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PLANT IMMIGRATION IN FRONT OF RETREATING GLACIERS, WITH EXAMPLES FROM THE KEBNEKAJSE AREA, NORTHERN SWEDEN

BY ADELAIDE STORK¹

Introduction

In Scandinavia as well as in many other parts of the world the present-day glaciers are shrinking, leaving behind them large fields of fresh morainic debris. With the passage of time plants will colonize the bare ground, and after several centuries the vegetation cover will be continuous. This process of plant colonization and succession in front of receding glaciers as a function of the age of the exposed land surface is the subject of the present study. In the Kebnekajse massif, northern Sweden, the termini of several glaciers have been surveyed from photographs or from measurements in the field in relation to fixed points ever since the beginning of the present century. Such data are especially numerous for one of these glaciers, but only a little information is available as far as the others are concerned. The outermost moraines probably coincide with the position of the glaciers at their maximum extent in historical time, i.e. in the mid- or latter part of the eighteenth century, when Norwegian mountain settlements were buried beneath advancing glaciers. However, recent work suggests that the moraines were formed during an earlier ice advance (personal communication from Dr. G. Østrem).

It is hoped that different methods employed in the Kebnekajse area, described below, will aid in determining the length of time that morainic deposits in similar areas have been exposed.

Studies of recessional moraines. — A short historical review

Vegetational changes normally take place very slowly and in many cases are hardly discernible during a human lifespan. Only when a steril habitat is exposed—as after the retreat of a glacier, after the draining of a lake, or after a severe fire—is plant succession conspicuous and easily observed. Early field observations of plant communities in morainic areas were made in Switzerland about a century ago, after the withdrawing glacier snouts left barren tracts behind them. Later on botanists from other areas with glaciers have become interested in the colonization on the fresh deposits which glaciers produce, and during the last three or four decades observations have been made at an increased rate. In the Alps analyses have been carried out by many workers, for example Lüdi has devoted several papers to this subject (see Lüdi 1929, 1930, 1934, 1945, 1958). Another interesting contribution to the discussion of moraine age has been made by Beschel (1950, 1957 a, 1957 b, 1958 a, 1958 b, 1961 a, 1961 b) whose work on the rate of growth of lichens in the Alps, Greenland, and northern Canada has shown the connection between lichen diameter and the age of morainic surfaces.

In America botanists early showed an interest in plant succession, and this was developed especially by Clements (1916) with his concept of climax, the final, stable vegetation of a certain site. Since then American students have more or less left the mere botanical problem to consider the development of the substrate, the

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soil itself (cf. Cooper 1923, 1926, 1939; Crocker and Dickson 1957; Crocker and Major 1955).

In Scandinavia Fægri (1933) has thoroughly analysed the plant successions in front of Jostedalsbre, South Norway, the results of which will be referred to below. However, only a few investigations have been made concerning the flora, vegetation, and soil properties of the deglaciated tracts of the North Scandinavian mountain chain (e.g. B. and O. Almén 1959).

Successional problems also exist from a zoological viewpoint. Although few studies have been made, a thorough treatise by Janetschek (1949) gives an account of his work on the animal successions following deglaciation in the Alps.

Methods

In determining the age of morainic debris, i.e. the length of time the deposits have been free of ice, different methods can be employed. In certain cases it is possible to trace the annual retreat of a glacier from photos or records made by visitors. When such information is available, the different phenomena studied in a morainic area can easily be plotted as a function of time, thus permitting conclusions as to the age of end moraines or ground moraine flats that cannot be dated otherwise.

Plant communities. The first observations of vegetation on recessional moraines in the Alps (cf. Coaz 1886) were concerned with the distribution of different plant species and plant communities following deglaciation. The pioneer plants are species incapable of competing against any rivals or adapted to localities with disturbed soils. Here they find a bare site to settle on. Or they are species with mobile disseminules, spores, seeds or fruits, adapted so as to be easily transported by wind over vast areas. In analysing the flora and vegetation some sort of sampling is necessary. If the deglaciated areas are very large, the simplest method of studying the invasion is to choose small sections, quadrats, representative of different states of development. The vegetation is thus studied at intervals from the glacier snout outward, the sizes and shapes of the quadrats being chosen with regard to the extent of the area involved, its relief, and the density of the plant cover. In the Swedish mountain region where vast boulder-covered

areas with scanty vegetation prevail, a square of 2×2 m has proved to be most suitable. The sample plots are easily preserved for future studies by marking them out with stakes or dyed stones. A more detailed picture of the vegetation pattern can be obtained by another, more time-consuming method. From the ice margin to the outermost moraines the vegetation can be recorded along a line transect, either along a true line with no width or along a transect treated as a very long, narrow rectangle. In the present study the latter method has been chosen, using a line transect of 2 m width. In the field this transect was divided into sections, each 2 m long. In the case of Storglaciär (see below), two such lines were sufficient; another one gave no additional information. Such transects also can be marked out or mapped for future studies.

The type of plant species as such is not the only thing which can tell us about the stabilisation of the ground. With increasing age the plant cover becomes more and more continuous and the number of species increases, especially where subsoil water comes to the surface or near meltwater rills. The composition of the flora normally changes from a stage with mosses as dominants in the first stages to a normal composition later on. The rôle of the mosses as humus producers is very important but is in no way necessary for further colonization (cf. Palmer and Miller 1961 p. 75). In Scandinavia the moss successions are very conspicuous, however.

Even boulders and rock surfaces show plant successions of their own. The first colonizers are lichens, ordinarily crustose types. Later umbilical species (rock-tripes) appear, being succeeded in turn by other foliose lichens, the so-called reindeer-mosses (fruticose lichens) and mosses.

Lichenometry. The lichenometric method involves measuring the diameters of the biggest thalli of certain crustose and umbilical lichens in an area of known age. The results are plotted against time, yielding an age-size graph. Lichen diameters measured on undated but similar surfaces in the same area can be dated approximately by reference to the graph. The method has been developed mainly by Beschel (see above) and has also been tried by Fægri (1951). As lichens grow very slowly—many species extremely slowly (1 mm or less



Fig. 1. *Storglaciär* formerly had a larger extent than today. The terminal moraine is well marked by a row of huge boulders, at about 450 m distance from the ice snout. Presumably the ice stood with its margin at this point in the latter part of the eighteenth century. The large terminal moraines thawed out in the beginning of the present century. Now the ice is retreating rapidly, about 10—15 m per year. The line transects mentioned in the text cross the middle part of the the ground moraine area from the ice tongue to the terminal moraine. Photo V. Schytt 25 July, 1955.

per year)—this method is useful for periods of several decades or centuries.

Tree rings. In mountain regions where ice tongues reach below the tree-line the trees themselves may help in dating moraines. In climates with marked seasons growth is not continuous, and the result is that the wood contains zones of different appearance. By boring into a tree trunk the number of rings can be counted, thus giving the age of the tree. At higher altitudes willows may serve the same purpose up to the high mountain regions where no shrubs occur at all. In Alaska this method has been tried by Lawrence (1950).

Soil properties. Alterations in soil properties take place synchronously with the development and differentiation of the plant communities. When a glacier deposits till at its margin, organic content is absent or scanty in most cases. But after the till is laid down plants and animals colonize it. Their waste material contributes to the formation of humus, and organic material is transported onto the till by means of wind and water. As time passes a humus layer will form, and the amount of organic matter in the soil thus increases the

longer a surface is exposed. Likewise the nitrogen component accumulates in the same way as the main sources of nitrogen are found in living organisms. The very young soil is rich in mineral salts. But leaching and to a less extent absorption by plants soon remove them from the surface layer.

Soil acidity, too, can be used as an indicator of age, provided the parent material is the same. Freshly deposited morainic material has a very basic reaction, at least if it derives from basic rocks. But once an area of moraine is exposed, agencies such as rain and meltwater leach the till, making it more acid.

Animal succession. Animals also colonize morainic debris close to the ice snout, and a faunal succession will be found similar to that of the flora. The same methods of sampling may be employed in gathering material.

The methods dealt with above are each by itself uncertain and sensitive to local environmental factors such as varying supply of water and nutrients, exposure etc. Not by *one* isolated method can we get reliable information

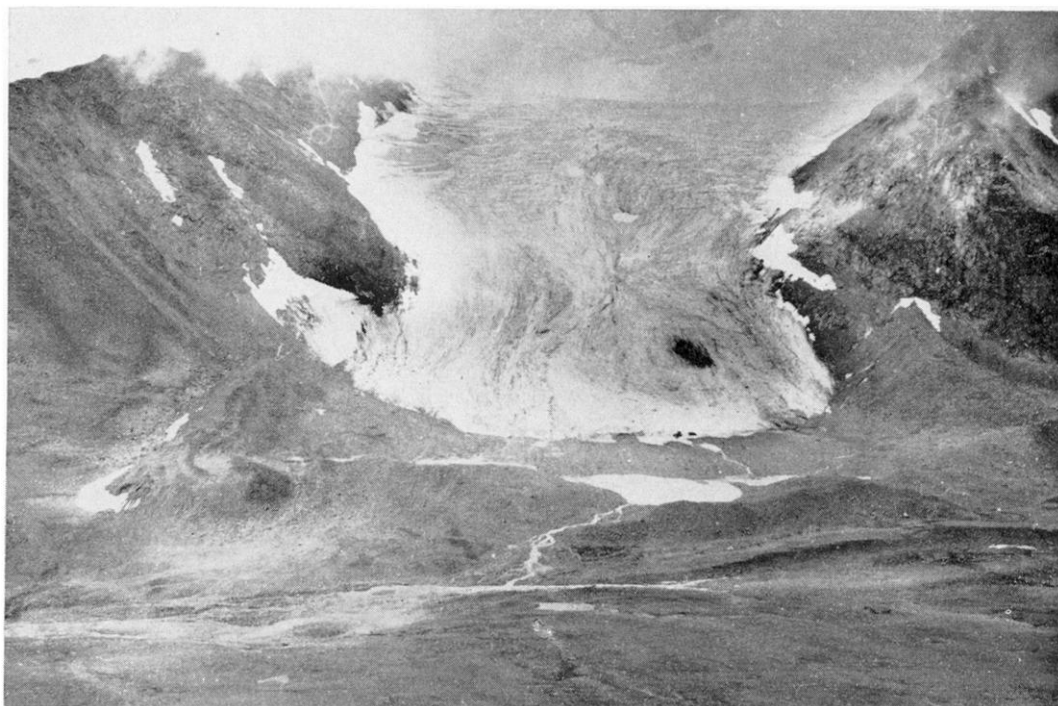


Fig. 2. *Isfallsglaciär* is situated about 1 km to the north of *Storglaciär*. The morainic area left bare behind the retreating ice shows a complicated pattern of moraines, especially in the northern part (to the right in the photo). The nunatak is seen as a dark spot in the ice (to the right). Photo 26 July, 1961.

about the age of the morainic surface. Different methods must be combined to elucidate the problem and to permit any conclusions concerning the age of the deposit to be drawn.

The study area

Much of the present investigation has been carried out on moraines in the Tarfala valley in the eastern part of the Kebnekajse massif. This north-south valley contains end moraines produced by glaciers in three tributary valleys on the west side. The three glaciers are shrinking rapidly but are still active. *Tarfalaglaciär*, also discussed below, is a small, rather inactive glacier in the northeastern corner of the massif.

Storglaciär, the southernmost and largest of the three glaciers flowing into the Tarfala valley, occupies an area of about 3 square km. Its front is at an altitude of about 1,100 m above sea-level. As mentioned earlier the glaciers in Sweden have been receding rapidly since the 1920's, leaving behind them large disorganized masses of morainic material. At

that time the large lateral moraines thawed out. The outermost terminal moraine, at about 450 m distance from the ice margin, was probably ice-covered during the maximum extension in the eighteenth century, but was presumably formed earlier (cf. the introduction). The rather smooth topography of the ground moraine is disturbed here and there by rivulets transporting meltwater. The distal part of the morainic area is somewhat higher and is very rich in boulders. In places a prominent end moraine of boulders is present (Fig. 1). A good part of the fine material has been carried away by meltwater and rain. The inner or proximal part, a gently sloping surface facing east, is almost devoid of vegetation, whereas the outer half is more vegetated, and the ground between the boulders of the terminal moraine having a continuous cover. The recession of *Storglaciär* is well documented since about the turn of the century from the accounts of visitors, by photos and maps, etc. The present study chiefly concerns the moraines of that glacier. Two line transects are located

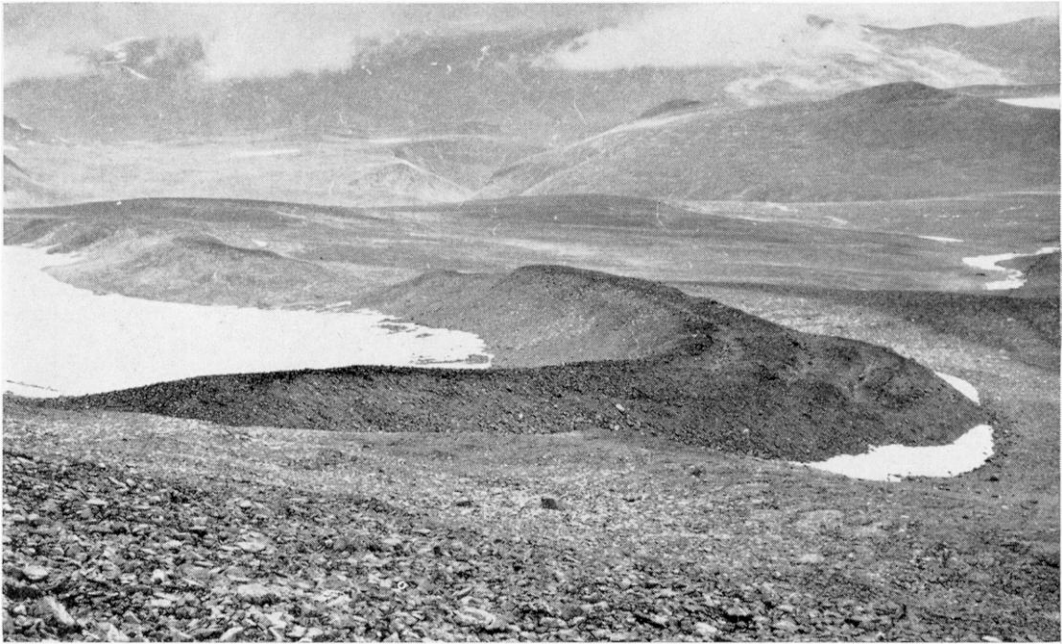


Fig. 3. *Tarfalaglaciär* has built up a huge lateral and terminal moraine, the surface age of which seems to be considerable, certainly many centuries, at least in the outer part. The inner part is cupshaped and is devoid of vegetation. As late as 1945 the ice stood with its margin at the terminal moraine. The distance between the snout and the terminal moraine was about 75 m in 1960, and the moraine rises about 15 m above the level of the ground moraine. Photo 26 July, 1961.

in a NNE direction from the glacier front and a number of quadrats are laid out in different places inside the terminal moraine.

Isfallsglaciär. The next glacier to the north is *Isfallsglaciär*, a glacier now only somewhat more than half the size of *Storglaciär*. Unlike the latter the morainic area is composed mainly of a series of large lateral and end moraines (Fig. 2). Here the annual retreat of the ice front is less well known. Therefore the results obtained at *Storglaciär* can be applied to this nearby locality, which has a similar climate. The snout of *Isfallsglaciär* is about 1,150 m above sea-level and the amphibolite constituting the mountain massif is common to both tributary valleys. During the summer of 1960, due to thinning of the glacier, a small nunatak appeared about 200 m from the snout and 1,250 m above sea-level. At the end of 1961 it had attained a size of 20×40 m. This virgin ground, covered in part with a thin layer of till, provides us with an interesting area for succession studies—on an isolated spot surrounded by ice.

The upper or northern part of the Tarfala valley, into which the glaciers debouch, belongs in the middle alpine region, vegetation-wise. There vascular plants only grow in patches and cryptogams predominate. Scrub and grass heaths are found on a surface subjected to frost action, which results in the presence of solifluction features and patterned ground.

Tarfalaglaciär has its snout at a still higher elevation, in the high alpine region where cryptogam communities predominate; extremely hardy species of vascular plants occur only here and there. Its outer moraine at about 1,450 m above sea-level forms a very large ridge with many minor crests on it. The inner part of the ground moraine area is cup-shaped and very light-coloured (due to the absence of vegetation), contrasting sharply with the dark lichen covered terminal moraine (Fig. 3).

The growing season in the upper Tarfala valley is restricted to the months of June, July and August, the mean temperature of which,

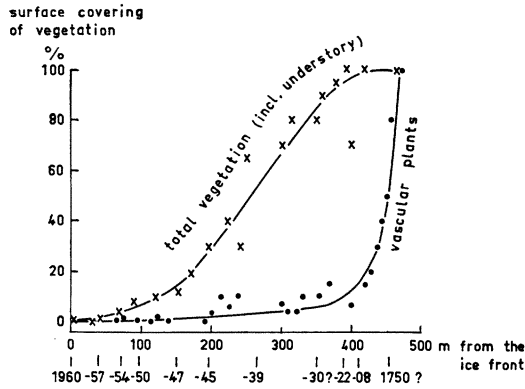


Fig. 4. A line transect in front of Storglaciär showing the course of colonization. Three phases are evident: the first one (first 10–15 years) slow, the second one (up to about 50 years after deglaciation) very fast, and the third one with a closed moss and lichen ground cover and beginning rapid invasion by vascular plants.

for the period 1946–1960, is about $6^{\circ}2^{\circ}\text{C}$ (personal communication from Dr. E. Woxnerud). The precipitation varies much from year to year, about 175 mm (7 inches) being a common value for July, whereas August has a still higher reading.¹ Cold winds sweep down the glaciers, affecting the temperature of the areas below them. The covering of snow is to a certain degree determined topographically, and it varies in thickness from 2 or 3 m in depressions to bare patches on the ridge tops. Some years the snow does not even melt from certain hollows in the valley floor.

Flora and vegetation successions

To the observer the complete barrenness of an area adjacent to a retreating glacier is a very striking phenomenon. But only for a few years will the area remain bare. Very soon mosses, grasses or other plants with light and/or numerous diaspores settle down. Colonization goes on at a leisurely pace during the first decade or so of ice-free status, the dominant vegetation being mosses. Here and there flowering plants grow. The vegetation covers only 10 to 20 percent of the surface. This first slow phase of colonization is succeeded by a more rapid one. Even now the mosses make up

¹ The mentioned temperature and precipitation figures are from the Tarfala Research Station at about 1,150 m above sea-level.

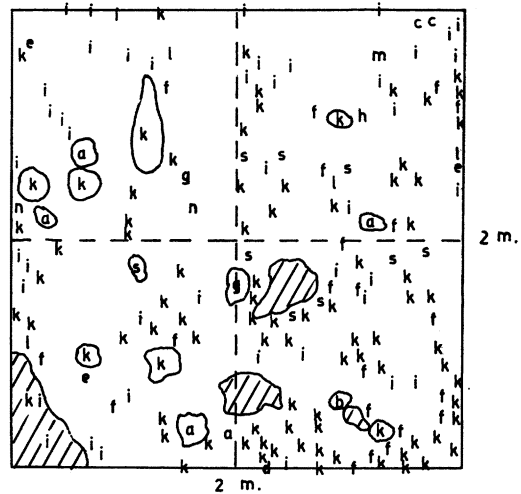


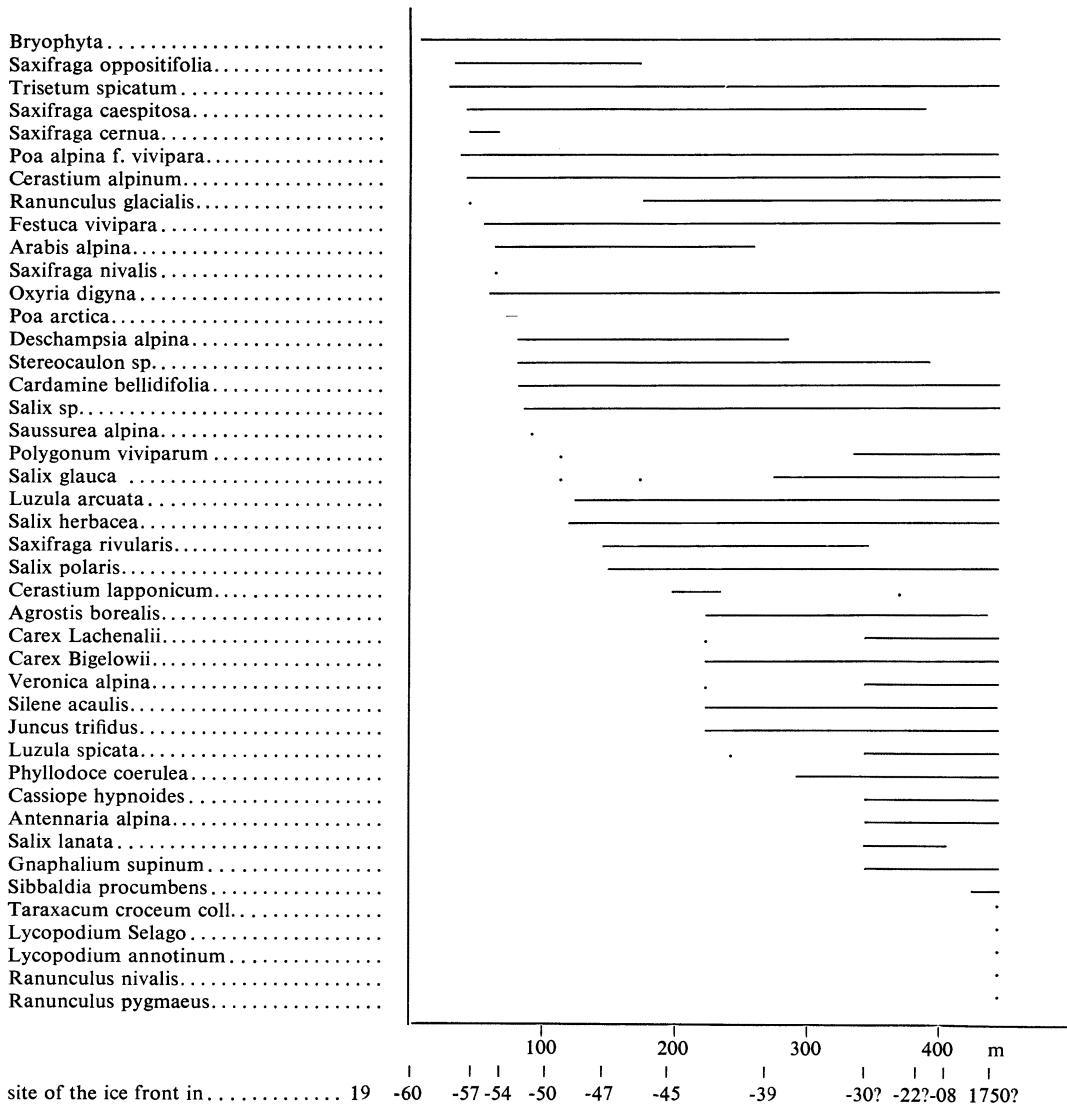
Fig. 5. A quadrat from the Storglaciär moraine showing the species and specimens of vascular plants on ground exposed for about 15 years. Phanerogams cover about 50 percent (field layer), cryptogams (mainly mosses) 70–80 percent of the surface (ground layer). a = *Carex Bigelowii*, b = *Carex Lachenalii*, c = *Cerastium alpinum*, d = *Cerastium arcticum*, e = *Cerastium* sp. (undeveloped plants of c or d), f = *Cerastium lapponicum*, g = *Festuca vivipara*, h = *Luzula arcuata*, i = *Oxyria digyna*, k = *Poa alpina* f. *vivipara*, l = *Salix* sp., m = *Salix herbacea*, n = *Salix polaris*, s = *Stereocaulon* spp. /// = stony area.

the bulk of the “invaders”, although the proportion of vascular plants increases. Lichens also belong to this second phase with the ingress of *Stereocaulon* onto the ground surface and crustose lichens onto boulders. After about fifty years the cryptogamic understorey is more or less complete, and at that time the definite conquest for the higher plants occurs. The course of development is seen in the graph (Fig. 4), representing a line transect in front of Storglaciär. A quadrat from the same area illustrates the colonization in a different way (Fig. 5). Here the individuals of the different species present are recorded on a map. By means of such maps it will be possible to study future changes in detail (cf. below).

As the course of ice recession is known only for the last half century, the early part of it must be reconstructed in some way. The most natural thing is to compare the Tarfala valley with neighbouring areas. In southern Norway, in the Jotunheim region, a thorough study on plant successions on moraines has been carried out by Fægri. There a period of about 150 years seems to be required for a complete

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Table 1. The appearance of vascular plants along a line transect in front of Storglaciär. The small dots represent a mere sporadic occurrence, quite separated from their main distribution area in the field



plant covering to develop (Fægri 1933 p. 143). It must be noted that the climate in the Jotunheim region is rather different from that in the Kebnekajse massif. The fronts of the Jotunheim glaciers are situated many hundreds of meters lower in altitude and in more southern latitudes (61° — 62° as compared with Storglaciär at about 68°). Likewise in the Sarek massif of northern Sweden about 150 years is needed for the vegetation to cover a morainic area (B. and O. Almén 1959 p. 48). In accordance

with those results obtained at other localities in the Scandinavian mountain chain the outermost moraine in front of Storglaciär must have been ice-free for at least about 150 years, perhaps we dare say at least 150.

Studying the vegetation at small spots in a large area may give very misleading results as local environmental factors play an important rôle in determining the vegetation pattern. In depressions, where the snow lies in deep drifts and does not melt until very late in the summer

Table 2. The occurrence of phanerogams on the moraines in front of Storglaciär

Group	Characteristics	Species
1	Species with a wide range	Mosses <i>Cerastium alpinum</i> <i>Poa alpina</i> f. <i>vivipara</i> <i>Trisetum spicatum</i>
1 a	Real pioneers, i.e. species on ground exposed less than 20—30 years	<i>Saxifraga caespitosa</i> <i>S. oppositifolia</i>
	Species on ground exposed more than 5 years:	
2	With a wide range	<i>Festuca vivipara</i> <i>Oxyria digyna</i>
2 a	With a narrow range, only on ground exposed less than 20—30 years	<i>Arabis alpina</i>
3—4	Species on ground exposed more than 10 years	<i>Luzula arcuata</i> <i>Ranunculus glacialis</i> <i>Salix polaris</i>
5 (for Storglaciär only)	Species on ground exposed more than 15—20 years	<i>Agrostis borealis</i> <i>Carex Bigelowii</i> <i>Juncus trifidus</i> <i>Silene acaulis</i>
6	Species on ground exposed more than 30 years	<i>Antennaria alpina</i> <i>Carex Lachenalii</i> <i>Cassiope hypnoides</i> <i>Luzula spicata</i> <i>Polygonum viviparum</i>
7	Species only in the most distal part of the morainic area	α in moist grass heath vegetation: <i>Ranunculus nivalis</i> <i>R. pygmaeus</i> <i>Sibbaldia procumbens</i> <i>Taraxacum croceum</i> coll. <i>Lycopodium Selago</i> β in dry scrub heath vegetation: <i>Erigeron uniflorum</i> <i>Hieracium alpinum</i> <i>Loiseleuria procumbens</i> <i>Minuartia biflora</i> <i>Veronica alpina</i> <i>Lycopodium Selago</i>
8	Species only sporadically occurring in the deglaciated area	<i>Chamaenerion angustifolium</i> <i>Poa arctica</i> <i>Potentilla Crantzii</i> <i>Saussurea alpina</i> <i>Saxifraga foliolosa</i> <i>S. nivalis</i> <i>S. rivularis</i> <i>Taraxacum croceum</i> coll.

season, or on sites where silt has accumulated, a plant cover is absent; on the other hand

where there is good supply of water, the plant cover may be a thick mat. Thus the environ-

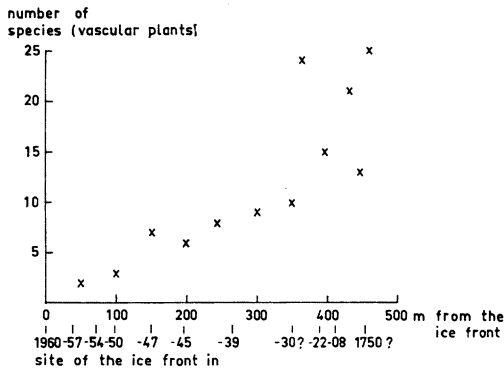


Fig. 6. Graph showing the variation in the number of species (vascular plants) in front of Storglaciär. The number does not increase uniformly, but swells enormously where the water supply (ground or meltwater) is good.

mental factors give rise to quite different vegetation patterns.

As the plant cover closes the number of species increases (Fig. 6). In the first few years the number is small, then it rises quickly but with great fluctuations. The local environmental control is significant even in this case. The water supply seems to be especially important, as the edges of the small streams harbour a rich flora.

In the whole area in front of Storglaciär about 40 species of vascular plants occur, some of them only rarely. On closer examination one will find that certain species occur at a certain distance (i.e. after a certain time interval) from the ice margin. A few species grow only in a narrow zone adjacent to the ice, others occur only in the distal part. Other species have a wider range, some of them ranging from the snout to the outermost moraine. Many of the latest immigrants also live close to the ice, but in a merely sporadic manner (Table 1). According to their occurrence on the moraines we may divide the plants as shown in Table 2.

Which plant species first colonize the bare ground is a matter of size and shape of the diaspores. The pioneers—mosses, liverworts, and lichens—usually have microscopic disseminules, spores, gemmae or soredia. The pioneer vascular plants are grasses and herbs with small seeds and fruits or suffrutescent plants with light semina. Also, the number of seeds produced plays a rôle. The greatest fertility is

shown by species in which every flower only produces *one* seed, such as grasses and composites. Vegetative reproduction by means of runners, etc., is also of importance.

The species occurring on the moraines are the same as those found in the upper part of the Tarfala valley, except for the willows found only in the more distal part of the ground moraine areas. Willows are abundant further down the valley, where they form a belt with its upper limit about 950—1,000 m above sea-level. The light, hairy seeds are easily transported by the wind, and this explains their occurrence on the moraines higher up. These willows are the only large woody plants on the moraines. Their ages can be told by the number of tree rings, and in this way the results of the other methods can be confirmed. Unfortunately no such countings have been performed by the writer. In southern Norway and the Alps, where deciduous forests grow close to the glaciers, this method is of great importance and is a simple way of determining the age of the vegetation.

Vegetation studies of morainic deposits in other parts of the world show that colonization, competition, and development of the vegetation occur in much the same way everywhere and can be summed up in Lüdi's words (Lüdi 1958 pp. 401, 402): "Übereinstimmend ist in allen Gletschervorfeldern als Erstbesiedlung eine zufällige Mischung von Arten der Umgebung, welche auf einem absoluten Rohboden zu keimen und zu wachsen vermögen. Übereinstimmend ist auch, dass in diesen ersten Stadien die Blütenpflanzen und die Moose voneinander unabhängig wachsen, also nicht etwa die Moose den Blütenpflanzen vorausgehen müssen oder umgekehrt. Wohl aber sind die Moose wirksame Humusbildner, die verhältnismässig rasch eine erste Anreicherung an dunklem Humus bewirken, meist in Form einer ganz dünnen Decke, die den Boden auch festigt und später für bestimmte Blütenpflanzen als Keimbett dienen kann. Übereinstimmend ist ferner der spätere Vorgang der Aussonderung nach Standorten, der zur Ausbildung besonderer Pflanzengesellschaften führt . . . Für die Weiterentwicklung ist sehr wichtig die Oberflächengestaltung: steile Hänge besiedeln sich sehr langsam, weil die Feinerde immer wieder ausgespült wird; flache Lagen oder Mulden sind viel günstiger und kommen rascher zu dichter Besiedlung." It should be

noted that in Scandinavia, as opposed to the Alps, the cryptogam communities become dominant much earlier, and they are the factors most responsible for the stabilization of the ground and the formation of a humus layer.

Detailed studies of the vegetational changes

In the previous section the results obtained on line transects in front of Storglaciär have been discussed. In the same area quadrats were studied also, in order to obtain additional information about changes in the vegetation. Data gathered in this way are more easily handled and are better suited to continuing investigations. In his "Besiedlung und Vegetationsentwicklung auf den jungen Seitenmoränen des grossen Aletschglatschers" Lüdi (1945 pp. 36 f.) discusses and emphasizes the importance of observing the degree of covering of a species (dominance), the density of a species, i.e. the number of individuals per area, and especially the vitality. These phenomena were thoroughly studied in the quadrats under discussion. The dominance was measured by estimation; a logarithmic scale of five degrees, suggested by Hult and Sernander (cf. Du Rietz 1921) was used. For the other factors the scales mentioned by Lüdi were employed. Also the distribution, sometimes called the frequency, that is the percentage of quadrats in which the species in question occurs, was determined. By thorough mapping of the plant individuals in a quadrat, a detailed analysis of vegetational changes becomes possible (Fig. 5). Yet, a great number of such sections are required, and the size of them must be adapted to the relief of the ground. In arctic and alpine regions large boulders often restrict one's choice.

Also, attention must be paid to secondary plant successions. When fire, water, storm, cattle, men, or other external agencies interrupt the course of a succession, a secondary succession is initiated. As the ground has been vegetated before, the soil is already prepared, as it were, so better opportunities are afforded for germination. The colonization and the stabilization of the vegetation take place rather rapidly under such conditions.

The above-mentioned nunatak in Isfallsglaciär also will give a good deal of information about plant migration onto bare ground. On a visit to the bare spot in July 1961, i.e. one year after its appearance, the author recorded two lichen

specimens (*Alectoria ochroleuca* and *Cetraria nivalis*) and one phanerogam (*Cerastium cf. alpinum*). These specimens were still loose on the ground. Probably they were transported there by wind or meltwater from the surface of the surrounding glacier, which is rich in plant fragments derived from vegetation-covered areas nearby (cf. Du Rietz 1931).

Vascular plants on the Tarfalaglaciär moraines

As noted above the glaciers on the west side of the Tarfala valley occur in an area characterized by middle alpine vegetation. Tarfalaglaciär, on the other hand, has its front in the high alpine region, where the true moss and lichen desert prevails. Only small patches with a few hardy phanerogams occur scattered about in sheltered sites. Grasses such as *Trisetum spicatum* and *Festuca vivipara*, and scrubs and herbs such as *Salix herbacea*, *Ranunculus glacialis*, and *Cardamine bellidifolia* are the ones that withstand the severe climate.

On these moraines we can hardly speak of phanerogamous successions. The question as to surface age must be reviewed in another way, with the aid of cryptogams and soil properties.

Cryptogam successions

Only a few years after ice recession the first mosses appear on the bare ground, often in a very young and undeveloped state. Hence not even their genus can be determined. In analyzing the line transects and the quadrats in front of the different glaciers, samples of the moss and lichen understory were collected. The results from the moraine areas in front of Storglaciär are shown in Tables 3—5, and the results from Isfallsglaciär are similar. The successions found on the Tarfalaglaciär moraines differ from the "Tarfala valley pattern", as will be further discussed below.

The first observable cryptogams on the present moraines of all glaciers are mosses, *Pohlia*- and *Bryum*-species, unfortunately too poorly developed for determination. Next come representatives of several genera (at least as regards Storglaciär), many of which do not remain very long, probably as a result of competition. Among the later arrivals are found species of *Dicranum*, *Polytrichum*, *Hylocomium*, and *Racomitrium*. In moss colonization, as for the phanerogams, the migration does not take place uniformly. The pioneers

Table 3. The succession of mosses in front of Storglaciär

	1957	1953	1952	1945	1930	1910—20				bef. 1900	ab. 1750?	1750?	Tarf. val.
						boulder	earth	earth	earth				
<i>Pohlia albicans</i>	×	×											
<i>Aulacomnium turgidum</i>	×		×										
<i>Bryum cirratum</i>		×											
<i>Ceratodon purpureus</i>		×	×										
<i>Conostomum tetragonum</i>		×								×			
<i>Drepanocladus uncinatus</i>		×	×	×			×	×		×			×
<i>Polytrichum juniperinum</i>		×											
<i>Philonotis tomentella</i>		×	×										
<i>Pohlia nutans</i>		×		×			×			×			
<i>Bryum</i> sp.....		×											
<i>Pogonatum</i> sp.....		×											
<i>Bryum cryophilum</i>			×										
<i>Pohlia Drummondii</i>			×										
" <i>gracilis</i>			×							×			
<i>Drepanocladus purpurascens</i>			×										
<i>Rhacomitrium fasciculare</i>			×										
<i>Polytrichum piliferum</i>				×			×		×	×	×	×	
<i>Rhacomitrium canescens</i>				×			×		×	×			
<i>Pohlia</i> sp.....									×				
<i>Polytrichum norvegicum</i>								×	×	×			
<i>Pogonatum capillare</i>							×						
" <i>alpinum</i>									×				
<i>Dicranum majus</i>											×		×
<i>Polytrichum hyperboreum</i>											×		
" sp.....											×		
<i>Rhacomitrium lanuginosum</i>											×	×	×
<i>Dicranoweisia crispula</i>												×	
<i>Dicranum glaciale</i>													×
" <i>fuscescens</i>													×
<i>Bryum pseudotriquetrum</i>													×
<i>Hylocomium alaskanum</i>													×
<i>Paraleucobryum nerve</i>													×
<i>Andreaea rupestris</i>													×

—only a few species—colonize the debris very rapidly, the next "invasion" follows a number of years afterwards, etc. In the first few decades after these early invasions, the moss flora is rather stable. On the large lateral moraines new species appear. The next change of the flora occurs on the outermost terminal moraines, where mats of *Dicranum*-species and *Rhacomitrium lanuginosum* (a species with a world wide distribution) cover the boulders and the ground. According to Fægri (1933 p. 141), in Norway this is characteristic of an old surface (more than 150 years), and he calls this stage the "Moss-*Alectoria*-stage".

The morainic debris deposited in front of Tarfalaglaciär conveys a unique impression to the visitor. The whole area from the snout to the moraine about 60—70 m distant, is an enormous

boulder field, steril and completely devoid of vegetation. The bright colour of the boulder field is due to the bare rocks. About halfway up the steep proximal slope of the terminal moraine the first mosses occur—*Pohlia*-species. When the edge of the flat top of the terminal moraine is reached, the contrast is striking—the bright, steril proximal part and the terminal moraine itself with its dark colour resulting from an abundance of blackened lichens and mosses. Their presence indicates that this part must have been exposed for a considerable time. The moss flora suddenly becomes rich in species (in a relative sense). Only the most acidophilous species are found. The mosses normally expected in similar regions are lacking. *Rhacomitrium lanuginosum* and *Kiaerea* sp. (formerly assigned to *Dicranum*) grow on the ridge. According to

Table 4. The succession of liverworts in front of Storglaciär

	1957	1953	1952	1945	1930	boulder	1910—20	earth	earth	earth	bef. 1900	ab. 1750?	1750?	Tarf. val.
<i>Marchantia alpestris</i>		×												
<i>Cephaloziella arctica</i>				×	×						×			
<i>Lophozia alpestris</i>				×	×	×		×		×		×	×	×
<i>Tritomaria quinquedentata</i>				×	×			×			×	×		×
<i>Anthelia Juratzkana</i>					×			×						×
<i>Barbilophozia Hatcheri</i>					×			×			×		×	×
<i>Cephalozia bicuspidata</i>					×									×
<i>Gymnocolea inflata</i>					×									
<i>Lophozia groenlandica</i>					×					×	×			×
" <i>Wenzelii</i>					×									
<i>Scapania hyperborea</i>					×									
" <i>irrigua</i>					×					×				×
" <i>lapponica</i>					×									
<i>Isopaches bicrenatus</i>								×						
<i>Lophozia ventricosa</i>								×						
<i>Orthocaulis attenuatus</i>								×						
<i>Gymnomitrium concinnum</i>										×				×
<i>Chandonanthus setiformis</i>											×	×	×	
<i>Pleuroclada albescens</i> v. <i>islandica</i>											×	×		
<i>Ptilidium ciliare</i>											×	×		×
<i>Cephalozia divaricata</i>													×	
<i>Sphenolobus minutus</i>													×	
<i>Anthelia Julacea</i>													×	×
<i>Blepharostoma trichophyllum</i>													×	×
<i>Cephaloziella subdentata</i>													×	×
<i>Jungermania sphaerocarpa</i>													×	×
<i>Nardia Breidlerii</i>													×	×
<i>Pleuroclada albescens</i>													×	×
<i>Gymnomitrium apiculatum</i>													×	×
<i>Orthocaulis Floerkii</i>													×	×
" <i>Kunzeanus</i>													×	×

Fægri (l. c.), at Jostedalsbre the age should be at least 150 years. If we take into consideration the extremely severe climate here compared with the conditions at the more southern Norwegian glaciers, this age must be a minimum value.

The liverworts also soon find their way onto the bare moraine areas. The first species to arrive near Storglaciär seems to be *Marchantia alpestris*, which grows under stones. Otherwise the liverworts are late invaders and the whole moraine field is poor in them. The *Marchantia*-species only grows in the most recently exposed areas, but it is later replaced by another species, *Scapania irrigua*. On the large lateral moraines only a few species grow. In the Tarfala valley floor, on the other hand, they are common. Unfortunately, using the succession of liverworts as a basis for dating moraines does not seem

possible. Many genera are represented, each in only one or two species, and these in turn are found scattered over the morainic fields. However, it appears that *Ptilidium ciliare* and *Gymnomitrium* spp. among others, arrive very late. These late invaders, like the late ones among the mosses, are also found on the terminal moraine of Tarfalaglaciär.

Lichens also constitute a very important group for determining the time a surface has been ice-free. The first visible organisms on rocks are crustose forms, which can easily obtain a foothold in irregularities of the surface, and there their small disseminules can germinate. The thalli grow very slowly, only one to a few millimeters per year in some extreme cases. Many environmental factors control their growth, e.g. exposure, humidity, temperature, snow condi-

Table 5. The succession of lichens in front of Storglaciär

	1957	1953	1952	1945	1930	1910—20				bef. 1900	ab. 1750?	1750?	Tarf. val.
						boulder	earth	earth	earth				
<i>Pannaria pezizoides</i>				×									
<i>Stereocaulon</i> sp.....				×	×	×	×			×		×	×
<i>Cetraria cucullata</i>					×								
" <i>Delisei</i>					×	×	×						×
" <i>commixta</i>								×					×
<i>Parmelia minuscula</i>								×	×				
" <i>pubescens</i>						×		×	×				
<i>Umbilicaria cylindrica</i>								×	×			×	×
" <i>Herrei</i>						×		×	×				
" <i>hyperborea</i>								×	×			×	×
" <i>proboscidea</i>						×		×	×			×	
" <i>torrefacta</i>						×		×	×			×	
<i>Peltigera malacea</i>							×	×					
<i>Cetraria crispa</i>						×	×					×	
" <i>nivalis</i>							×						
<i>Cornicularia aculeata</i>						×						×	
<i>Cladonia gracilis</i>						×							
" <i>mitis</i>						×	×						×
<i>Solorina crocea</i>						×	×			×		×	×
<i>Alectoria ochroleuca</i>							×						×
<i>Cladonia coccifera</i>						×	×			×		×	
<i>Cornicularia divergens</i>							×						
<i>Cladonia gracilis</i> v. <i>chordalis</i>										×			×
" <i>uncialis</i>										×			

tions, etc. What chances exist of their surviving a glaciation of short or long duration? Conservation by means of deep freezing is of course possible as with other living organisms. Can the lichens continue growing afterwards? Meltwater will cover the thallus which may be unfavourable to that organism. There will be little risk of finding lichens older than the surface age of the morainic deposit. However, Goldthwait (1960) has found mosses and lichens undisturbed 30 m back under a glacier (under about 40 m of ice). Another source of error is boulders torn loose from the rocks surrounding the glaciers and transported as surface moraine. Plants living on such boulders may continue their growth.

The first species found on morainic debris are clumps of *Stereocaulon* growing on the barren soil and a gray crustose species, probably a *Lecidea* or a similar lichen, on stones where the surface has been ice-free about 5—10 years. Both the beautiful green and orange coloured *Solorina crocea* and *Pannaria pezizoides*, a brown crustose species found on bare soil, are also characteristic of young morainic debris. Green *Rhizocarpon* spp., a crustose genus that is very common in the northern Swedish mountain chain, and small

Umbilicaria spp., darkish brown foliose lichens, arrive somewhat later. This stage, characterized by crustose forms, is called the "crustose-lichen-stage" by Fægri (1933 p. 141) and develops back about 20 to 40 years after deglaciation. This stage is succeeded by a "*Gyrophora* (= *Umbilicaria*)-stage" on boulders exposed for 40—60 years. The latter stage is found in the Tarfala valley on the large lateral moraines which became ice-free at the beginning of the 20th century after the stagnation or possible readvance of the glaciers (cf. above). Here also *Cetraria* spp. and *Parmelia pubescens* contribute to the darkish colour of the ground and the boulders. In this case too we can make a comparison with Fægri's results (Fægri l. c.). The outermost terminal moraine of Storglaciär, heavily covered with *Cladonia* spp., *Cetraria* spp. and *Parmelia* spp. in the mossmats consisting of *Rhacomitrium lanuginosum* and species of *Dicranum*, may be compared to Fægri's two stages of "*Parmelia*" and of "*Moss-Alectoria*", which were interpreted as indicating an age of at least 150 years. The "*Moss-Alectoria*-stage" is the one found on the inner part of the terminal moraine of Tarfala-glaciär, suggesting that its minimum age is about

150 years. Similar results are arrived at by another method, lichenometry, as outlined in the following section.

Lichenometrical results

It has been noted already that lichens on the moraines are likely to be of the same age or, more possibly, a little younger than the exposed surface. Thus in a given spot it is important to find the largest thalli, as these represent the oldest lichens. Measurements of the diameters of crustose and umbilical lichens have been carried out in different regions of northern Scandinavia during the last decade. At present only some general results will be discussed. In different parts of the world various species of the genera *Rhizocarpon*, *Lecidea*, and *Umbilicaria* are present. These genera are also represented on the moraines in Kebnekajse, and certain of the species are identical with those growing in other glaciated regions. In Scandinavia *Rhizocarpon geographicum*, *R. oreites*, *Umbilicaria cylindrica*, and *U. proboscidea* are of particular interest. In the present investigation area the *Rhizocarpon* spp. yield rather good information about the ages of recently exposed surfaces. If a curve is drawn based on the known age of the moraine ridges and ground moraine in front of Storglaciär (Fig. 7), it will also be possible to date the Isfallsglaciär and Tarfalaglaciär moraines, provided that the environmental factors are similar. The lichen development suggests that the time of exposure of the inner part of the southern lateral moraine of Isfallsglaciär is a little longer than the northern lateral moraine of Storglaciär. On the other hand, the more distal parts of the southern lateral moraine of Isfallsglaciär appear to be older, and the outermost parts became ice-free perhaps contemporaneously with the terminal moraine of Storglaciär. The northern lateral moraine of Isfallsglaciär is very complicated. Parts of it probably thawed out when the southern lateral moraine did. A very young system of small ridges in its northern part indicates the existence of recent ice which thawed about 30–40 years ago according to the results of the lichen measurements.

The ground moraine near the front of Tarfalaglaciär is apparently very young. About 75 m from the snout (July 1961) the first thalli of *Rhizocarpon* and *Umbilicaria* appear. Their sizes, compared with those of the same species from

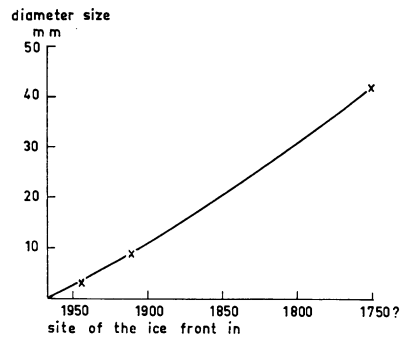


Fig. 7. Diameter of *Rhizocarpon geographicum* coll. in front of Storglaciär.

the Storglaciär area, indicate that the surface is about 10 years old. These 10 years should in this case be a minimum value (cf. the discussion above). At the inner edge of the flat top of the end moraine the age is slightly greater. The middle part of the innermost crest of the terminal moraine is older, perhaps as much as a century. The next crest outward is about 150–200 years old, and the outermost crests are probably even older. The retreat of the glacier appears to have occurred in two main phases. The large moraine ridge with the parallel crests on its top seems to have been exposed for a rather long time. The area behind it is much younger. If we assume that the first visible crustose lichen is found after a spot has been ice-free for 5 years (as for Storglaciär)—here 45 m from the ice snout—the recession per year is about 9 m. This is by no means an absurd value, as the glaciers in the Tarfala valley are retreating now at that rate if not faster. The edge of the flat top of the end moraine will then be about 10–15 years old, a result which agrees well with an observation from 1945, when the ice reached this very point (personal communication from Dr. V. Schytt).

The use of lichens as a tool for glaciological research thus seems plausible. The *Rhizocarpon* spp. are reliable and can be used for a considerable time. The *Umbilicaria* spp. are less suitable, as they yield varying results on moraine areas of the same age. Why this is the case is difficult to answer. Beschel holds the same view, and he states (Beschel 1957 p. 60): “Any crustaceous and foliaceous lichens will yield important data. Of special interest are lichens that are seasonally submerged in meltwater. Their growth does not depend on the amount of precipitation, but is determined almost exclusively by temperature.

Data from these lichens will provide details of some of the complex climatic factors that are integrated by the rate of growth of ordinary rock lichens. Fruticose lichens, such as the so-called reindeer-moss and rock-tripe (*Umbilicaria* spp.) are less suitable."

Measurements of lichen diameters in different regions might yield information about the climatic control of lichen growth. For this reason the present author studied lichen thalli in a locality a little further north, in the Riksgräns area, where the altitude is less (about 350—525 m above sea-level), and consequently the climate is milder. Nevertheless the results agree quite well with those from Kebnekajse. Thus there must be another factor, such as ultraviolet radiation, which controls lichen growth, in addition to obvious climatic factors of temperature, etc. The yearly growth of lichens could easily be studied in the field by means of marked thalli at different locations. At intervals the diameter sizes could be measured and a graph representing the growth of these individuals could be drawn. At Storglaciär such an experiment is under way.

Soil development

As was mentioned in the introduction, it was not until recently that scientists became aware that changes occur in the substrate of the plants, the till itself, after its deposition by a glacier. Morainic debris which has no vegetation cover must have little humus too. Windblown fragments of plants and dead animals constitute the only organic material present. On the other hand the soil is rich in mineral salts. Simultaneously the readily soluble salts are washed out by rain and meltwater. The final result in humid climates (to which the northern Scandinavian mountains belong because of high precipitation coupled with low evaporation) are the podsoles. In alpine regions, however, this process is more or less counterbalanced by frost heaving and solifluction. In front of Storglaciär samples of till have been collected which were air-dried and chemically analyzed. A small number of samples were also taken from near Isfallsglaciär and Tarfalaglaciär. The tests performed in other glaciated regions have principally been to determine soil acidity, carbon and nitrogen contents, and the mechanical composition. In the Kebnekajse area the present author has considered the possibility of using the washing out of certain mineral salts as an aid to

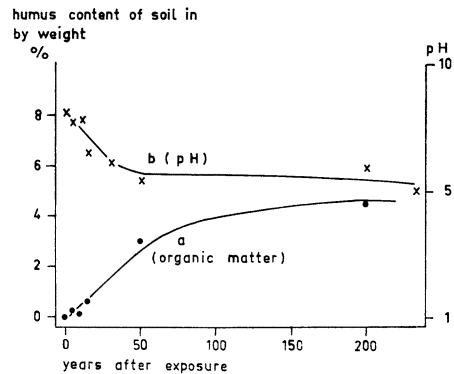


Fig. 8. Content of combustible matter (humus) (a), and hydrogen ion concentration (b) of till (surface layer), Storglaciär. (Omit the word "in" in "humus content of soil by weight".)

dating moraines. Unfortunately only one test series is available, but this one shows the general trends of the curves. All chemical analyses are carried out on the fine fraction of the till, sieved through a 2 mm screen.

Humus content. The relative abundance or scarcity of combustible organic material and of total nitrogen both indicate the amount of organic matter (humus) at a certain spot. Hence graphs showing these two components in a soil have the same appearance, i.e. the sigmoid curve typical of organic processes with a very fast ascending initial phase within the first half century. Later on the curve flattens out when more stable conditions are reached (Fig. 8 and Table 6).

Soil acidity. The raw material of the soil is derived from the bedrock of the area from where the glaciers are situated. Amphibolite alternating with micaschist and gneiss constitutes the main body of the Kebnekajse massif at higher levels (Quensel 1919, Johansson 1952). As amphibolite is a basic rock, the hydrogen ion concentration is expected to be low. At the snout of Storglaciär a pH of 8.1 was found. The curve showing soil acidity (Fig. 8 and Table 6) is the reverse of that showing humus content; i.e. it has a fast descending phase (in the first half century) from the initial level above the neutral point to a pH of about 5.5. The acidity of the till in front of Isfallsglaciär is about the same. The Tarfalaglaciär debris, however, is very acid (pH 5.9) close to the ice margin, but in conformity with the other areas of moraine the curve shows a descending trend. The explanation must be due to the original rock, whose main

Table 6. Analyses of soil properties on Storglaciär moraines (particles < 2 mm diam.).

Approx. time of exposure (in years)	Combustible organic matter in % by weight of dry substance	Total-N mg/100 g air-dried substance	P-AL mg P/100 g air-dried substance	Ca-AL mg Ca/100 g air-dried substance	K-HCl mg K/100 g air-dried substance	Reaction (pH)
0	—	4	14.7	86	65	8.1
5	0.2	4	17	78	60	7.7
10	0.1	25	15.8	82	75	7.8
15	0.6	9	4.3	32	53	6.5
30	—	14	2.7	26	50	6.1
50	3	19	2.6	16	37	5.4
200	4.5	48	1.3	40	10	5.9

body is made up of micaschist, and the high value of potassium also confirms this.

Content of calcium, phosphate, and potassium in the moraines. Mineral salts are derived from the bedrock underneath the glaciers also. When the bedrock is ground up by the ice into fine particles and the resulting material is laid down as till, the salt content is very high close to the ice margin, but on exposure the leaching processes begin which deplete and modify the till. Calcium, phosphate, and potassium are removed from the surface in the reverse of the accumulation of organic material. The curve showing this slopes steeply in the first few decades, but has reached a rather stable status after about 50 years (Figs. 9, 10 and Table 6).

The present results are very similar to those reached in Alaska by Crocker and Dickson (1957 pp. 174 ff.). The maturing processes of the soil run their course in the same way with a fast initial phase, slowing down after about half a century when the stabilization of soil and vegetation seems to commence.

Summary and conclusions

The morainic debris left behind by a retreating glacier is immediately subject to colonization by various biota, the conspicuous bulk of which initially consists of the lower plants. The scope of the present study is to consider some botanic and pedologic methods of dating moraines of unknown age by means of comparing those results

with such obtained in dated areas with similar climate. The area chosen for the present investigation is situated in the high mountain chain of the northernmost part of Sweden, in the Kebnekajse region, where the Tarfala Research Station is situated.

The vegetation can be studied by different methods from many points of view. In following the vegetational or biological changes in deglaciated areas, the entire area of moraines can be studied on different line transects from the glacier snout to the outermost moraine, either by recording the observations on the line itself or by utilizing a long narrow rectangle, where analyses can be carried out more thoroughly regarding degree of covering, frequency of occurrence, etc. On a smaller scale this can be done by means of small quadrats at certain intervals. If these are marked out or mapped in relation to fixed points, the investigations can be continued in the future.

A microscopic analysis of till from the ice margin revealed only fragments of mosses and a large quantity of bacteria. After only one year moss plants are visible to the naked eye. At about the same time that the mosses appear the first grasses and herbs germinate on the bare ground. Among the pioneers *Trisetum spicatum*, *Poa alpina* f. *vivipara*, *Cardamine bellidifolia*, and *Saxifraga oppositifolia* are common. *Pohlia* and *Bryum* are the first moss genera. Ten years after deglaciation the cryptogamic understory covers about 10—20 percent of the surface, whereas the phanerogamous part is rather constant. By the

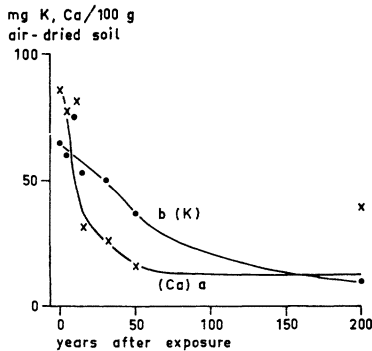


Fig. 9. Content of calcium (a) and potassium (b) in till (surface layer), Storglaciär.

end of the second decade the vegetation is still of an open character but about 40 percent of the ground is covered. However, the part accounted for by phanerogams is only slightly greater than before. After half a century there is a complete covering of mosses and lichens. At this point the flora changes its character in that the flowering plants increase very fast in number of individuals. After about 150–200 years the vegetation is closed. The number of species increases at a steady rate, totalling about 40 species in front of Storglaciär. Certain plants which are not capable of competing for light or space only appear in the youngest areas, where the plant cover is very open. The migration of species onto the barren area takes place by more or less sudden changes, thus one swarm of species succeeds or is added to the former stock. The cryptogams also behave in this way. The moss successions especially seem to give reliable information as to the age of the exposed surface, and together with the lichen communities they constitute special cryptogamic successions (cf. Fægri 1933 p. 141). On the basis of these successions the author has tried to estimate the length of time that the moraines at Isfallsglaciär and Tarfalaglaciär have been ice-free.

Another method is lichenometry, worked out and tested by Beschel in the Alps, Greenland, and northern Canada. Circular lichens, such as *Rhizocarpon* spp. and *Umbilicaria* spp. and a sterile gray crustose lichen (probably a *Lecidea*) are employed for this purpose. The latter is a rather rapidly growing species, but the *Rhizocarpon*-species are very suitable for observation over long periods of time. The genus *Umbilicaria* seems to vary greatly and dating based upon it

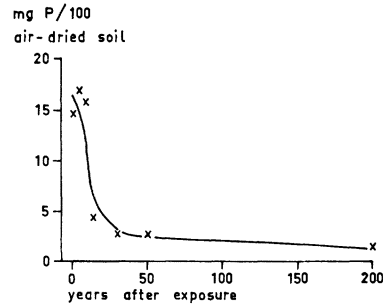


Fig. 10. The phosphate content of the till (surface layer), Storglaciär. (Inadvertently, the letter "g" has been omitted after "mg P/100" in the graph.)

is more uncertain. An experiment aimed at giving information as to lichen growth on different sites on the ground moraine in front of Storglaciär is in progress; i.e. by marking out certain thalli on boulders and measuring them at intervals, the yearly growth in millimeters can be obtained.

The parent material of the moraines of Storglaciär and Isfallsglaciär is amphibolite, while micaschist constitutes the parent rock beneath Tarfalaglaciär. Samples of till were collected close to the vegetation quadrats and were air-dried. The mechanical analyses show a decreasing percentage by weight of coarse debris with increasing surface age. Yet the result must be judged very critically, as local disturbances of different sorts are common.

The humus content of the newly deposited till is very low, or non-existent, but as a result of colonization of the area by plants, especially mosses, a humus layer forms. Analyses for determining the organic combustible matter and the total nitrogen content have been made. During the first few decades the accumulation of these elements is very rapid, but after 50–60 years equilibrium is reached. The reverse type of graph illustrates the washing out of soluble mineral salts from the surface layer. Calcium, phosphate, and potassium are removed relatively soon after the deposition of the till. The same sort of curve also illustrates the soil acidity.

To sum up, the development of the moraines in the Tarfala region, northern Sweden, can be compared with Jostedalsbre, South Norway (Fægri 1933) in the following manner: In front of Storglaciär the different positions of the ice front are well known and mapped since about

1900. During this period vegetational and pedologic changes have resulted in the establishment of equilibrium in the processes involved. The rapid initial phase typical of organic processes is dominant for about one or two decades, thereafter slowing down until the "normal" is reached after about half a century. Our knowledge of the deglaciation prior to this point in the Swedish mountain chain is very slight, but as a result of comparisons with recent ice recession in Norway the outermost terminal moraines seem to have been covered over (but not formed) by ice in the middle or late eighteenth century. At Jostedalsbre moraines exposed for more than 150 years are covered with certain moss and lichen communities and these same communities are found on the "oldest" moraines in the Kebnekajse area. Perhaps we dare conclude that the outermost moraines in the Tarfala valley have been ice-free for *at least* 150 years, as the climate in northernmost Sweden, especially at an elevation of about 1,100–1,450 m above sea-level, is more severe than that in the Jotunheim region of Norway. In front of Tarfalaglaciär the inner or proximal part of the huge lateral—terminal moraine ridge might have been exposed for the same period of time. Judging from the greater lichen diameters of *Rhizocarpon* the outer part of this moraine ridge must be still older.

A definite answer to the question of the age of recently exposed morainic surfaces in the Kebnekajse area is by no means given. The control of plant growth and soil development by climate and other environmental factors is an intricate problem, and many unexpected changes occur. By observing permanent quadrats and marked lichen thalli year after year in different parts of morainic debris areas we hope to understand better the relations between the phenomena observed and the age of the exposed surfaces.

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Appendix

A summary of lichenometrical studies by geography

In the preceding report lichenometry has been treated only very briefly, since it has not been the main object of the study. A short account of lichenometrical methods (mainly European material presented here) as well as of results obtained at Scandinavian glaciers may, however, be of value to other students. All numerical data are collected from unpublished reports by Bornfeldt and Österborg (1958), Larsson and Logewall (1958) and Stork (1960 and 1962). Their permission to publish this compilation is gratefully acknowledged.

Lichenometry is a young science. Notes about lichen diameter measurements can be found in various older publications, e.g. Frey 1922 and Fægri 1933, but truly

systematical methods were introduced by Beschel in 1950. His study, carried out in the Eastern Alps, dealt especially with the crustose lichen genus *Rhizocarpon*. In a series of later publications he has also studied other genera, crustose as well as foliose. The species involved are of circular shape. Other plants, which may also be suitable, are cushions of mosses (such as *Grimmia* spp.) and phanerogams (*Silene acaulis*, *Saxifraga* spp. etc.). A number of investigations have been carried out in southern Norway (Fægri 1933, 1951; Bornfeldt and Österborg 1958) and in northern Sweden (Bergström 1955 b; Larsson and Logewall 1958; Stork 1960, 1962).

Where fresh rock or boulder surfaces have been exposed to the atmosphere, plant successions are initiated. On this type of substrate a lithophyte series starts. The first settlers are crustose lichens, which will be visible to the naked eye a few years after the exposure of the surface. As lichen growth is very sensitive to local climatic and other environmental conditions, it is doubtful whether their growth rate might be used for dating purposes. Beschel, however, who is a trained lichenologist, states (Beschel 1961 p. 1045): "Within an area of equal exposure time, the micro-environment varies, permitting faster growth on some surfaces, delaying it on others. As any smaller plant may be either younger or stunted by its micro-environment, a consideration of the largest plants of one species as age indicators will simultaneously select the individua growing under optimal local conditions. Only the most common and competitive species will show a close correlation between their maximum sizes and the age of the exposure of the substratum, if it lies within the age limit of the plant. The individua or their aggregates must be clearly bordered as any confluence with similar units would invalidate an age determination based on size." With these words of Beschel we also touch upon the lichenometrical method. In his works Beschel uses the largest thallus or thalli as a measure for surface exposure. As it is not always apparent whether a lichen has germinated on the surface at the time of exposure, or whether it had started to grow on boulders while they were still carried down on the glacier surface, we have (in Scandinavia) measured the five largest thalli of a species and averaged the five diameters. Thus we get a value that is more adapted to the medium size and not based on a solitary specimen, which might be older than the exposure age. It is also of importance to choose an area, not too small, within which the measurements are made. Beschel says (Beschel 1961 p. 1047): "As the first thalli grow in a very scattered manner on a new rock surface, often with distributions of one plant to a few square metres, and as only few of these will have found close to optimal microenvironmental conditions, the rock surface to be studied should at least be of the order of 100 square metres." The sizes of the areas chosen in the North Swedish studies differ. Usually five separate squares of 5×5 metres are used and the average is computed from the largest thallus of each square. To permit the application of this method a few prerequisites are needed. Beschel (1961 pp. 1047, 1048) states: "Indirect measurement through the comparison of circular thalli with the largest diameters on substrata of known ages of exposure gives a simplified picture that is very useful. . . . Nevertheless, a number of uncertainties arise. The plants being compared must belong to the same species or at least to closely related ones with nearly identical growth curves. As the determination of most crustaceous

Table 7. Lichen diameters in mm (average of the 5 largest thalli). R = *Rhizocarpon geographicum* and other green species of Rh. Ro = *Rhizocarpon oreites* when specifically stated. Uc = *Umbilicaria cylindrica*. Up = *Umbilicaria proboscidea*. L = *Lecidea* (a gray crustose lichen in front of Storglaciär)

Northern Sweden:

Kebnekajse (67°55' N, 18°30' E):

Storglaciär (1100 m. Stork 1960. Measured 1960)

	R	Ro	Uc	Up	L
1952					7.5
1944	3		17.5	25.5	10
1930					19
1910	9		30	38	31
1750?	42	37.5	34	49	

Storglaciär (Larsson and Logewall 1958. Measured 1958)

1910	5		19	23	
1750?	51		26	37	

Isfallsglaciär (1200 m. Larsson and Logewall 1958. Measured 1958)

1930	1		6	7	
1910	3		18	28	

S. Ö. Kaskasatjåkkoglaciär (1300 m. Larsson and Logewall 1958. Measured 1958)

1910—20	4		28	26	
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Björlings glaciär (1440 m. Larsson and Logewall 1958. Measured 1958)

1934	3		23 (22)	22	
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Abisko area (concerns no glaciers):

Tornehamn (68°25' N, 18°41' E. 345 m. Stork 1962. Measured 1961)

1900	11		13	27	
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Riksgränsen (68°25' N, 18° E. 520 m. Stork 1962. Measured 1961)

1900	10		15	24	
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South Norway (All Bornfeldt and Österborg 1958. Measured 1958):

Jostedalsbre (61°45' N, 7°10' E):

Nigardsbre (295 m)

	R	Ro
1930	16	15
1909	32	29
1875	51	49
1850	65	63
1750	95	100

Briksdalsbre (326 m)

	R	Ro
1926	20	21
1904	37	34
1874	48	52
1859	57	60
1852	61	65
1835	70	72

Bersetbre (401 m)

	R	Ro
1923	21	20
1911	31	28
1886	42	40
1875	53	50
1855	59	63
1845	66	66
1841	68	68
1823	74	78
1782	89	92
1753	96	97

Åbrekkebre (266 m)

	R	Ro
1929	17	18
1914	25	29
1889	43	40
1875	51	50
1848	63	66
1798	85	87

Lodalsbre (698 m)

	R	Ro
1917	24	26
1898	37	36
1880	51	52
1854	61	62
1806	82	84

The Horung massif:

Styggedalsbre (61°29' N, 7°53' E. 1278 m)

	R	Ro
1888	46	41
1869	53	53
1855	60	63
1793	83	92

lichens can only be made using the microscope, any rapid field method introduces errors . . . By measuring as many common species as possible the accuracy of the method may be increased. The size relations of different species remain rather constant as long as the growth velocities stay constant . . . An indirect measurement treats the old and large thalli as if they had had the same environment, especially the same climate in their youth many centuries ago, as the small thalli on a much more recently exposed substratum experienced in the most recent past. Indirect measurement of the growth velocity is only possible where it can be based on the known age of exposure of at least one and preferably more substrata."

The species used in lichenometrical research are above all representatives of the genera *Lecidea*, *Rhizocarpon*, *Umbilicaria*, *Parmelia* and *Caloplaca*. The results obtained by Beschel and Fægri are published in their various papers (cf. the bibliography below). In northern Sweden a fast-growing crustose lichen, probably a *Lecidea*, is used as well as the green, crustose *Rhizocarpon geographicum* and *Rh. oreites*, and the foliose *Umbilicaria cylindrica* and *U. proboscidea*. It has turned out that the results of the two *Rhizocarpon*-species and the two *Umbilicaria*-species are much alike among themselves. The two species of each genus can thus be treated together. This facilitates the investigations in the way that also less trained observers and students can make the field observations.

The areas chosen are: in northern Sweden the Kebnekajse area and the region of Abisko, in South Norway the Jostedalssbre area and the Horung massif. It must be emphasized, however, that the students are no lichenologists and therefore the data presented in Table 7 may vary in accuracy.

Also direct measurements of lichens have been made. For nearly forty years Frey (1959) has studied the growth of certain specimens by means of measurements and photographs. In Kebnekajse the author has in progress measurements on marked thalli. On sloping surfaces in different locations the rock immediately below a number of thalli of different species has been painted. These specimens were measured and mapped in 1960 and the observations will be continued.

The lichen diameter measurements carried out by students from the University of Stockholm have been compiled in Table 7. The considerable differences between corresponding values may be due both to observation errors and to insufficient knowledge of the chronology of the glacier's retreat.

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