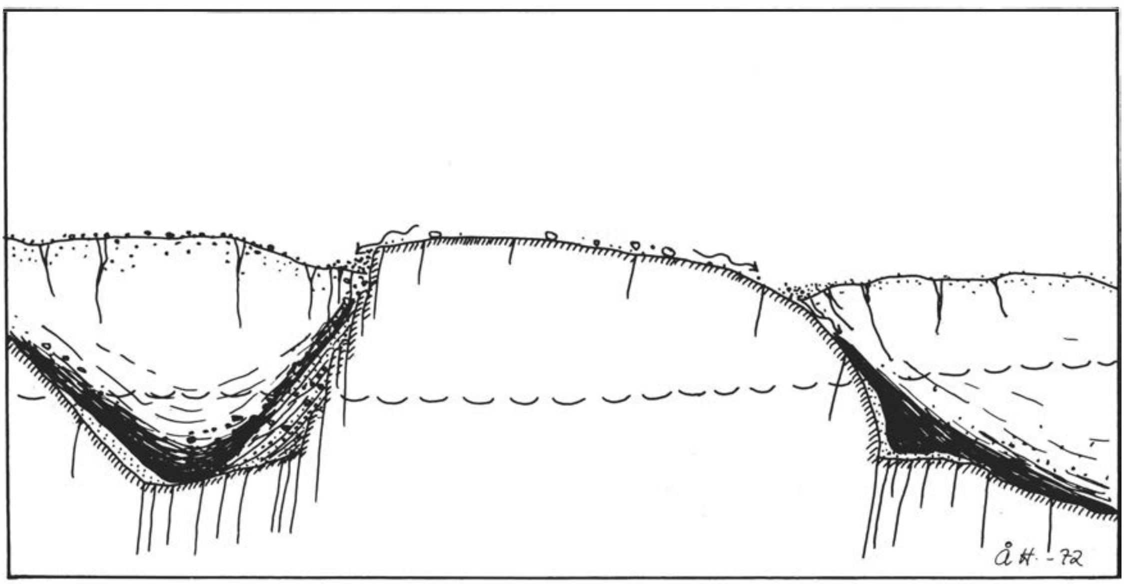
Fig. 13, a–d. Series of sections showing the formation of stoss- and lee-side moraines. Not to scale.
(a) The inland ice is thick. Pressure meltwater is produced in the stoss-side position. This water may here cut *p*-forms. The rock surface is striated by the till and frozen to the basal layers of the flowing ice. Fine sand and silt are released from the ice and form the crust on the steep stoss side (cf. Fig. 8). The meltwater produced runs to some extent to the lee side, where it freezes in joints and structure planes because of the lower pressure. There it then causes frost bursting. Long arrows indicate a faster-moving ice, shorter arrows a slower-moving ice.



(b) The inland ice has thinned. Compressive flow in the stoss-side position and extensive flow in the lee-side position cause crevassing in the ice, enlargement of the ice surface and therefore increased melting and also a corresponding bulging up over the bedrock ridge. The ice has more or less become temperate. Meltwater runs down from the ice surface and is also produced by melting of basal ice layers. A reservoir of ground water is formed probably at different levels. Its gently sloping surface is schematically marked by a curved, dashed line. The cycloids of the slip-line fields of the inland ice have increased their radii, which has led to basal till (and ice) being detached from the moving inland ice in the stoss-side position. The meltwater abrades ice-plucked rock surfaces in the lee-side position and crusts of limestone may be precipitated and thin layers of fine sand deposited. No accumulation of till in front of the more gently sloping stoss side to the left.



(c) The thinning of the inland ice has gone further and tension cracks have appeared in the icebulging up over the bedrock ridge. The deposition has also continued, resulting in thicker and thicker covers of till in the stoss-side positions and of sediments and till in the lee-side positions. The ground-water level is probably somewhat lowered. A detailed section has been inset, showing the subglacial hollow in the lee side with meltwater (hatched and with winding arrows) flowing and sickering in a distal direction.



(d) The inland ice has ceased moving and lies in the valleys. This situation is thought to have come about above the marine limit or at such high levels that the calving was of no importance. The till upon the surface of the freed rock is washed by meltwater streams (winding arrows), which are swiftly drained through the decaying ice.

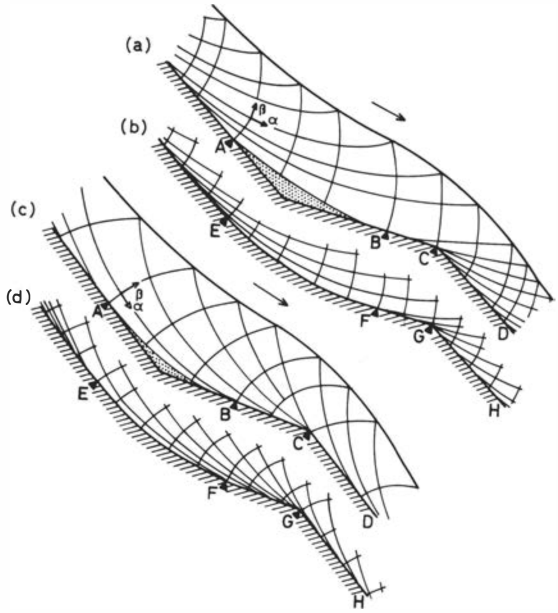


Fig. 14. Slip-line fields (not to scale). *(a)* Compressive flow, before erosion; *(b)* compressive flow, after erosion; (*c*) extensive flow, before erosion; (*d*) extensive flow, after erosion.
Compressive flow is in action along the stoss sides and extensive flow along the lee sides. This is the theoretical explanation of the preservation of the deeply weathered rocks in stoss- and lee side positions as the accumulation of debris in subglacial hollows. By the glacial plucking, "new" subglacial hollows and caves may be opened and may serve as depots for glacio-fluvial material and till. (After Nye and Martin, 1968).

how the grains of different sizes are arranged in accordance with the shear planes (Fig. 15).

As the till in the stoss-side moraines was heavily compacted, it grew brittle, and tension and compression cracks were produced in it as low-angle shear planes as a function of the ice movement over it. Both the till and the ice probably moved as "shear lenses".

In the lee-side positions, the deposition of water-borne debris continued as the openings grew more and more spacious with the gradual thinning of the ice. Now and then, stones were loosened from the grasp of the ice. They dropped down and were buried, quite unexpectedly, in the stratified sediments. The ice might also carry away sheets of debris that had occasionally frozen to its basal layers, a process which caused discontinuities in the sediments.

Even in the lee-side positions, isolated or debris-rich and thus slower-moving ice bodies may have been detached from ice situated higher up, which was cleaner and thus flowed more actively. These subglacial "dead ice bodies" may have somewhat hindered the continual deposition of debris, as in the stoss-side positions. The lack of lee-side deposits along some valley sides where they might be expected may be explained by such a subdivision of the ice sheet. The lenses and slabs of till which occur as xenoliths in the sediments probably originated through till-containing ice layers being detached from the sole of the flowing inland ice (cf. Fig. 13 *d*).

The *third stage* in the development of stoss- and lee-side moraines took place when the deglaciation had proceeded to such an extent that the actual places lay near the ice margin. During earlier stages, they had lain in more inframarginal zones of the ice sheet. It is impossible to determine more accurately the distance to the ice margin. Yet the place of formation of stoss- and lee-side deposits must have been situated in a zone where the ice was temperate, since cold ice cannot slide over its basement, nor striate it. Now, as has already been mentioned, the stoss- and lee-side moraines normally rest upon glacier-striated bedrock.

During the deglaciation phase, western Sweden was to a great extent isostatically pressed down by the ice and inundated by the sea. But some areas rose above the sea-level. The stratigraphy of the stoss-side and especially of the lee-side moraines was influenced by the hydraulic systems within the ice and consequently by the ground-water level, much like that of a karstic bedrock area; it could be regulated by the sea-level and/or by the levels of sporadic ice lakes. If there was a rapid lowering of the hydraulic pressure, as was quite natural in such an unstable drainage system as the englacial one, the ice might subside and this might lead

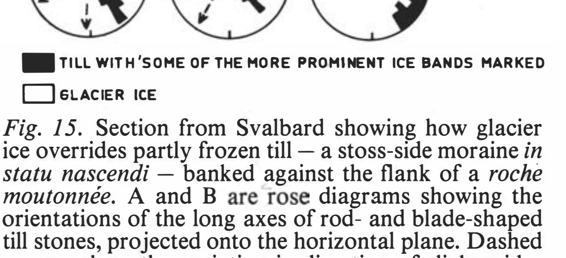


Fig. 15. Section from Svalbard showing how glacier ice overrides partly frozen till — a stoss-side moraine *in statu nascendi* — banked against the flank of a *roche moutonnée.* A and B are rose diagrams showing the orientations of the long axes of rod- and blade-shaped till stones, projected onto the horizontal plane. Dashed arrows show the variation in direction of slickensides on sub-horizontal shear planes at these two horizons, reflecting the direction of glacier overriding. C shows the orientations of 24 high-angle joints measured throughout the till. (After Boulton, 1970).

to the closing of lee-side hollows. Then the deposition of sediments ceased and might be replaced by glacial erosion or by accumulation of basal till.

If the caves were still open after a sudden lowering of the englacial ground-water level, the subglacial streams could carry away easily eroded sediment layers of the lee-side deposits, since the counter-pressure had decreased and the flow velocity must accordingly have increased. This might otherwise have happened without it being possible to map the process now.

It is very probable that the giant kettles and other glacial p-forms, especially cavettos, were formed by just such subglacial, rapid and short-lived streams, when ponded meltwater was suddenly released (cf. R.Dahl, 1965). Nor is it unthinkable that such features have survived from earlier glaciations (Hillefors, 1963, p. 35).

During this stage the conditions changed rapidly in other ways too. If layers of till were deposited during one phase of the building up of the lee-side moraines, thin strata or lenses of sand might be deposited in the next phase. This process might be repeated rhythmically, leading to the accumulation of the stratified till cover on the top of the lee-side sediments.

The ice moved during this stage too, but not very actively. The direction of movement might also change rapidly as a result of changes of the balance of the ice margin, caused by differential melting and disintegration. The existence of crossing systems of striae of different ages proves this fact. The stoss and lee-side deposits may thereby also have been eroded and decapitated. But it is difficult to demonstrate an undisputable connection between ice movements and special deposits or stratigraphic units. This has also been shown in recent glacier margins by Boulton (1970).

On the subsidence of the ice masses, the stoss- and lee-side deposits might yield to the pressure from the weight of the ice. This may now be indicated by the sliding phenomena observed in the sediments below the lee-side precipices. But, of course, such phenomena may also have appeared during any phase of the building-up stage of the lee-side moraines, because the depositions took place in steep layers and in an unstable environment, where the support down-glacier and towards the sides may have yielded at any time.

The *final stage* of the formation of stoss- and lee-side moraines took place in two ways, depending on whether the ice ended sub- or supra-aquatically. If the ice calved into the sea—as has already been mentioned, local ice lakes were of limited extents and duration in western Sweden—there was no deposition of ablation till, as this flowed away with the calving ice and icebergs. But such a till layer could really form when ice remnants with englacial and supraglacial debris finally melted in basins and below steep rock walls, as was the case in supramarine areas (cf. Fig. 13 *d*).

During the *epilogue stage* the stoss- and lee-side moraines were exposed to periglacial processes. Frost bursting thus resulted in the boulder-rich ground surface of especially the lee-side moraines below steep rock precipices close to and above the marine limit. The water-soaked, fine-grained, ground till in the stoss-side moraines probably slid and was smoothed out just by solifluction. It is also possible that it expanded somewhat when released from the weight of the inland ice, which may have caused the origin of some fissures which now serve as arteries to the ground water and in places give rise to difficulties in road construction, for example.

The deposits deeper below the marine limit were wave-washed during the Late Glacial and postglacial shore displacement. But these processes do not directly refer to the glacial morphology.

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