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WIND EROSION — PREPARATION OF MAPS SHOWING THE DIRECTION OF ERODING WINDS

Abstract

First the consequences of wind activity in the Swedish mountains are discussed. The most important one is snow drift, but wind erosion of the ground is also important in some areas. Wind activity, however, has not been much studied in the Swedish mountains, and a lot of problems concerning the subject have not so far been discussed at all. The author has dealt with two of these problems: the distribution of wind eroded surfaces, and, in the present paper, the direction of the eroding wind. The method of mapping the wind direction by means of the erosion features on the ground is discussed. The most important features are scars in the vegetation, distribution of lichens on boulders, and shrub vegetation on lee sides. Two maps from the Swedish moutains are presented, and for comparison a third map from Axel Heiberg Island, Arctic Canada. The influence of gravity winds seeems to be high in all the maps. The main purpose of the paper is to test the method. This is done by seeing if the wind arrows, based on the individual observations, give a reasonable picture when compared with our general knowledge of wind systems in mountains in cold climates.

GENERAL DISCUSSION

The importance of wind activity in the Swedish mountains is well known, at least as regards some of the most obvious consequences. The most striking among these is snow drift, causing almost snow-free areas on hill tops, ridges and spurs, as well as heavy snow drifts on lee sides, in gullies, and all sort of depressions connected with structural details of the outcropping rock or with the uneveness of the drift cover. The long lasting snow patches are the consequences of the prevailing wind and topography, and are found in the same positions in most years. Even on old photographs they have almost the same appearance as they have now. In any one area the snow fields face more or less the same direction. Very often they are influenced by winds from the west. It is quite obvious, that redistribution by wind is far more important for the long lasting snow than insolation and other climatic parameters. To the same category of features as the snow fields belong the small glaciers of the present, mostly belonging to the cirque type (Vilborg, 1962). According to the classical study of Enquist (1916) and modern revisions, based on aerial

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photos, by Schytt (1960) most of these glaciers are oriented to NE-E-SE. Of course the locations of glaciers are also intimately related to topography, especially with the high frequency of east-facing steep slopes. The influence of westerly winds on snow drift is, however, obvious — as are indeed the majority of large snow fields. In several parts of the Swedish mountains, cirques which had glaciers during the initial stages of the Quaternary glaciations, but are now empty, have the same orientation as the cirques with glaciers.

From a geomorphological point of view the redistribution of snow could be regarded as the most important wind activity, but it is not the only one. Evidence of wind erosion on the ground is quite common in certain parts of the mountains. Examples are wind scars in the vegetation, wind eroded areas on spurs, the development of shrub vegetation in close dependence on lee and windward directions, deformation of trees, preferred direction of lichen growth on boulders with almost lichen-free sides on the windward side etc.

In spite of the general importance of wind activity we have so far no comprehensive study of the features and the problems. The thesis by Samuelsson (1926) on the wind activity in the cold and temperate regions certainly also deals with the Swedish mountains, and most of the above listed erosion features are mentioned, but the paper is rather old and incomplete in its details and its discussion of the problems. Complementary observations are added in a popular and much read textbook by G. Lundqvist about the Swedish fjells (1949).

Several problems concerning wind activity in the mountains have not yet been studied at all, such as the eroding process itself and its possible tools, the amount of erosion, wind-borne sediments, the influence of animals, e.g. overgrassing by domesticated reindeers — which is possible. Also a lot of the indirect consequences are incompletely known, such as avalanches and — notably — nivation processes. These latter in turn are combined with „niveo-fluvial" processes, which have been just mentioned (Rudberg, 1954, p. 204) but never studied in any detail. We even lack any form of more detailed information about areas of strong wind erosion, about their regional occurrence and their possibly zonal distribution with altitude. Concerning the eroding winds we know only the general outlines, such as the high frequency of strong winds during the winter, and the general dominance of westerly winds, but we have no knowledge of the wind systems which are of importance for wind erosion in the mountains: their direction, seasonal variation, strength, or any possible pattern in their occurrence.

The author has paid some attention to wind erosion during other work in the mountains, mainly concerning two of the points in the list above: the distribution of wind-eroded surfaces in a mountain area, and the directions of the eroding winds. As to the first point, the mapping of surfaces revealing wind erosion was performed during the mapping of periglacial small scale features by student teams during 1960—1963 within a selected area in the Norra Storfjäll Mt., southern Swedish Lappland. After revision and supplementary observations in the field by the author a map was drawn, showing areas or zones of varying periglacial features more detailed than the normal subdivision into forest zone, tundra zone and frost shatter zone. In the lower part of the tundra zone the wind erosion proved to be one of the characteristic features, but not to the same extent in higher zones. The reason for this distribution is essentially edaphic. The wind erosion is mainly registered by the vegetation, by scars or lack of vegetation in otherwise vegetated areas. This type of ground belongs to rather dry areas, and the vegetation is of the heath type. On the wetter slopes higher up the dominating grass cover is more resistant to wind erosion, and in the highest zones the vegetation is too sparse to allow any mapping of wind erosion features at first sight. The prerequisites for wind erosion also involve geology. The wind erosion is found on hills and ridges of glacial deposits, and is specially well developed on eskers. Such forms are restricted to a low zone of the mountains, as the thinning out of the drift cover does not allow the formation of individual forms of any size with increasing altitude. The broad plateaux of cyclical origin, in detail often composed of groups of small hills and knobs, with free access for wind from different directions, are also mainly restricted to lower zones. Whether the eroding winds in just these zones are particularly strong, or even stronger than in other parts of the mountain, is an open question.

The map showing the zonation of the periglacial features is presented in another paper (Rudberg, 1966 in print).

The main topic of the present paper is the direction of the eroding winds, and if possible some information about their nature. From the widely separated weather stations, very few of which are situated within the mountain proper, no detailed data are obtainable about the wind systems of the mountains. We do not know whether the main wind system, including deflections caused by topography, is the most important, or whether some local type of wind system is still more important. From the snow drift the directions of the transporting wind during the winter could be learned in some detail directly in the field. Snow drift is already at work at such moderate wind velocities as 5—7 m/sec (Liljequist, 1962, p. 199), and some general ideas about the wind system in an area could be gained by observation in clear weather, allowing observations at some distance. About the snow drift in bad weather, which might certainly be the most important, only observations on single points are possible. The effects of the snow drift could more easily be seen from the results: from snow dunes, „skavler", or better from snow banks and snow patches. These latter could be mapped in early summer, when they are still present in all altitudinal zones of the mountains, or mapped from aerial photos, taken in the same season. As to the erosion features on the ground, however, it is possible but not to be taken for granted, that the same wind which is responsible for the redistribution of snow is also able to transport minerogenic matter.

One way to get the direction of the wind eroding the ground, is to use just the erosion features, as some of them may obviously give the wind-direction or can be assumed to do so. This method has been tried in two areas in the Swedish mountains: one in the Norra Storfjäll area in southern Lappland, where the mapping was done by the present author during the field seasons 1963 and 1966 (map in print 1963); the other in the Torneträsk area or Abisko area in northern Lappland, where a map was prepared as part of examination work by P. Magnusson 1966, a student of the Geography Department in Göteborg. Older than these maps, is a first attempt at mapping on Axel Heiberg Island in the Canadian Arctic, where the author, as a member of the Jacobsen—McGill expedition 1961, had to prepare a geomorphological map, showing the small-scale results of the morphological processes of the present. It was supposed that wind erosion would prove to play an important rôle among these processes. The three maps are discussed below. A part of the Axel Heiberg map, including arrows for the directions of the eroding winds, is printed (Rudberg, 1963). In another area, the upper Rhône valley, the deformation of trees was used by Yoshino (1964, with several references) for the mapping of dominant wind directions and of variations in force of the wind.

METHODS OF MAPPING DIRECTIONS OF ERODING WINDS

When mapping the wind direction by means of the wind erosion features on the ground a lot of features are used, of which some are well known, others are mentioned in the literature *en passant*, and a few may be new observations. For some of the features no other generating processes than wind erosion are possible, while others may be somewhat more problematic. The use of some of the features for getting wind directions is tentative.

In the Swedish mountains we have made most use of scars in the vegetation. Such scars are particularly common in areas with a vegetation of the heath type. The dimensions range from a few decimetres to several metres. The larger ones are especially found on glacifluvial deposits such as eskers and terraces. The smaller ones often occur together in groups, notably on dry spurs. One side of the scar normally has a notch, where the vegetation is undermined and in front of which the roots are laid bare and stretched more or less parallel to the ground. This notch is the place from which the erosion scar widens, if the wind erosion is at an active stage. The notch opens towards the wind as well as the normally concave intersection between the notch and the ground. The direction of the wind is to be regarded as more or less parallel to the axis of the concavity. A lot of observations are normally made at different scars on the same site to get the most accurate estimate of wind direction.

Boulders protruding from the ground on a wind-eroded surface normally have a far better lichen growth on the lee side than on the windward side, which might lack certain species or be completely bare. In the latter case there is normally a clear colour contrast between the two sides, a phenomenon which is described by, for instance, Samuelsson (1926). The direction of the eroding wind can be roughly inferred from the observation of a single boulder, but better still from that of many boulders in the same site. Boulders in the described position sometimes show wind scour or wind polish, probably caused by minerogenic matter, which is carried by the wind from the eroded surface in the vicinity and used as a tool (Lundqvist, 1948, p. 419). Observations of this kind, which are less frequent than other observations described here, have not been of importance in the construction of the maps from the Swedish mountains.

Other types of vegetation too are often better developed on the lee side of boulders. The local vegetation sometimes grows out like a tail behind a boulder, and in this case it is assumed to give a quite accurate indication of the wind direction. At certain sites the feature is quite common. On the windward side of boulders there are sometimes hollows, found at the base of the boulder, and eroded by wind eddies.

The shrubs which are normally found in several areas of the tundra zone, in this case notably *Juniperus* and *Betula nana*, are far better developed on lee sides of hills, spurs, sheltered valley sides etc. Sometimes this vegetation is cut off at almost exactly the same level as the nearby ridge or hill top in the close vicinity. The phenomenon is often described in botanical papers.

The birches of the upper forest zone, notably those which grow at

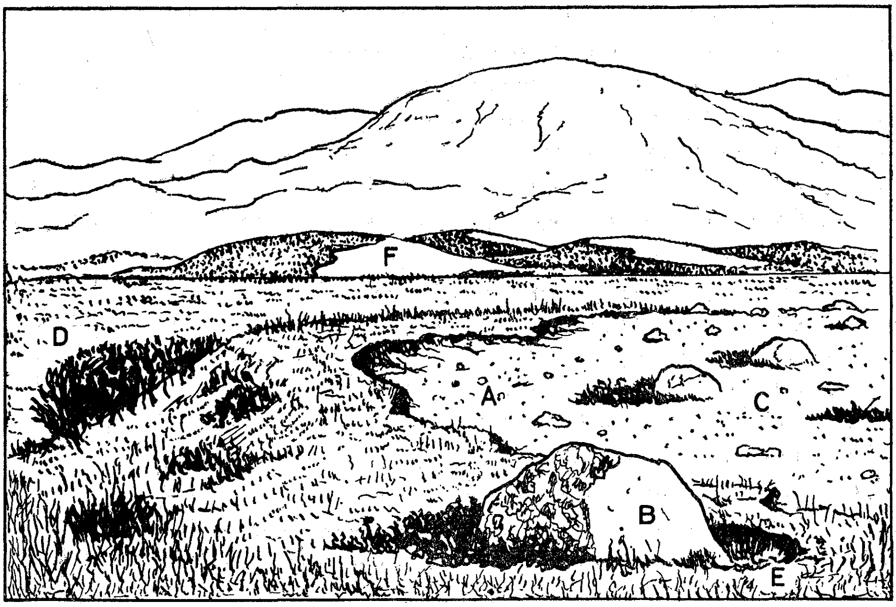

Fig. 1. Sketch showing typical wind-caused erosional features used for the determination of the direction of the eroding winds in the Swedish mountains

A — scar in the vegetation with concave fronts and notches; B — boulder with difference in lichen growth between windward side and leeward side; C — tails of vegetation in leeward position behind boulders; D — shrubs in a leeward position; E— hollow at the windward side of a boulder; F — broad eroded surfaces on he windward sides and the crests of hills built of glacial deposits (eskers)

some distance from other trees, are often deformed by the wind. Lichens growing on the birch trunks are sometimes absent on the windward side, obviously killed by snow drift (O. Pehrsson, 1965). Observations on tree deformation and other tree damage have only occasionally been of importance for the maps, as they mainly refer to the tundra zone.

On Axel Heiberg Island the indications of wind erosion were in part different, as the vegetation is far more scanty and gives a complete coverage only on small surfaces. Special features of this area are flutings or small scale grooves of the ground in places where the surface layers are rich in fine-grained material and the vegetation cover is intermittent. The flutings are sometimes connected witch notches of a similar kind to those discribed in the Swedish mountains. These observations where the ones most used in the construction of the map. Less frequent are localities with wind polish on outcropping rock or with grooves on gypsum outcrops. Earth hummocks are normally best developed on lee sides.

As mentioned above, some of the features used for getting the wind direction are somewhat hypothetical in their origin, and the wind is only the most probable generating process. Examples are to be found in some of the observations from Axel Heiberg Island. The only way to check the methods of constructing the wind direction maps is pragmatic. An examination of the maps will show if the construction looks reasonable in the light of our general knowledge of mountain climates in the mountain areas in question.

DISCUSSION OF THE WIND DIRECTION MAPS

In the following examination of the maps a few complementary remarks will be given about the main geographical features outside the mapped area. A comparison will also be made with available information about the snow drift.

The geometrically most simple wind system is that of the Axel Heiberg Island map. The valley in the center of the map is the Expedition River valley, which drains the melt water from the Thompson Glacier and the White Glacier. To the north of the mapped area is the main ice cap of the island, to the S at some distance the second ice cap in size. The Thompson Glacier drains the former ice cap, while the White Glacier and the Crusoe Glacier have draining basins of their own within the continuous ice field. The Thompson Glacier is by far the largest of the three outlet glaciers. It has a length of about 20 km, following all the way a marked valley with steep sides. the Expedition River valley (the main valley on the map) is a continuation of the Thompson Glacier valley. The wind arrows of the map follow the main valley, with a tendency to down-slope direction on some of the steeper valley sides. The Crusoe Glacier valley has not got its own wind system, and no local wind systems are developed through the valleys in the south, which lead over a peninsula to the next fiord. The wind on the map could most naturally be explained as the glacier wind, a gravity wind generated on the high ice surface and guided by the Thompson Glacier valley. The wind arrows on the northern side of the valley, having a tendency to a down-slope direction, could be influenced by the position of the main ice field, or the direction could be a sort of compromise between the glacier wind and the tendency of heavy snow--laden air to follow the easiest route.

About the comparison with snow drift it is difficult to make any statement, as the snow drift had obviously been of very little importance during the year, when the observations were made. No long-lasting snow patches remained after the main snow had melted. The aerial photos also show very little snow. At some sites it was found that minerogenic matter had been transported by the wind out on a snow cover. The wind activity in the mapped area, however, proved to be less strong than was

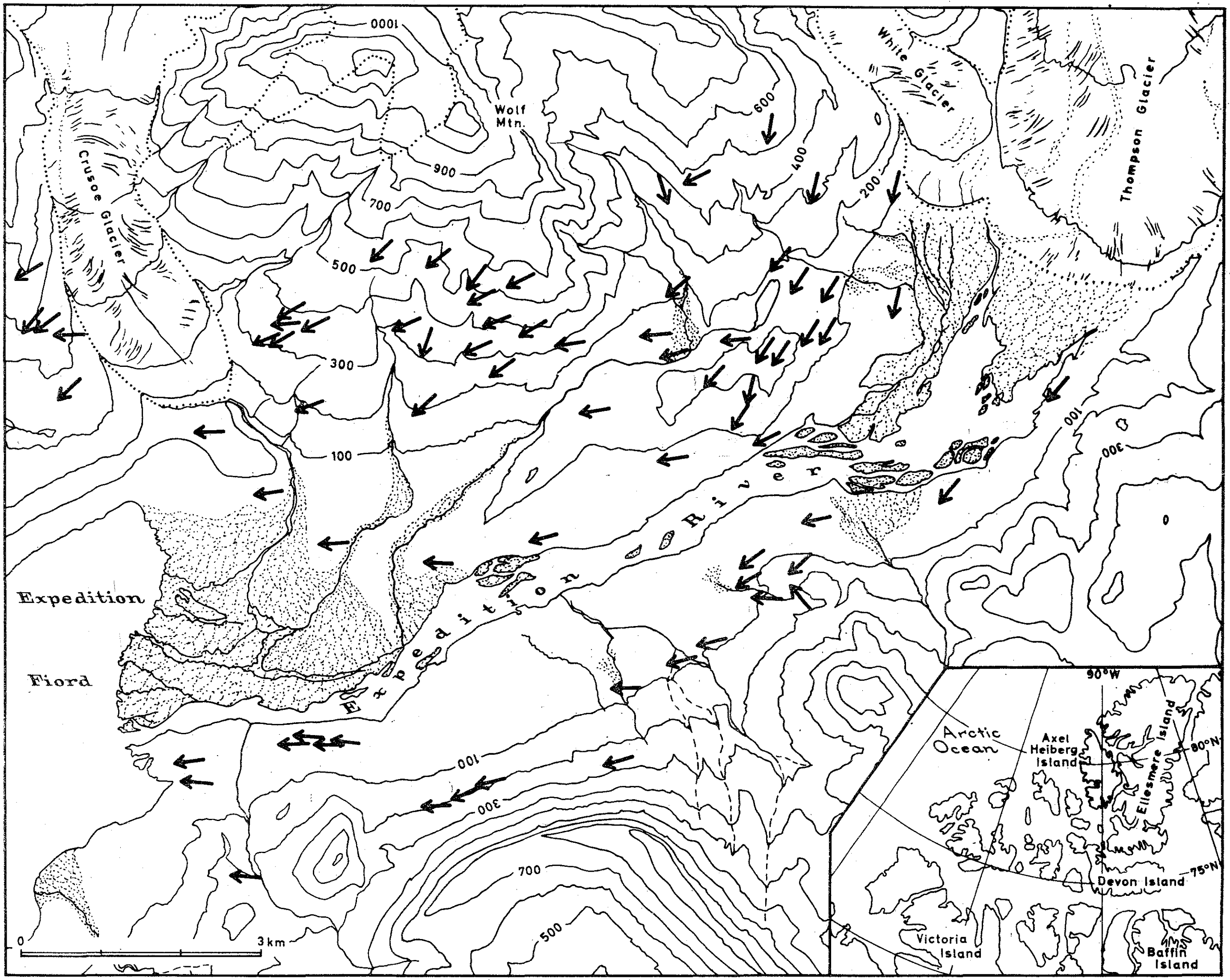

Fig. 2. Directions of the winds eroding the ground on Axel Heiberg Island, Expedition River area Field work 1961 by S. Rudberg

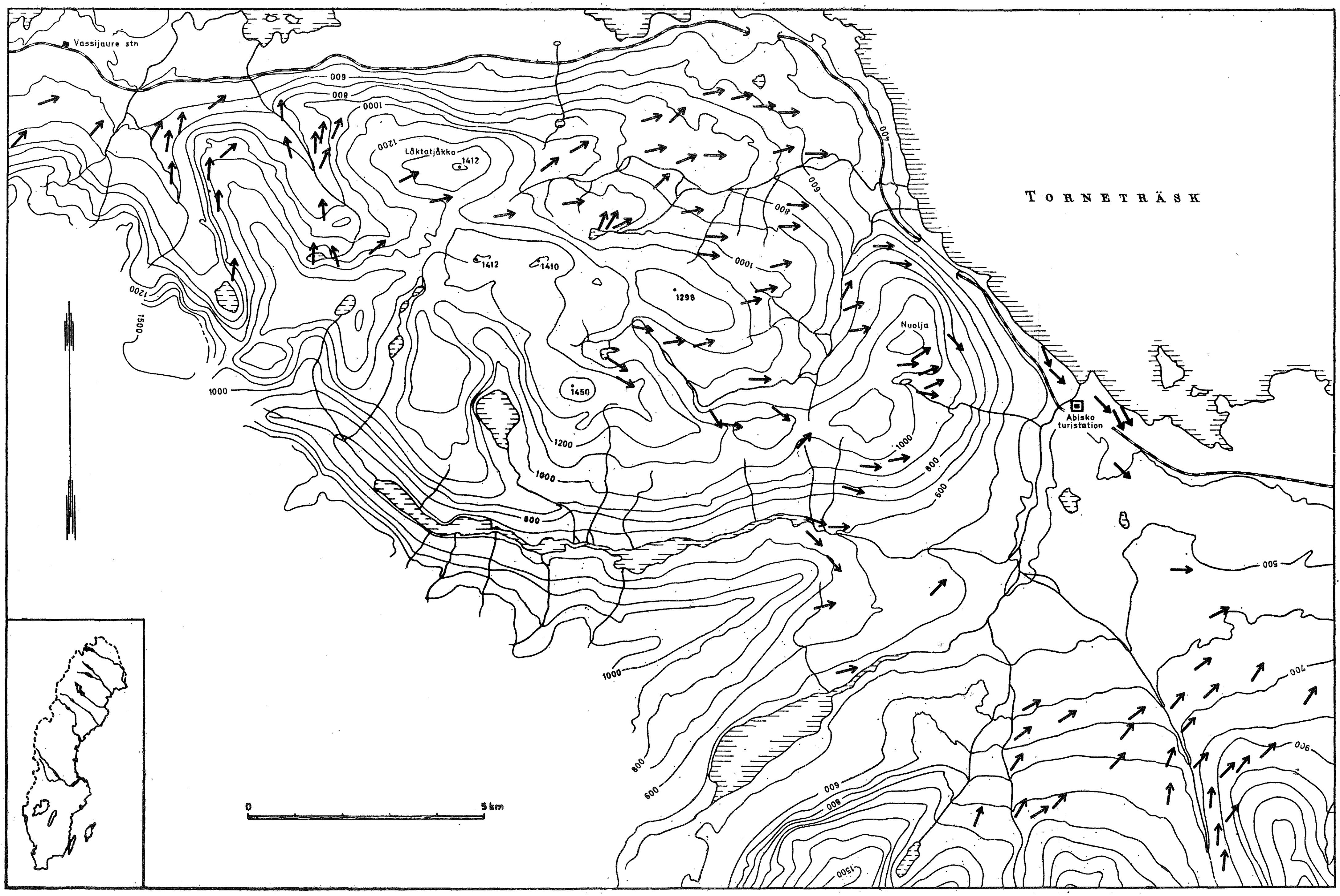

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Fig. 3. Directions of winds eroding the ground in the Torneträsk area, northern Swedish Lappland

Field work 1966 by P. Magnusson

expected. Strong winds were only observed in a few cases. The observed wind direction of the area was often the same as the arrows on the map. Other parts of the island, where large snow patches remain in the summer, obviously have more snow drift.

The wind system of the Torneträsk area looks more complicated. The topography has a simple outline, with the broad open valley of Lake Torneträsk, which is continued by a valley straight through the mountains, to the west, forming a break in the mountain barrier and a passage for the dominating wind from the west. To the south of the lake valley is high relief, with summits increasing from 1100—1400 m immediately south of the valley to about 1700 at some distance. Some of the summits are broad and flat, others show a more alpine topography. Wind from the west dominates the picture, agreeing with the principal features of the topography, but the exceptions are numerous. All tributary valleys of any importance have their own wind system in a down valley direction. In the most pronounced examples it is difficult to see these local winds as merely simple deflections of the main wind. It is thus probable that these valley winds are some kind of gravity winds, or maybe rather modifications of the normal westerly winds by gravity winds.

A comparison with the snow drift shows, for the northern part of the area, where a comparison has been possible, that the largest snow fields are in a leeward position to the dominatig wind from the west, apparently more consequently than the wind arrows indicate. According to field experience, however, some of the strongest deflections are also locally followed by the orientation of snow patches.

The wind system of the Norra Storfjäll area is the most complicated. The topography too could be regarded as somewhat more intricate. The mountains are divided in two parts by a straight U-shaped valley. The highest altitudes are situated close to the east, and the eastern slopes are very steep and not much dissected by tributary valleys, as are the western slopes. To the east of the area is a flat lowlying area; to the west the mountains are limited by the main valley of the Ume river, which has a valley bottom at 450—500 m. In the southern part it is broad and open, and is continued to the west by other open valleys and by low mountains giving a free passage for the winds from the west. The northern part of the valley is narrow and the terrain west of the valley is mountainuous, 1100—1400 m high in the immediate vicinity and considerably higher further to the west. To the north and south more open areas meet, but in both directions higher areas occur at a distance of some tens of kilometres, though these are lower than the mapped area. A few small glaciers occur in the Norra Storfjäll area, mainly on east-facing slopes.

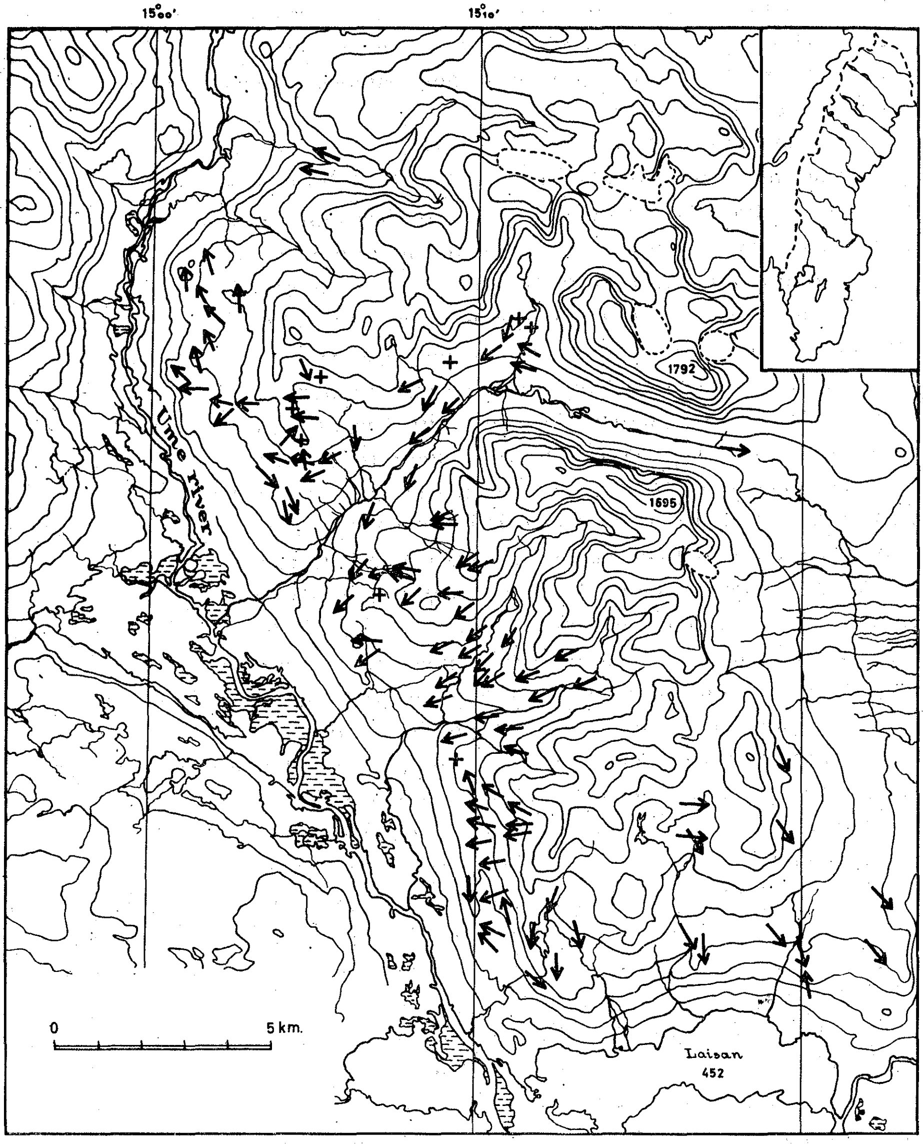

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Fig. 4. Directions of winds eroding the ground in the Norra Storfjäll area, southern Swedish Lappland

Field work 1963 and 1966 by S. Rudberg

No main wind direction is found on the map, which is dominated by the local wind systems. In the tributary valleys, irrespective of their direction, the main trend of the wind is in a down valley direction. On the eastern side of the mountain where the observations made are still few, the tendency is less pronounced. On the plateaux or bench land close to the Ume river valley the wind follows the plateaux, parallel to the valley, but in opposite direction in different parts of the mapped area. The wind directions of an important part of the mapped area could be explained as local deflections of a wind from E or NE, but not the wind directions of other parts of the map. The more frequent, often strong westerly winds can only be traced — directly or topographically deflected — in the wind arrows or a few places. Most probably the mapped winds are mainly gravity winds of some kind.

The relation between the mapped wind directions and the winds responsible for the snow drift in the form of remaining snow patches can quite easily be studied by means of aerial photos of all the mapped area. It proves that the winds responsible for the large snow fields and the snow cornices found on higher altitudes with a high consequence are W or WSW winds. The small snow patches in the lower part of the mountain, where the observations of the wind erosion were made, show a high variability in direction. These accord closely with the winds which are eroding the ground.

DISCUSSION OF THE MAPS

The first question is whether the field method of mapping is adequate or not. At this stage of the work — in the absence of all information on the erosion at work — the only test is whether the maps give a reasonable picture of wind systems or not. If we keep in mind that the mapped winds are the winds close to the ground, maybe in a thin layer of air, it can be stated that the map from Axel Heiberg Island shows the wind system which could have been expected according to previous experience of heavily glaciated arctic areas. As to the two areas in the Swedish mountains, the wind systems here are perhaps not the expected ones. The map from the Norra Storfjäll area in particular shows a marked contrast between the winds responsible for the largest snow fields and the eroding winds of the valleys. A gravity wind, caused by winds from the east, is not unknown in other areas. In some parts of northern Norway very strong winds are generated in the narrow Norwegian valleys, when cold heavy air passes the watershed from the east. The conditions here are in part similar. Perhaps — but this is only a possibility — the steep eastern wall of the Norra Storfäll mountain may act as a dam, producing a pulsatory strength in the wind.

Thus it would seem that the large snow banks and the wind erosion on the ground are not produced by the same wind — in all places. The former probably accord with the most frequent winds. Snow drift begins to occur at a wind speed of 5—7 m/sec. It is possible that the main work of redistribution of the snow is done by frequent and moderately strong winds, while erosion on the ground needs winds of a more exceptional force and these winds are possibly gravity winds, strengthened by topography and cold snow-laden air. As there is also good correlation between wind caused erosion on the ground and snow patches in the same local areas, it is probable that the wind erosion is done during winter, at least in part. Wind-blown material on snow is sometimes observed — but mainly vegetation detritus.

If this theory about wind erosion and gravity wind is correct, it gives some information about the climate in the mountain in question, which could be of practical interest. Whether the variations in the force of the wind could be learned from studies of the erosion in the tundra zone — much as Yoshino (1964) could read it from the varying degree of deformation in trees — is not known.

This study and particularly the climatic interpretation is to be regarded as a first approach.

The way of mapping strong winds and/or dominating winds by means of the vegetation is a method that can be used in other areas. In an unpublished paper made by a student of the Geography Department in Göteborg (Lindblom, 1964) the method was tried in the streets of Göteborg. The deformation direction of trees was shown by arrows, forming a system strongly influenced by the street pattern.

ACKNOWLEDGEMENTS

The author has had the opportunity to use an unpublished map by P. Magnusson, Göteborg. The observations for the map from Axel Heiberg Island were made when the author was a member of the Jacobsen — McGill Arctic Expedition 1961. The stay was sponsored mainly by different Canadian funds. The scientific leader of the expedition was prof. F. Müller.

ADDENDUM

Since the manuscript was finished a third map of a Swedish mountain area has been made by another student team (Bergenkull-Löfvendahl, 1967). In short the results are as follows. The mapped Helagsfjäll mountain is situated in the southernmost part of the Swedish Caledonides. It is an isolated mountain, 8 km in diameter, with a maximum altitude of 1.798 m. It is a rather compact mountain dissected by a few, broad, steep valleys, and it has a single deeply incised cirque with a small dwindling glacier, facing east. The surroundings form a flat open rolling landscape with an altitude of 900—1.200 m.

The wind arrows indicate local wind systems radiating out in all direction from the mountain following the valleys but also undissected slopes. Only in a few places they can be interpreted as the result of deflection of the frequent westerly winds.

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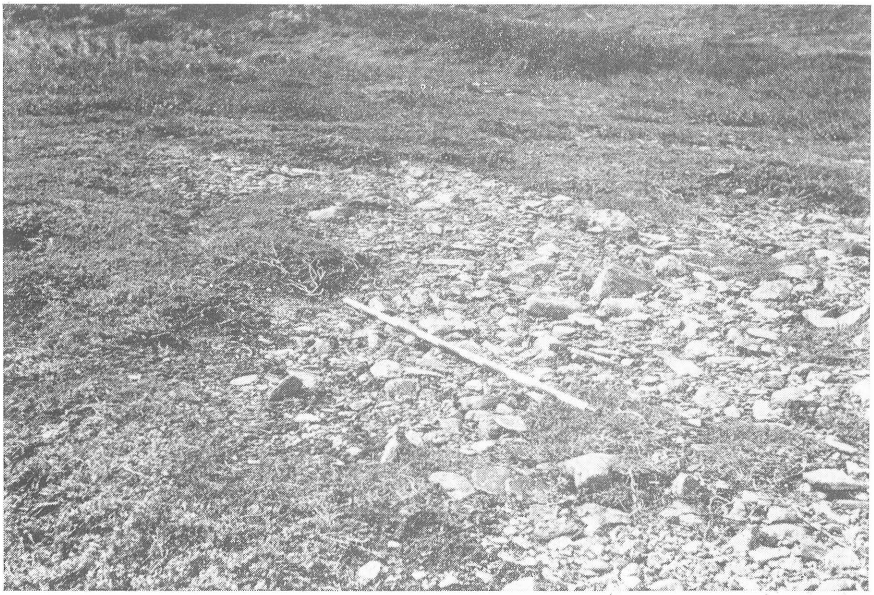
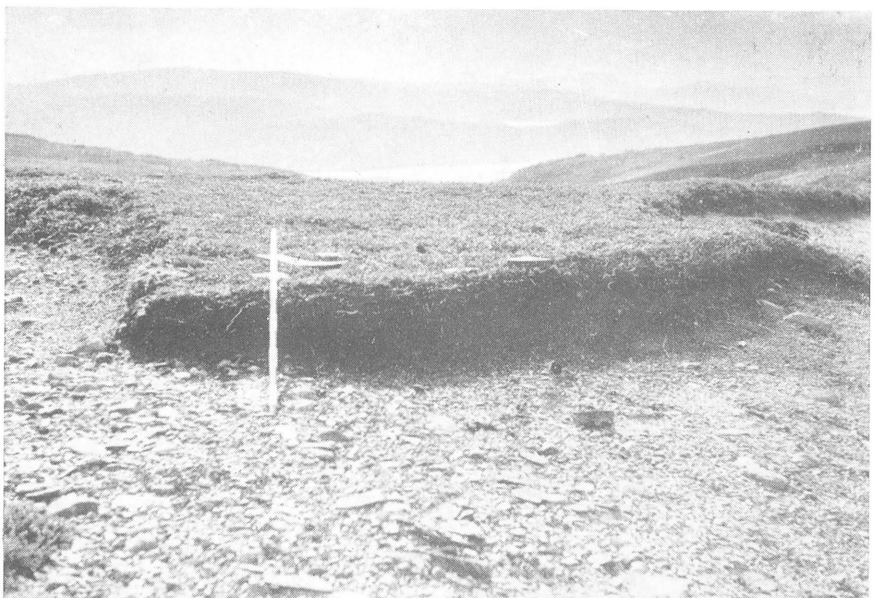
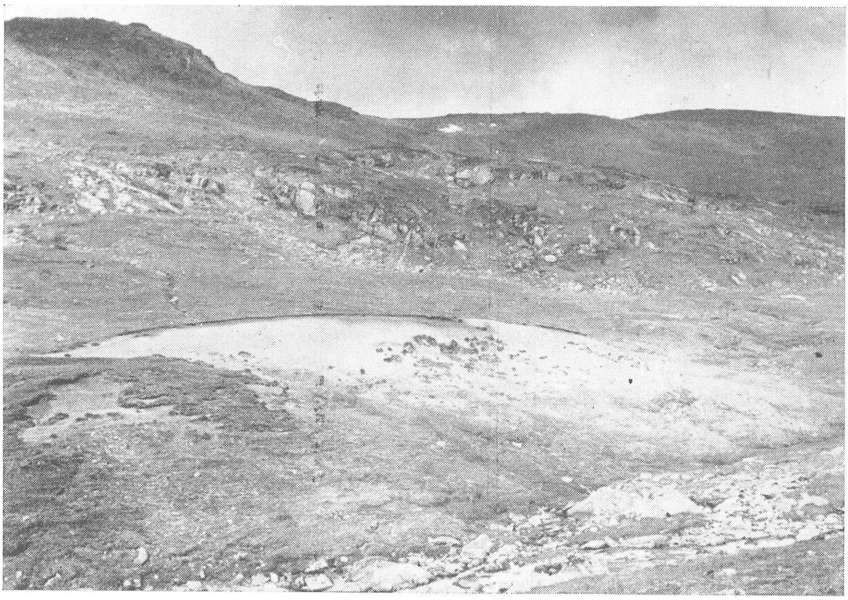
Pl. 1. Wind eroded scar on an esker. Mt. Pältsa area, northernmost Swedish Lappland



Pl. 2. Wind eroded scar in vegetation with notches and bare roots. Wind from the lower right. The Norra Storfjäll mountain, Sweden

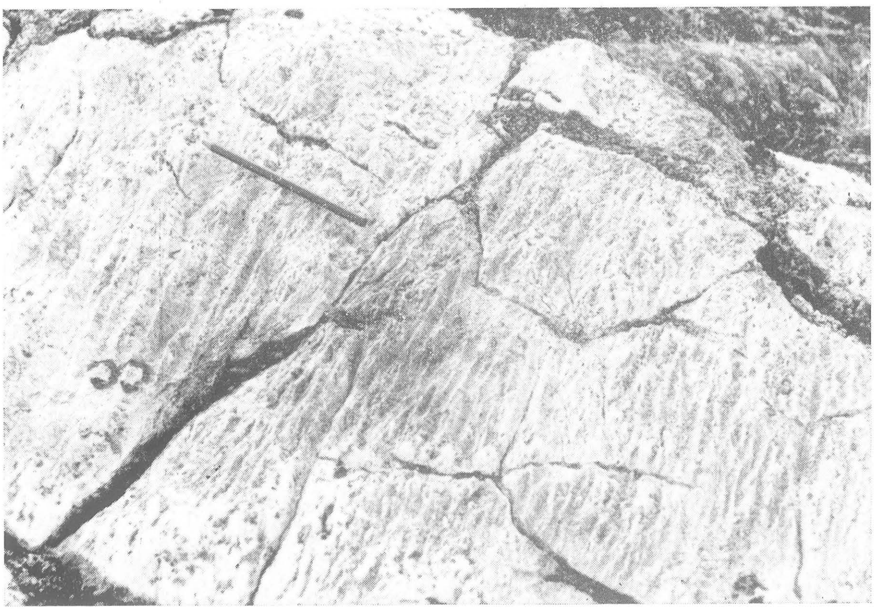


Pl. 3. Wind eroded scar with well-developed notch. The Norra Storfjäll mountain, Sweden



Pl. 4. Wind erosion on a small esker. Wind from the right. The Norra Storfjäll mountain, Sweden

Pl. 5. Flutings on the ground and small notches, interpreted as caused by wind erosion. Wind from the lower left. Axel Heiberg Island, Arctic Canada



Pl. 6. Grooves in a gypsum outcrop, interpreted as caused by wind erosion. Axel Heiberg Island, Arctic Canada