GEOLOGINEN TUTKIMUSLAITOS

BULLETIN

DE LA

COMMISSION GÉOLOGIQUE

DE FINLANDE

N:o 155

GLACIAL GEOLOGY OF THE SUOMUSSALMI AREA, EAST FINLAND

BY

K. VIRKKALA

WITH 26 FIGURES IN THE TEXT AND
6 FIGURES ON ONE PLATE

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GOVERNMENT PRESS

Helsinki 1951. Valtioneuvoston kirjapaino

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PREFACE

The field studies for this research were undertaken in the summers of 1947, 1948, and 1949, during which time I carried out mapping of superficial deposits in northern Kainuu, mainly in the parish of Suomussalmi. During the mapping there arose interesting points of view, which led to more detailed research, and gave rise to the present paper.

Among the persons to whom I want to express my sincere thanks I will here first mention Professor Matti Sauramo for leading my studies of geology in the Helsinki University.

To the Director of the Geological Survey of Finland, Professor Aarne Laitakari, I am greatly indepted for his kindness in allowing this work to be published in the serie of the Geological Survey.

To Dr. Esa Hyyppä, Chief Geologist of the Geological Survey, I am grateful for his valuable advice during the research both in field work and in discussions of glacial geological problems.

Dr. Donald H. Chapman, Professor of Geology in the University of New Hampshire, I will especially thank for the reading and correcting of my manuscript and for the discussions of glacial geology during his excursion in Finland in summer 1950.

Mr. R. Kanerva, M. A., has assisted me in the field work, Mrs. Lyyli Orasmaa has drawn the maps and diagrams. Mrs. Anna-Leena Okko, M. A. has helped me in the translation of this paper into English and Mrs. Joyce Preston, M. A., has revised the English of the manuscript. For all this I am deeply grateful.

Geological Survey of Finland, Helsinki, February, 1951.

K. Virkkala

INTRODUCTION

Glacial geology has recently attracted steadily increased attention in our country. New methods of investigation and the improvement of earlier methods have advanced study in this field. Here in Finland the most interesting subjects for investigation are the movements of the Pleistocene Ice Sheet, its final wastage and the genesis of the deposits connected with these events. Various directions of movement of ice sheet have been determined by exact and detailed analysis of the polished surfaces of the bedrock. Investigations of till structure, till texture and the orientation of till stones have thrown new light on problems associated with glacial features. Analysis of the mechanical and lithologic composition of glacial drift has made clear the manner and routes of transport. The morphology of deposits, which was earlier the most important in glacial geological research, has also been taken into consideration in this current study.

Investigations in glacial geology in Finland have been mainly directed to definite, more or less limited areas (Helaakoski 1940, Hyyppä 1948, 1950, Mikkola 1932, Okko 1941, 1949, Tanner 1915, Virkkala 1949) or have taken the form of general reviews of the whole country (Kivekäs 1946, Sauramo 1929, 1940). These investigations have ascertained several directions of glacial movement that are not limited to certain small areas, but probably affect more extensive parts of Finland. The Suomussalmi area is in part connected with the network of observations, the purpose of which is to explain the features of our glacial geology.

Investigations carried out south of the Suomussalmi area in southern Kainuu and northern Karelia (Virkkala 1949) show clearly discernible directions of glacial movement, which can be expected also in the Suomussalmi area further north. The present study is mainly concerned with the movement of Pleistocene ice, marks made by glacial erosion, and the origin of the deposits which are most closely connected with the movements of glacial ice. However, the material of these sediments has only been investigated in so far as it elucidates the ice movement and the genesis of the deposits.

1882/51

No information on the glacial geology of Suomussalmi exists in literature. However, the adjacent areas have been investigated to some extent, though not in detail (Hyyppä 1948, Virkkala 1949), so that comparison with neighbouring areas is possible.

GEOGRAPHICAL REVIEW

The area investigated lies in eastern Fennoscandia as shown on the map, Fig. 1. To the east it is limited by the frontier between USSR and Finland; the other borders are quite arbitrary. Although the area

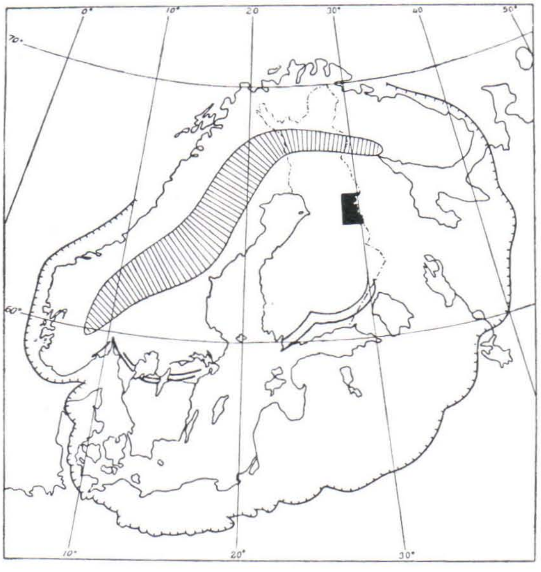

Fig. 1. Location of the area investigated in Fennoscandia (black), drift borders of the Fourth Glacial stage (hatched line), ice divide (ruled area), Salpausselkä ridges in South Finland, and their continuation in Central Sweden. According to Ljungner (1949), von Klebelsberg (1948), *etc.*

is situated in Middle Finland, geographically it resembles North Finland. Its climate is rather northern, the flora and fauna possessing a great many northern features. Settlement is as sparse as in North Finland, and the extensive watershed areas are entirely or almost entirely uninhabited.

The watercourses and watersheds of the area are shown on the map, Fig. 2. Most of the area belongs to the Hyrynsalmi basin which discharges through Lake Oulujärvi into the Gulf of Bothnia. In the south-eastern

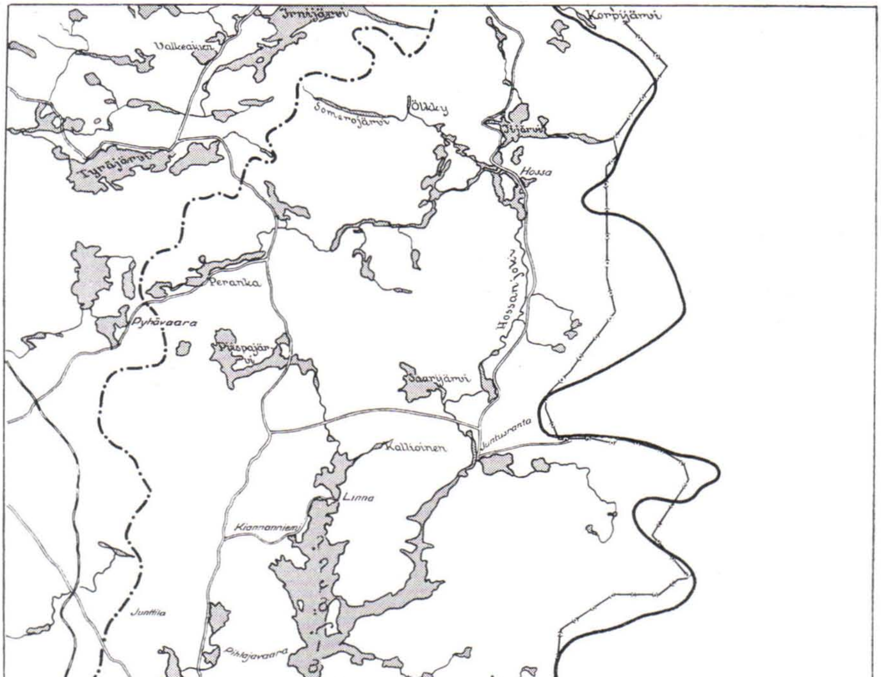

Fig. 2. Watercourses and watersheds of the area. 1. the main watershed, 2. the watershed between drainage basins of Rivers Oulujoki and Iijoki, 3. the watershed between the watercourses of Sotkamo and Hyrynsalmi.

corner is a small part of the Sotkamo drainage basin, also discharging into Lake Oulujärvi. The north-western part belongs to the Iijoki River basin draining into the Gulf of Bothnia. For the most part, the international boundary follows the main watershed. Only small parts on the eastern border drain to the White Sea. Thus divide features are characteristic of the area.

The map, Fig. 2, shows that many rather long lakes and arms of lakes have definite trends, and to make this still clearer, Fig. 3 has been constructed. This diagram indicates the direction of the long axes of 200 lakes all over one kilometer in length. The direction of the axes has been plotted on the map, without regard to origin or size of lake. Thus it will be seen that the lakes in the southern part of the area trend W.N.W., while in the northern part, they trend W.—E. To some degree this can also be seen in the directions of rivers and brooks. The second

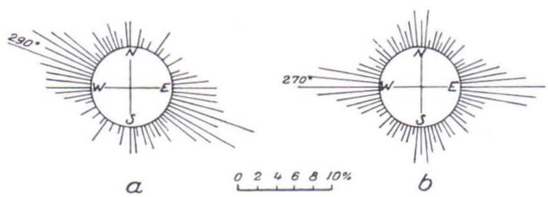

Fig. 3. The trends of the lakes in the area, diagram a. in the southern half, diagram b. in the northern half.

trend of the watercourses and lakes is, according to the diagrams, northerly. The most important lake with this direction is Kiantajärvi. A definite orientation, however, cannot be ascertained for many watercourses, and several lakes are roundish without distinct long axes.

Figure 4 shows the absolute heights above sea-level of the area investigated. The highest summit, Rajavaara in the parish of Kuusamo, rises about 340 m. above sea-level, while the level of Lake Hyrynjärvi in the south-west lies at 155 m. The chief part of the area is situated between the contour lines of 200—275 meters, the average altitude being about 226 m. (Renkonen 1933). In general, the absolute height increases from the south, northwards.

Locally the heights in the area vary within very small limits, being less than 25 meters throughout the greatest part of the area, and the extensive watershed regions are mainly flat, and monotonous, varying in height by less than 10 meters. Local relief in the vicinity of the watercourses and especially, the differences in elevation between adjacent large lakes may reach 25—50 meters, but only in small areas does such relief exceed 50 m. East of Hyrynsalmi Church, locally in the neighbourhood of Lake Kiantajärvi as well as south and east of Lake Irnijärvi, Kuusamo, the differences in height are about 100 m. It should be noted,

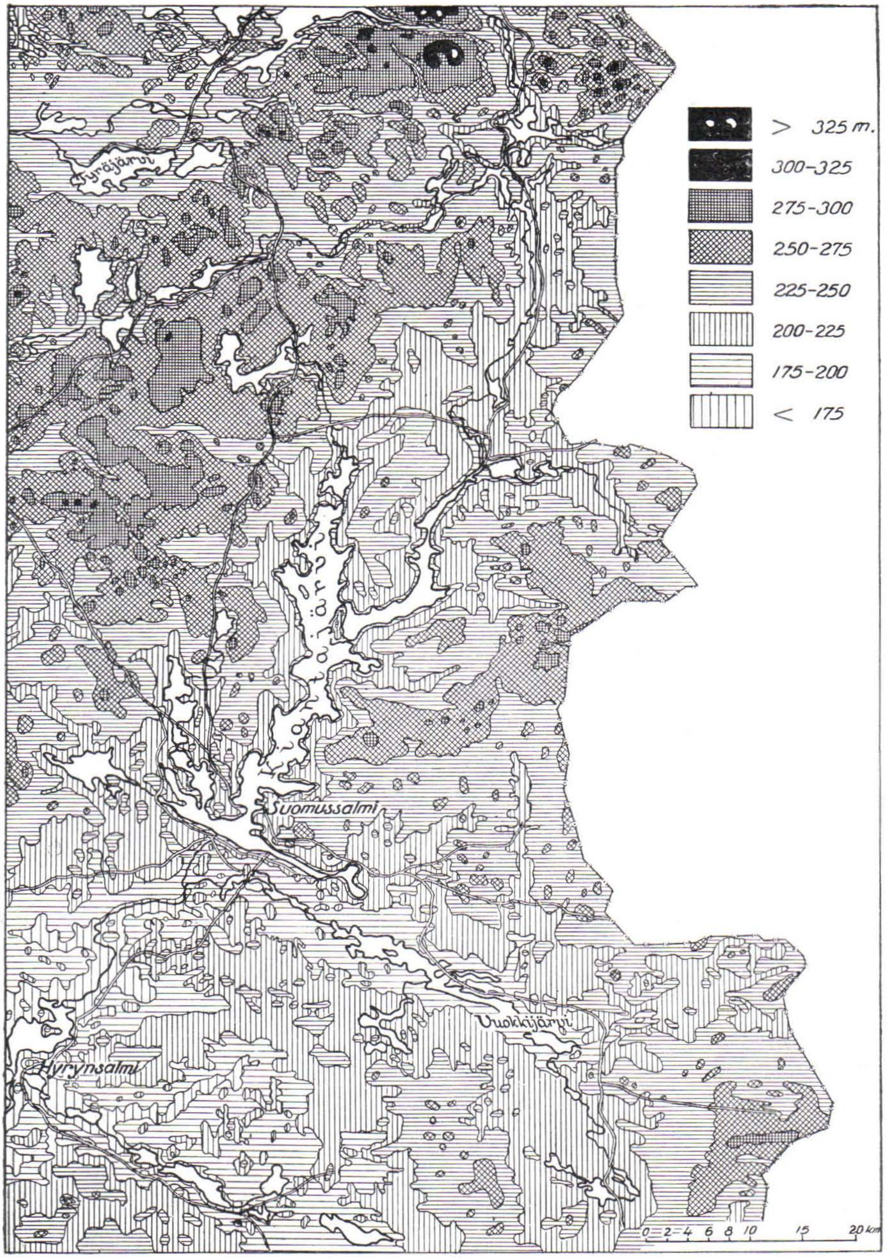

Fig. 4. Relief map of the area investigated.

however, that these figures would be greater if the depths of the lakes were taken into consideration.

Morphologically the area is a peneplain. Wooded hills, separated or occurring in small groups are typical of the whole area. They are 20—40 m. in height often running in an west—east direction. Tanner (1938) used the term »Berghügellandschaft» (mountain-hill landscape) for this topography. Their sides, if not affected by later tectonic movements, slope gently, indicating clearly that the hills are residual. In many instances it can be noted that the western and north-western sides of these hills are steepest (Virkkala 1949). Opposite slopes are gentle since drift is banked up against the lee sides. Furthermore, the stoss sides were not much affected by glacial erosion nor, in general was such erosion effective in forming large relief features (*cf.*, *e.g.* Brigham 1929, Rutherford 1941).

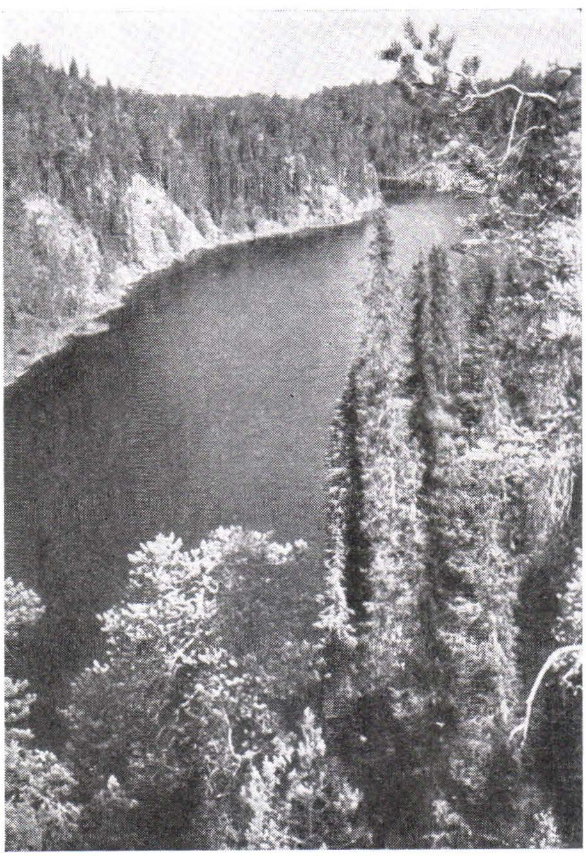

Fig. 5. Lake Julma Ölkky is situated in a tectonic valley, as are many other lakes in the north-eastern part of the area.

The bedrock in the northern part of the area investigated is broken by tectonic valley systems running in various directions. The main directions are west — east, north — south, and north-west to south-east. Tanner (1944) used the term »fissure-valley topography» for these features, which in places contain fjord-like lakes with rocky shores (Fig. 5). These lakes are typical of the north-eastern part of the area (Lakes Somerojärvi, Julma Ölkky, Irnijärvi, Korpijärvi, Jysmänjärvi, *etc.*).

Bedrock relief in the area has been formed by erosion of long duration, resulting in gently undulating features. These ancient forms have been broken by later tectonic movements, which have created a great number of steep, angular forms, to which glacial erosion has given the final polish.

The bedrock of the area comprises Pre-Cambrian gneissose granites and granites. A narrow belt of basic schists belonging to the Karelidic formation runs in a north—south direction across the area, beginning in the neighbourhood of Lake Mikitänjärvi, Hyrynsalmi and continuing via Lake Jumalisjärvi (Wilkman 1921) to the east of Suomussalmi church village. There it is broken off and begins anew as a fairly broad belt around the northern end of Lake Kiantajärvi, continuing with breaks passed Lake Saarijärvi to the N. E. corner of the area. These series of schists are mainly basic schists, and ultrabasic intrusions; in addition, two rather large occurrences of quartzite are found in the southern part of the area. The gneissose granitic bedrock is cut by gabbros, granodiorites, microcline granites, and diabase veins, which are very numerous, but of small extent. Especially diabase veins are common in the north-western and south-eastern parts of the area. A broad quartzite belt of the Karelidic formation runs parallel to the southern half of the western border of the area, and a few kilometers to the west.

THE SUPERFICIAL DEPOSITS AND THEIR DISTRIBUTION IN THE AREA

Till is the most common and important of the superficial deposits in the area. On the map it covers about a half of the land area and, in addition, forms the base for most of the other superficial deposits. Only the small rock exposures are not covered by it. The till most typical of the area is unsorted, poor in stones, in fact, often quite stoneless (Fig. 6); rich in fine sand, but poor in clay. The till occurs as ground moraine forming undulating plains on the surface of the bedrock, and as morainic hills and drumlins. Morainic hills forming smaller or larger groups are found throughout the area, but appear in greatest numbers within a zone resembling an asymmetric arc, running in an west — easterly direction across the area (Fig. 7). Drumlins are scattered here and there but compared with

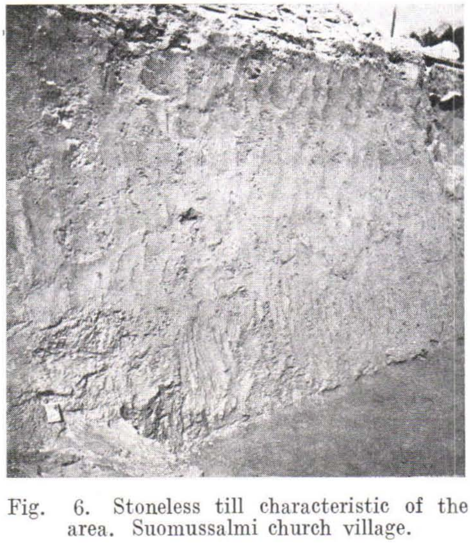

Fig. 6. Stoneless till characteristic of the area. Suomussalmi church village.

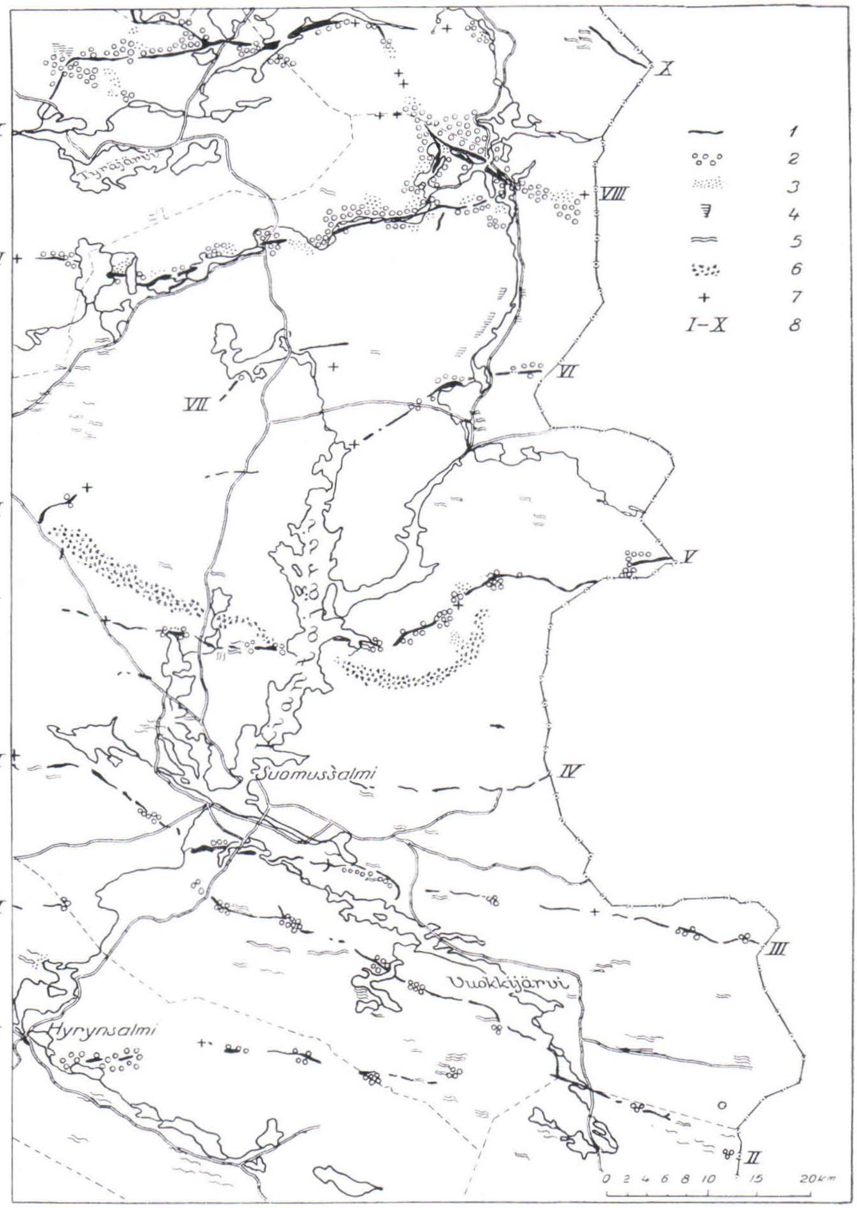

Fig. 7. Some glacial forms in Suomussalmi. 1. esker, 2. kame, 3. sand plain, 4. ice-contact terrace, 5. drumlin, 6. end moraine, 7. tectonic valley, 8. numbers of the esker chains.

the drumlins farther north at Kuusamo (Hänninen 1915), the Suomussalmi drumlins are more weakly developed and the orientation of the terrain is more indistinct.

The most common of the sorted superficial deposits are gravel, sand and fine sand. Gravel is found especially in the numerous esker chains and adjacent kames. A thin cover of shore gravel on the surface of the till is common, particularly in the southern part of the area. Sand and fine sand, in addition to that found in eskers, occur in wide, more or less flat plains, typical of the area (Fig. 7). Sand and fine sand occur in dunes especially in the great basin, containing from north to south, Hossanjoki River, Lake Kiantajärvi, Emäjoki River and Lake Hyrynjärvi (Fig. 4). Clay is not found in the area, and silt is only met with as tiny occurrences on the shores of the lakes and at the bottom of peat bogs.

Peat deposits are very common. According to Ilvessalo (1930), the bogs with peat in thickness exceeding 30 cm., comprise 41—42 per cent of the area. The bogs in the present area do not form wide continuous plains, but occur as a network of bogs covering the lowest places of the terrain. Sloping peat bogs are relatively common. The abundance of brown moors is a feature of North Finland (Plate I, Fig. 1).

LATE-PLEISTOCENE CHANGES OF LEVEL

The mode of disappearance of ice sheet depends to a great extent on whether the retreat takes place on emergent land or in water (*e. g.* Flint 1942, 1947). The retreat of a glacier on emergent land takes place mainly by melting (Antevs 1939), in water by calving (Antevs 1932). The formations resulting from the direct or indirect activity of the glacier are dependent on their relation to the level of the water. This applies, for the most part, to stratified drift, and also to a certain degree to unstratified drift. Consequently, it is necessary to consider the regional changes of level as well as the relations between the ancient water level of the area and that of the Ocean and Baltic Basin.

According to Sauramo (1929, 1940), most of the Suomussalmi area belongs to the supra-aquatic land area, which was above sea-level throughout all deglaciation. Hyyppä (1936) states that the highest shore around Lake Irnijärvi in the northern part of the area is c. 270 m. above sea-level. The author has made a great many observations concerning the spread of the ancient water body, paying the greatest attention to the shore deposits.

Indications of a water level are found up to the contour line of c. 300 meters, and it seems that the lack of any higher hills explains why no higher shore lines have been found (Virkkala 1948). The shore formations are in part wave-cut cliffs, and in part shore accumulations. The most common and convincing of the shore marks are the sand plains where wave action has truncated the tops of the eskers. The highest of such esker plains is situated at an elevation of about 290 meters.

The highest marks of water level in the area are marine deposits between 230—300 meters in the east and between 260—300 meters in the west (Virkkala 1948). A poor marine diatom flora is found in some of these accumulations. The lowest thresholds measured in the watershed areas on the eastern frontier are situated at a height of about 230 meters. Thus the oldest sea in this area, called »Karelian Ice Sea» by Hyyppä (1943), was connected with the White Sea (*cf.* also Jakowlew 1924, 1934 and Markow 1933, 1935). The shore deposits found below this marine phase, between the contour lines of about 190—230 meters in the eastern part of the area and between 220—260 meters in the west, were on the other hand, formed in the Baltic Ice Lake (Hyyppä 1936, Sauramo 1940). The youngest marks of water level are those of the marine Yoldia deposits of the Baltic Basin found only in the low-lying south-western part of the area (Virkkala 1948). Owing to the continued land upheaval, the distribution of land and water in the area was about the same as at present even at very early date.

The whole area investigated belongs, as a matter of fact, to the area which was sub-aquatic in the late-Pleistocene. But the summits of the very highest hills may possibly have risen above the highest water level.

STRIATIONS

The best indicators of glacial movements are the striations cut in bedrock by the advancing glacier. Comparatively thin, moving glacier tends to conform to topographic irregularities, therefore simultaneously forming striations which diverge very considerably in trend within limited areas (Goldthwait 1941, Lundqvist 1935, Sauramo 1924). Even beneath a fairly thick ice sheet, striations of various directions may be formed simultaneously in the same locality, especially if there are steep rock slopes in question. Very small topographic irregularities have been ascertained to have caused a divergence of even 40 degrees in the main directions of striations on a flat surface (Demorest 1938, Edelman 1951, Holmes 1937). Such great divergencies in striations of the same age have not been found in the Suomussalmi area. Divergencies are few, not over 10—15 degrees, and represent striations of the same age, as is proved by the fact that the most divergent striations change through intermediate ones into the striations of other directions. When making observations of striations, the average and most predominant direction of striations belonging to the same group has been taken into account in each locality.

The striation observations have been made by compass to the nearest 5 degrees, selecting localities where the topographic changes have had the least possible effect upon the directions of striations. A detailed list of the numerous points of observations has not been given, but the map, Fig. 8, presents the greater part of the striation observations made in the area investigated. Where numbers of striations of the same direction are situated near one another, they are shown as one single observation to simplify the map. The magnetic declination has been corrected when plotting the striations.

83 per cent of the striations run in a west — east direction. In the northern part of the area this direction turns to W.S.W—E.N.E. and in southern part to W.N.W.—E.S.E. Almost without exception, other erosion forms in bedrock run in the same direction; the stoss sides of the polished outcrops as well as grooves and various friction cracks. Grooves occur fairly commonly and always run in a W.—E. direction. On the other hand, friction cracks are much rarer in the area as outcrops of bedrock are of a relatively small extent. The friction cracks are crescentic gouges, and crescentic fractures (Harris 1943). The convex side of the crescentic fractures is either backward or forward (Flint 1947, Okko 1950, Saksela 1949). No one type predominates over the other. The size of the crescentic fractures varies considerably, from a few centimeters to about half a meter. The bisector of the arc conforms to the regularly predominant westerly direction of the striations. Crescentic gouges varying from some centimeters to a few meters, have been met with comparatively rarely on the lee sides or the polished surfaces of the rocks. The steeper side of the smaller gouges faces into the direction of movement of the ice (Plate I, Fig. 2). The crack causing the chip, dips downstream according to Flint (1947) and Harris (1943).

Sometimes the polishing of a rock has been so thorough that no striation is to be seen. The material embedded in the glacier was so fine-grained that the formation of striations was impossible. The form of the polished rock even under these circumstances shows the direction of the glacial movement.

Thus the most general and numerous small-scale features of glacial erosion in the area show the W.—E. direction. This most distinct and predominant direction of striations and erosion is shown on the map, Fig. 8, by striation arrows with four short transverse lines.

The average direction of the west—east striations in the northern part of the area is 267°[1] (ranging from 251° to 283°), in the southern part the average is 273° (ranging from 246° to 297°), and the mean of the whole area being 270°.

[1]) The number of degrees indicates the upstream azimuth of the ice movement.

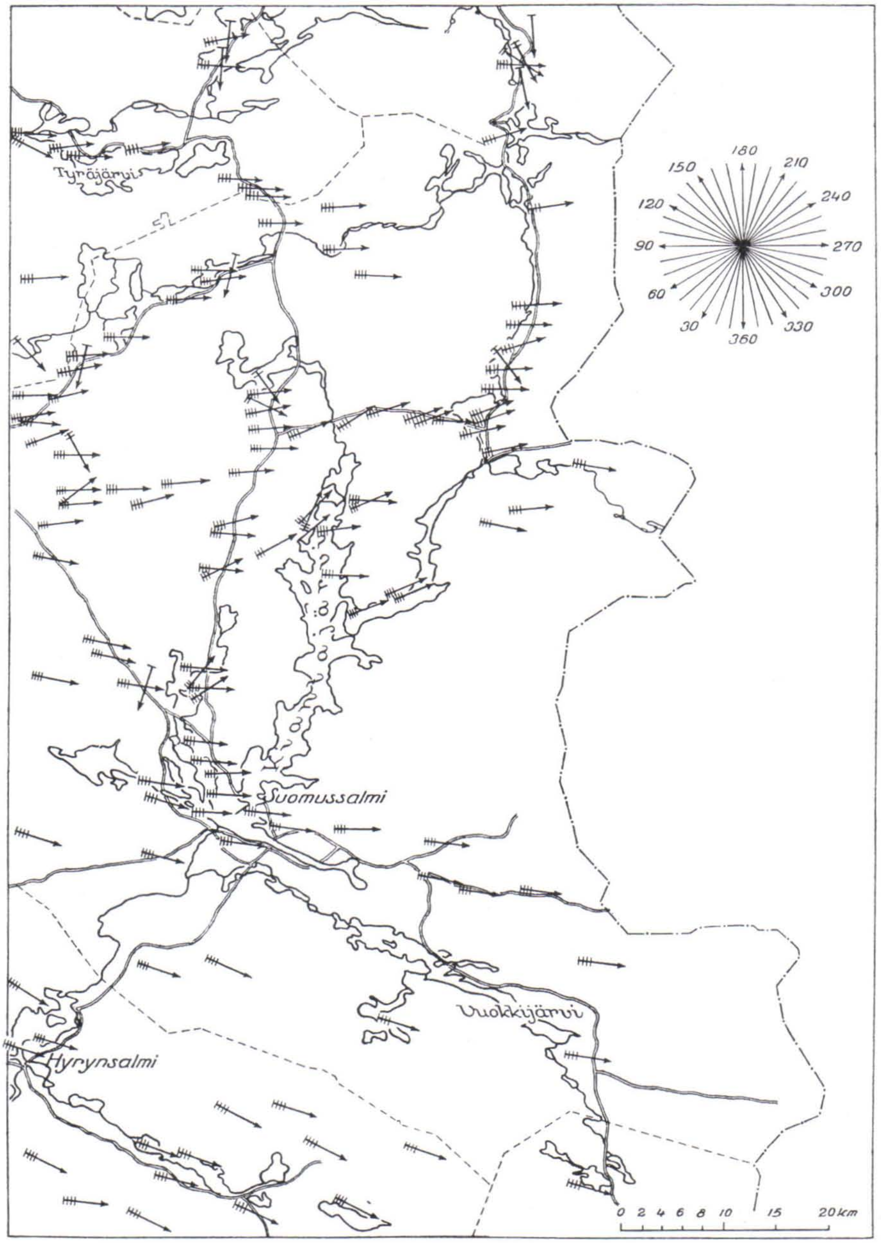

Fig. 8. The striations. The relative age of striations is shown by the number of transverse lines on the arrow, which increases in proportion to age.

In addition to this dominating trend, a number of observations of other trends have been made and these can be classified into three groups: from the south-west, north-west and north.

The S.W.—N.E. trend of striations appears almost exclusively in the neighbourhood of Lake Kiantajärvi where 11 observations have been made. In most instances small-scale bedrock erosion forms indicate a glacier advancing from the south-west and not from the opposite direction. In five localities the south-westerly striation is found crossing the westerly striations, thus being younger in age. The greater distinctness and finer structure of these striations also indicate their younger age (*cf.*, *e. g.* Lundqvist 1943). The average trend of the south-westerly striations is 235° (ranging from 218° to 248°). On the map, Fig. 8, these striations are marked by three short transverse lines on the arrow. On the map the striations north of Lake Kiantajärvi are counted as westerly, but it was impossible to ascertain the correct group, as the westerly striations in the northern part of the area seem to trend a little to the south-west.

The north-westerly striations have been found in nine localities in the northern part of the area. The average direction of the north-westerly striations is 317° (ranging from 310° to 333°). They cross the westerly striations at four localities north of Lake Kiantajärvi and along the abandoned Hyrynsalmi—Kuusamo military railway, near the western margin of the area. Finer and sharper north-westerly striations cut the coarser and broader westerly striations (Plate I, Fig. 2). In places it has been observed that the north-westerly striation has eroded the south side (stoss side) of the westerly striation to a gentler slope than the north side. The north-westerly trend of striations is thus younger than the westerly one, but the writer has not been able to ascertain its relation to the south-westerly striations. On the map, Fig. 8, the north-westerly striations are marked by two short transverse lines across the arrow.

The northerly striations are the last group of the striations. These have been met with in seven localities. The average trend is 8° within the limits 351°—18°. Most of the observations are those of crossing striae, where the sharper and finer northerly striations cut the stronger and coarser westerly striations, thus being younger in origin. In other instances the northerly striation is situated on the northern slopes of the bedrock, while the westerly striation and erosion forms predominate in the other places. Weathering has in places destroyed the fine and weak northerly striations. On the map, Fig. 8, the northerly striations are marked by one transverse line across the arrow.

Thus the observations show that the strongest, most numerous and distinct glacial scratches in the area run from west to east. In addition to this direction, at least three more trends are met with in the area. All these are younger than the westerly trend, yet their mutual age relations could not be determined on the basis of the striations.

Figure 9 gives a general view of all striation observations in the present area. The orientation diagram gives the percentages of the striations with various azimuths in the southern and northern parts of the area separately, as well as in the whole area investigated. The directions of the striations in the diagram are to the nearest five degrees. It is clearly seen from the diagram B that striations other than westerly are concentrated in the northern part of the area, and that the north-westerly and northerly striations form independent groups of their own, whereas the south-westerly striations, pass gradually into westerly ones. Diagram C clearly shows the relative scarcity of striations divergent from the main trend.

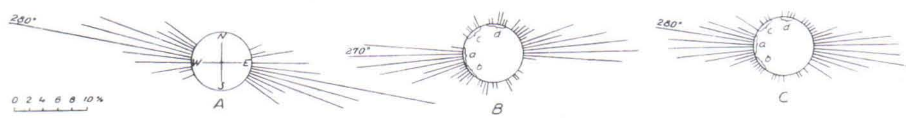

Fig. 9. Summary of the trends of the striations. The diagram A. in the southern part, B in the northern part, C. in the whole area; a. westerly, b. south-westerly, c. north-westerly and d. northerly striations.

A comparison of Figs. 3 and 9 shows an astonishing parallelism between the trends of lakes and westerly striations. It is hardly a coincidence that the directions of both in the southern part of the area run west-north-west and in the northern part nearly west. However, the parallelism between the northerly trends of lakes and striations is less evident. In every case it seems clear that such parallelism is the result of the movement of ice.

The importance to be attributed to the definite grouping of striations of various trends has not yet been ascertained. Such grouping may be the result of exceptional trends of the ice produced by local irregularities, and if so, cannot be given too great a significance in the investigation of glacial movements. On the other hand, they may indicate independent movements of the glacier, and in that case should occur over wide areas, and be of great use in the elucidation of the last stages of the Ice Age. The greatest caution, however, must be observed in the interpretation of striations, a fact that has been emphasized by many investigators (*e. g.* Flint 1947, Hyyppä 1948, Sauramo 1924). To ascertain the glacial movements, an additional method, the study of till stones, must to be used.

TILL STONES

LITHOLOGIC COMPOSITION

The determination of the lithologic composition of till stones is one of the best indicators of ice flow (Flint 1947), and its importance has been emphasized especially by Sauramo (1924) and by Geijer (1917). The bedrock of the present area, however, is comparatively unsuitable for this purpose. Primarily, this is due to the lack of distinctive rock types. A broad zone of quartzite just beyond the western margin of the area and numerous quartzite outcrops of small extent within the area have been the source of quartzite stones found over the entire region. This applies to an even greater extent to the basic rocks scattered throughout the area in numerous, small outcrops. Some possibilities of tracing the path of till stones are provided by the central schist zone (*cf.* above p. 13), as the following example will make clear.

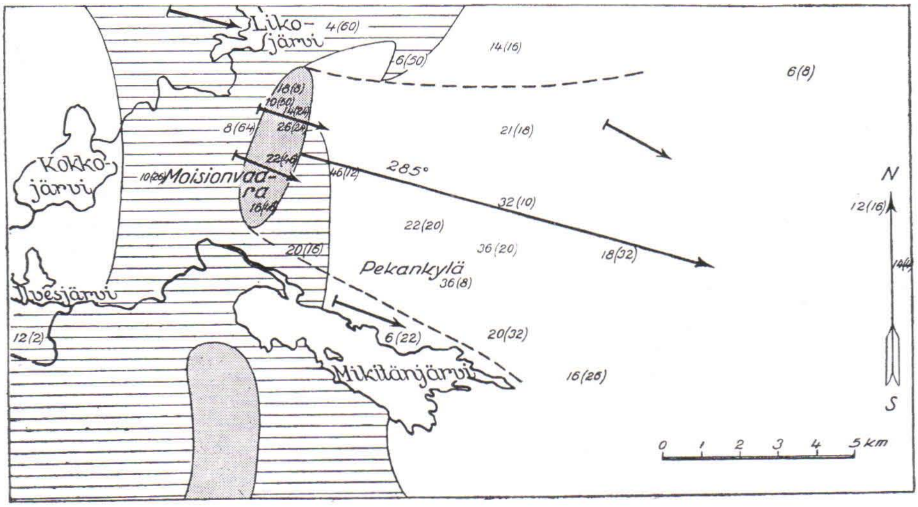

Fig. 10. Stone counts in the environment of the hill Moisionvaara. Numbers without brackets indicate the percentage of quartzites, numbers in brackets the percentage of basic rocks, lined areas — basic bedrock, gray areas — quartzitic bedrock, white areas — granites; the limits and the average trend of the quartzitic boulder train, as well as some observations of striations are drawn on the map.

The hill Moisionvaara in Hyrynsalmi rises as a quartzite hill to a height of 30—40 meters above its flat and boggy surroundings. Marks of glacial erosion are clearly seen on the hill, and drift transported by the continental ice has been carried from the hill into the neighbourhood. West of Moisionvaara is a zone of basic, metamorphic schists 3—5 km. in width, and west of this, as well as east of Moisionvaara, are wide areas of granite (Wilkman 1921).

On the hill Moisionvaara and in its vicinity, many counts have been made of stones 5—10 cm. in diameter, and the results are presented in Fig. 10. To make it clearer, the rock types have been divided into three groups: quartzites, granitic and basic rocks. The proportion of the quartzite and basic rocks is given as a percentage at each point of observation, while that of the granites can be calculated.

The stone counts show that the proportion of quartzites on Moisionvaara is approximately 20 per cent of the till stones. The amount of quartzite is greatest east of the hill, but farther eastwards the amount steadily decreases. Immediately west of the hill about 10 per cent of the stones are quartzite originating from the wide quartzite area situated still farther to the west. The proportion of the quartzite stones in the till increases steadily towards the west-north-west. The transport of the quartzite stones has thus taken place in an east-south-east direction. On the basis of the quartzite stone counts, it is possible to determine the limits of the Moisionvaara drift with considerable accuracy. The boulder train obtained in this way is drawn on the map, Fig. 10. The direction of its bisector (285°) shows the average trend of the transport of drift, to be almost parallel to the striations in the area (290°—295°). Stones from the outcroups of basic rocks in the vicinity of Moisionvaara also seem to have spread in an west-north-west—east-south-east direction.

In the same way the main part of the till stones in the area can be ascertained to have spread in an west—east direction. The quantity of quartzite stones, is greatest 40—50 per cent, at the south-western edge of the area, and decreases steadily eastwards. Basic till stones occur most abundantly in the eastern part or a little to the east of the central schist zone. Thus stone counts show that transport of till has taken place mainly in an west—east direction, corresponding rather accurately to the predominant direction of striations in the area. On the other hand transport corresponding to other trends of striation could not be ascertained in the lithologic composition of till stones (*cf.* also Geijer 1917).

TILL STONE ORIENTATION

Richter (1933, 1936), Holmes (1938, 1941) and Krumbein (1939) ascertained that the long axes of stones are usually oriented parallel to glacier flow, but in some instances are transverse to it. After the publication of these studies on till fabric many investigations were carried out in Finland and fabric analysis successfully applied as an indicator of the direction of ice movements (Hyyppä 1948, 1950, Kivekäs 1946, Mölder 1948, Okko 1949, Virkkala 1949). As several directions of striations have been found in the Suomussalmi area, the orientation of till stones has played an important rôle in estimating the significance of striation as an indicator of glacier movements. Two examples will throw light on the relation between till stone orientation and the direction of striation in the area.

The first fabric analysis of till was made at a depth of about 0.6 m. on the slope of Kypärävaara hill, Hyrynsalmi. The trends of the stones were determined by compass to the nearest 5 degrees. For analysis the only stones considered were those with a long axis at least 1 ½ times longer than the next axis and lying at an angle of not more than 30 degrees to the horizontal (Holmes 1941). The trend of the long axis of 50 stones was determined in this and the following fabric analyses, this number usually being sufficient to indicate the preferred axial orientation of stones, if any. The author generally found, contrary to Holmes (1941), that more elongated the axis, the more clearly is the stone orientated in the direction of glacial flow. The analysis was made using stones less than 10 cm. in diameter, but larger stones were also considered if found. Following Holmes's method, boulders were omitted, and this is contrary to Lundqvist (1948) who deals only with the orientation of boulders. The best stones for fabric analysis are schistose ones, but they are comparatively rare in the area.

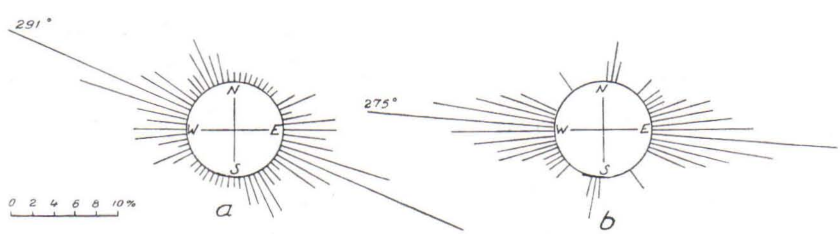

Fig. 11. Two orientation diagrams of till stones in the area. a. Kypärävaara, b. Pyhävaara.

The results of the Kypärävaara analysis are presented by a orientation diagram, Fig. 11 a. The percentage of stones orientated in each direction is indicated by the length of line measured outwards from the circumference of the circle. The diagram clearly shows the main trend to be west-north-west; the maximum being 291° and the minimum transverse to it. Clear striations at 294° are found on the gentle slopes of Kypärävaara (Fig. 8). Thus the direction of till stone orientation closely corresponds to that of local striations in indicating the direction of ice flow in the area.

The second example is taken from the excavation for the new Pyhävaara elementary school at Suomussalmi in the northern part of the area. Two fabric analyses were made here; one at a depth of about one meter, and the other at about 2 ½ meters. The results of the deeper analysis are seen in Fig. 11 b, but the two analyses were very similar. The fabric analyses and the diagram were constructed by the method described above. The Pyhävaara analysis is an ideal one, the dominant direction being almost westerly and the maximum being 275°. The number of oriented stones decreases evenly on both sides from the maximum. Transverse to the main direction is another smaller, but still clear maximum. This represents, according to Holmes (1941), stones which have not moved by sliding, but have rotated on their long axes in the direction of ice flow. Stones situated at right angles to the main direction are only 8 per cent of all stones counted.

Striations are not found in the immediate vicinity of the Pyhävaara locality. However, two kilometers away is an outcrop with striations on the weathered surface running in a direction of 276°, which agrees with the maximum of the fabric analysis.

These two examples prove that fabric analysis can be successfully used in the Suomussalmi area as an indicator of glacial movements thus throwing additional light on observations of striations.

About a hundred fabric analyses of till stones have been made in the Suomussalmi area, all of them carried out by the methods described above. In many instances, analyses at various depths have been made at the same locality, this having been proved necessary and useful, after several trends of striations had been observed in the area. The depths at which analyses were taken vary from 0.5 to 5 meters. The upper part of the till, down to a depth of about ½ m. usually has no orientation of till stones, probably due to secondary factors such as frost, washing, *etc.*

All fabric analyses made in the area could not be represented by separate orientation diagrams, as is the case with the examples above. Instead, the maximum orientation of each fabric analysis has been shown by a simple arrow; thus for instance the maximum of the Kypärävaara analysis is 291°; Pyhävaara of 275°. The result of 80 fabric analyses from 68 observation points is seen on the map, Fig. 12. Analyses without a clear maximum or with the same orientation at several depths at the same locality have been omitted for the sake of simplicity. The magnitude of an orientation maximum is indicated by the length of the arrow as seen by the scale on the map. The figure inside the circle is the number of the locality, the other figure indicating the direction of the orientation maximum. When two fabric analyses have been made at the same locality (*e. g.* point 50), the two arrows are joined by a short line, the lower analysis — as drawn on the map — having been made from the deeper part of the till. Two maxima in the same analysis at the same depth are represented by diverging arrows. Finally, maxima probably belonging to the different groups are distinguished by black circles on the arrows. In three instances (localities 13, 51, and 61), the group could not be ascertained.

The map (Fig. 12) shows the clearest and strongest maximum to be situated between west and west-north-west. The predominant trend in the southern half of the area is W. N. W., the mean being 283° (ranging from 266° to 294°). The same trend predominates over all the northern part as well but is in places a little south of west, the average direction being 273° (ranging from 256° to 285°). Some 60 per cent of

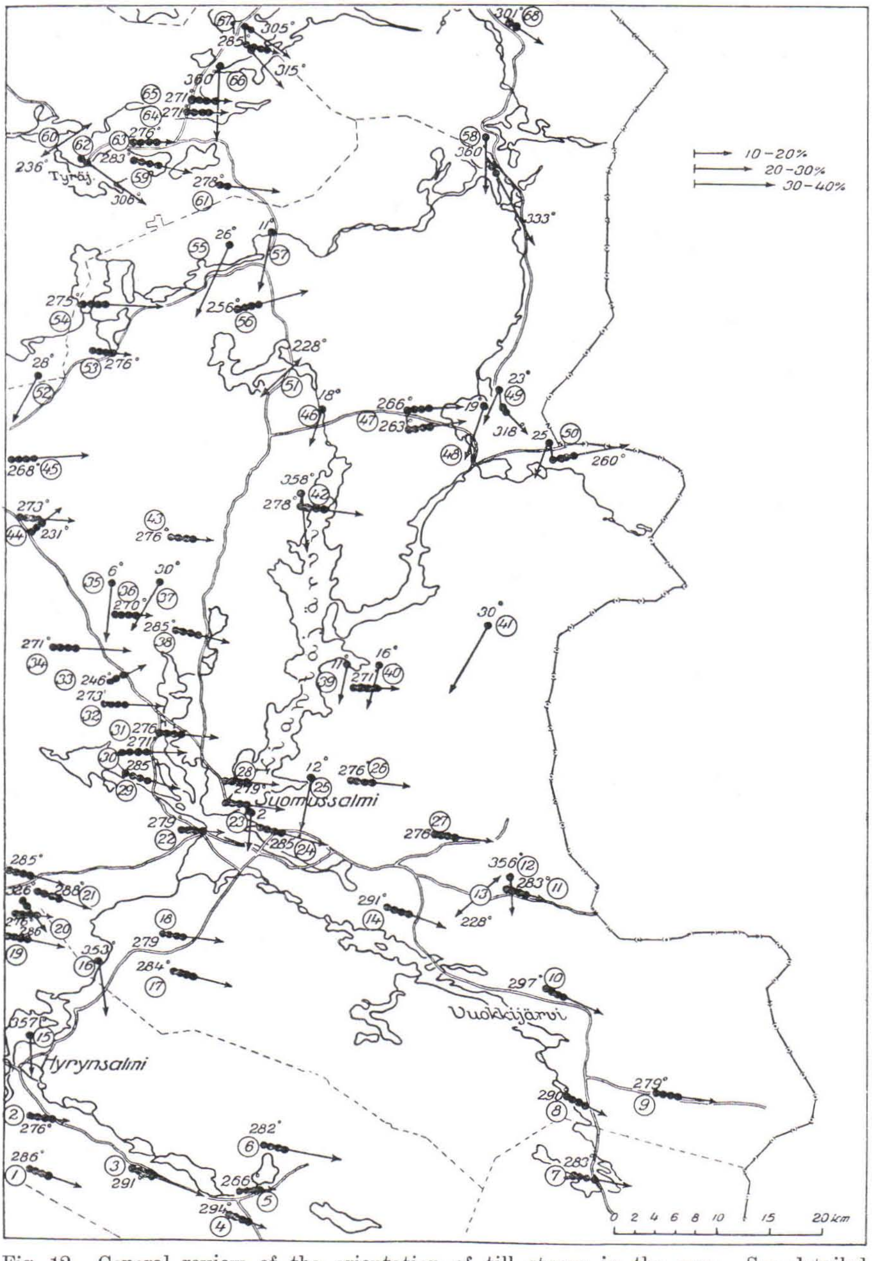

Fig. 12. General review of the orientation of till stones in the area. See detailed explanation p. 24.

the fabric analyses have a westerly trend, the mean of all westerly analyses being 278°. Fabric analyses with a westerly direction are marked by four black dots on the arrow. The westerly trend is found alone or together with other directions.

In places till with W.—E. oriented stones has been found to overlie stratified drift. Such till is found near Laaja railway station (see below), as well as near Iijoki River, on the Suomussalmi—Kuusamo highroad (locality 64), where a layer of westerly till about 2 meters in depth was found above thick sorted sand.

Thus, from the map a westerly direction can be seen to be predominant, as was the case with striation observations, but there are also other directions: south-west, north-west and north.

There are only two observations of the south-westerly direction (nos. 33 and 44), both presenting a rather weak maximum, the mean of both directions being 238°. At locality no. 44 there was also the westerly main direction in the same fabric analysis.

Seven observations ranging from 301° to 333° have been made of the north-westerly direction having the average trend of 315°. This direction sometimes occurs as the sole orientation maximum (nos. 62 and 68), and sometimes together with other directions. In localities 49 and 58 it is found in the basal layers of the till, the upper part of which shows a northerly direction. It appears together with the westerly direction in localities 20 and 67.

There is a mantle of till ½—1 meter thick lying on stratified sand and gravel near Laaja railway station on the Suomussalmi—Puolanka road (locality 20). The contact between till and gravel is very irregular (Plate I, Fig. 3), and the till stones are considerably rounded and may have come in part from the underlying washed drift. The orientation of the till stones shows two weak maxima, one from the west and the other from the north-west. A similar arrangement of layers has been observed in some localities around the western end of Lake Pesiöjärvi, but no fabric analyses have been made of that till. Analyses with the north-westerly orientation are shown by arrows with two black dots on the end.

There are 20 observations of the northerly direction, the average being 12° (within the limits of 353°—30°). In 15 localities the northerly direction predominates, occurring either in upper till where for practical reasons most of the fabric analyses have been made, or deeper in the underlying till (nos. 48 and 55). Of greater interest are two observations (nos. 58 and 42) showing the northerly trend together with other directions, both observations with two separated till layers, and these will be described in detail.

Figure 13 gives a schematic drawing of a section of till on the north-western shore of Lake Iijärvi, Kuusamo (locality no. 58, Fig. 12). On the northern margin of the section is a layer of till A, about 1 ½ m. in thickness but thinning southward. As shown by Fig. 13, this till has a distinctly northerly orientation. It is typical of the area; rich in sand, unsorted and unwashed. Beneath this is layer B, also tapering towards the southern limit of the section, and consisting of well washed till, all

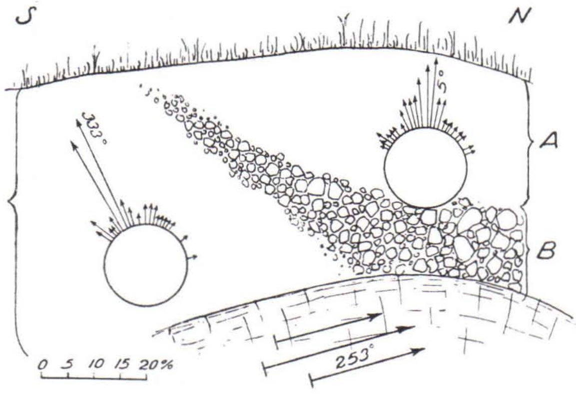

Fig. 13. Diagram showing the till beds and their orientation, Kuusamo, Iijärvi. The upper till bed A shows a clear northerly orientation of till stones, while in the lowest bed C the orientation of till stones is 333°. The bedrock has west-south-westerly striations.

material finer than gravel being lacking. Layer B lies directly on the bedrock in the northern part of the section, but towards the south it rises gradually to the surface, with layer C beneath. The material of C is similar to that of A, but its stones are very clearly orientated in a direction of 330°—335°. A rock at the base of the section shows a clear striation running in a direction 253°. The till section in question thus distinctly indicates that movement of ice has taken place in three directions, namely from the west-south-west, the north-west and from the north, the first being the oldest and the last the youngest.

Two layers of till, one above the other, were found on the western shore of Linnasalmi north of the village of Kiannanniemi, Suomussalmi (locality 42). There, the beds of till occur as horizontal layers while between them is a layer of washed till about 1 meter thick, its stones showing no orientation. The overlying till, about 1 ½ m. thick, shows a very clear northerly orientation (358°), while the underlying, unwashed till has of a distinctly westerly one (278°). The lowest till continues down to a depth of 5 meters, there grading into a very tough and compact hardpan. Particle-size analyses (Fig. 14) show no essential difference between the westerly and northerly till, while the lithologic composition of the till layers varies to some extent, as shown by the table below.

	northerly till			washed till			westerly till		
granitic rocks	40		per cent	42		per cent	64		per cent
quartzites	12		» »	24		» »	22		» »
greenstone schist ..	40	48	» »	30	34	» »	10	14	» »
gabbro-diabase	8			4			4		

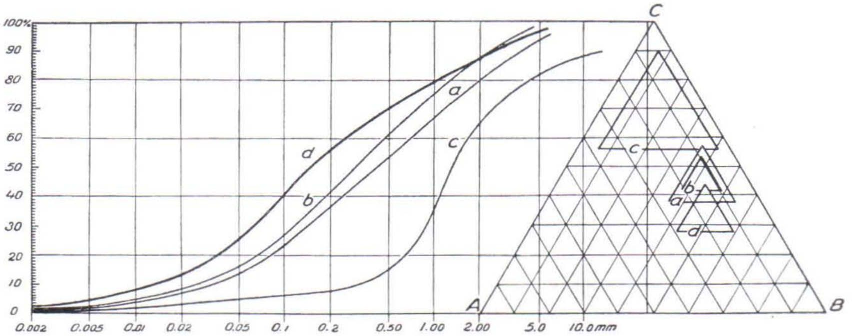

Fig. 14. Grain-size analysis of till beds in Kiannanniemi presented by cumulative curves (left) and by triangle diagram (right). A. clay and silt, B. fine sand, C. sand, the size of the small triangles indicates the amount of gravel (Krumbein and Pettijohn 1938); a. northerly till, b. westerly till, c. washed till, d. the average composition of till in the Suomussalmi area.

The amount of basic rocks in the northerly till (48 per cent) is thus considerably greater than in the westerly one (14 per cent). The local bedrock is greenstone schist while the granitic area in the north as well as in the west is at the same distance from this locality (Matisto, field notes 1949). The northerly till thus indicates that transport has been local and taken place over a shorter distance.

The Linnasalmi fabric analyses show very clearly that the layers of till have been deposited by glaciers advancing from two different directions. The younger northerly movement was weaker, while the westerly one indicates the dominant trend of ice movement and erosion in the area.

Localities resembling these, but not showing different layers in the till, are nos. 49 and 50. Locality 49 indicates an indistinct north-north-easterly orientation in till of about 0.8 m. in depth, and at a depth of 2 meters the orientation of till is weakly north-westerly. No visible limit between different trends could be ascertained.

The surface layer of the till at locality 50 has a weak north-north-easterly orientation, while the westerly orientation deeper down is remarkably more distinct. Till beds could not be distinguished in this instance either.

Both observations, like the former ones, show that the northerly to north-north-easterly direction of ice flow is the youngest of the trends found in the area.

Northerly till overlying stratified drift has been found on the northern shore of Lake Pieni Parvajärvi on the Raate road (locality 12, Plate I, Fig. 4). The layer of till is about 1 ½ m. thick and below it sand continues down a depth of at least 3 meters. This till shows a comparatively weak maximum indicating that the material has been transported approximately from the direction 356°.

As the ground moraine of the area forms a relatively thin mantle, it was possible in the case of many fabric analyses to ascertain the direction of striation either immediately at the bottom of the pit or in its vicinity. In most instances there was a regular westerly orientation of both till and striation with only few and slight deviations between one and the other. The striation clearly originates from an earlier phase of the Ice Age than does the overlying till.

In some instances a northerly orientation of till stones could be ascertained deviating from the trend indicated by the striation of an underlying or adjacent bedrock. An instance has been presented above (p. 27, Fig. 13) where till transported from the north and the north-west has been found on a bedrock eroded by the westerly movement. Many similar observations have been made, all of them in the northern half of the area. This phenomenon indicates that in the northern part of the area the westerly movement of glacial ice is followed by younger, north-westerly and northerly movements which have accumulated till on the bedrock eroded by westerly ice flow.

On a rock at the junction of the Juntusranta, Hossa and Suomussalmi roads (locality 48) there is sandy till, typical of the area, about 2 ½ m. thick. This till is of a weak north-north-easterly orientation, while the clear and strong striation of the rock under the till runs exclusively in a direction of 258°.

The same circumstances exist in the village of Peranka (locality 55). Crossing striations were found on the outcrops by the road, along the northern slopes of a gently rising morainic hill. Such fine and weak, but sharp north-north-easterly striations (from a direction of 19°), were only encountered on rock surfaces sloping northward. They can be traced down into the bottom of the broad and strong striations running in a direction of 266°, and have in part eroded these westerly striations asymmetrically. A clear north-north-easterly (26°) orientation of till stones was ascertained by fabric analyses made on the south-western slope of the same morainic hill. This orientation continues down to a depth of 2 ½ meters where bedrock without striations is encountered.

The most distinct observation of this kind was made, however, on the western slope of the hill Valkeaisenvaara (locality 66) near the northern margin of the area investigated. The bedrock can be seen in many places in the roadside ditches. The erosion forms run in a W. to E. direction and a coarse and weathered westerly striation is seen on the rocks. A very fine striation with a north—south trend is found on unweathered rock surfaces sloping northwards. The rocks on the slopes of the hill Valkeaisenvaara are overlain by a mantle of till 1—1 ½ meters thick. Northerly striations forming clear crossing striations are found on the rocks beneath the till, better preserved there than on the weathered outcrops. The orientation of the till stone material is very clear. About

65 per cent of the small stones in the till are orientated between the directions of 356°—11°.

Along the abandoned military railway between Hyrynsalmi and Kuusamo near the boundary of the parish of Taivalkoski, there is a large gravel pit (locality 52) with bedrock at the base showing abundant striations in the directions 266°—276°. The thickness of the till there is 3—4 meters. Part of the till is unwashed and unsorted, part of it consists of strongly washed layers. The lower layer of the till shows clear signs of washing, and the limit between the different layers is strongly marked (Plate I, Fig 5). The material in the superficial till is clearly oriented in a north-north-easterly direction (28°).

Observations of a northerly orientation are marked on the map (Fig. 12) by an orientation arrow with one black dot at the end.

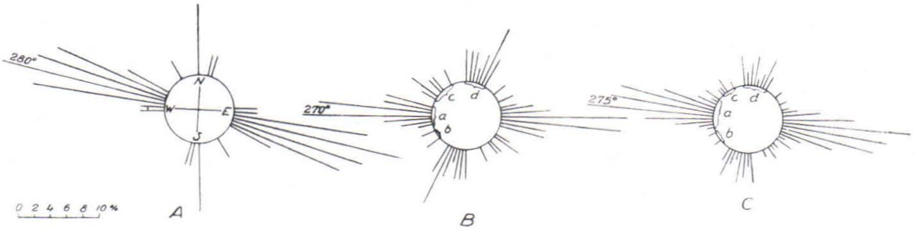

Fig. 15. Summary of the trends of the fabric analyses. A. in the southern part, B. in the northern part, C. in the whole area; a. the westerly, b. the south-westerly, c. the north-westerly, and d. the northerly orientation.

Diagrams A, B and C (Fig. 15) give a summary of the fabric analyses made in the area. In constructing the diagrams, only the number of maxima of the different directions has been considered, not the magnitude of the maxima in the different localities. According to the diagrams the north-westerly and northerly orientations are mainly found in the northern part of the area, where they form an independent group quite distinct from the westerly orientation. The south-westerly orientation of till stones, poorly represented in the fabric analyses, seems, instead, to merge with the westerly direction.

STRIATIONS AND FABRIC ANALYSES AS INDICATORS OF ICE MOVEMENT

In many respects striations and fabric analyses are complementary, for, the erosive action of glacial ice is indicated by the striation, while fabric analyses indirectly show its accumulative work. To explain this relationship, we may draw the following comparisons.

As shown by Figs. 8 and 12, the westerly direction predominates in the striations as well as in the orientation of till stones throughout the entire area. The south-westerly trend is found only in the central portion of the area and in the vicinity of Lake Kiantajärvi, while the north-westerly direction, with one exception, is restricted to the northern part. The northerly striation also occurs almost exclusively in the northern part, and here, too, is where till fabric with a northerly orientation is mainly found. A weaker northerly orientation of till is encountered in the southern portion of the area, but the corresponding observations of striation are lacking there. For the most part, observations of striation and till fabric diverging from the westerly trend were made in the northern part of the area investigated.

In general it is true that the younger the striations in question, the smaller is the number of observations made. 118 observations were made of the westerly striation, 11 of the south-westerly, 9 of the north-westerly and only 7 of the northerly striation. When the ice first moved across this area, it smoothed and striated the rock floor. But it also deposited a more or less continuous till sheet. When the ice changed its direction of flow, it had less opportunity to erode the bedrock because the rock floor was buried in till. And this later ice movement was not sufficiently strong to remove the till and expose the bedrock to further erosion.

With the exception of the westerly direction the fabric analyses show the reverse. Most of the observations (47) have been made of the westerly direction, only 2 of the south-westerly, 7 of the north-westerly and 20 of the northerly one. For practical reasons, the fabric analyses have been made of the superficial part of the till. Thus, excepting the most distributed westerly oriented till, there have been more opportunities to find the younger till.

A comparison between the trends of the striation and of the fabric analyses is presented in the table below.

	Striations		Fabric analyses	
	average direction	range	average direction	range
Westerly direction				
Northern part	267°	251°—283°	273°	256°—285°
Southern part	273°	246°—297°	283°	266°—294°
The whole area	270°	246°—297°	278°	256°—294°
South-westerly direction	235°	218°—248°	238°	231°—246°
North-westerly direction	317°	310°—333°	315°	301°—333°
Northerly direction	8°	351°— 18°	12°	353°— 30°

The average orientation of corresponding groups of striations and till fabric diverge from each other by approximately 5 degrees, which is the same as the degree of accuracy of the compass readings, and thus to all intents and purposes shows that we are dealing with the same directions of ice movement. The range of the striation trends differ from that of the fabric analyses on average of 7 degrees. Striations belonging to any one group have a range of approximately 32 degrees, the corresponding figure for the fabric analyses being 28 degrees. This kind of divergence is to be expected in the normal movement of glacier flow over so great an area as the present one.

A comparison between the striation and fabric analyses may be made by referring to Figs. 9 and 15. In the northern part of the area (diagram B), the correspondence between the two types of orientation is especially evident. The same applies to the striation and orientation diagram C. A clear similarity is also shown by the grouping of the observations of the striation and fabric analyses. The westerly, north-westerly and northerly directions are clearly distinguishable as separate groups, intermediate stages not having been found. The south-westerly direction, on the other hand, merges into the westerly trend.

The age relations of the striation and fabric analyses of the different trends are without exception the same in every locality. In the striation as well as in the fabric analyses the westerly orientation is the oldest, the south-westerly, north-westerly and northerly ones being younger in origin. By means of fabric analyses, the northerly orientation has been ascertained to be younger than the north-westerly one.

On the basis of the foregoing, it is evident that the striation and orientation maxima belonging to the various groups really correspond to each other, and that they indicate the directions of the same ice movements. So the various directions of ice movements cannot be entirely due to the backward shifting of the ice margin caused by the shrinkage of the glacier, because in this case the different directions would grade into one another. On the other hand, they cannot have been entirely caused by the increasing influence of local topography upon thinning of the ice, because then they would not be of such wide distribution. It does not seem likely that the various directions of striations and till stones could have resulted from temporary influence of other local factors. It is thus evident that the various corresponding trends of striation and orientation maxima are indicators of extensive, independent ice movements. This applies especially to the westerly, north-westerly and northerly directions, but the south-westerly trend, with a more limited and less independent distribution, is to be regarded as the result of the influence of local factors on the ice movements. This is shown by the gradual northward turning of the striation in the neighbourhood of the large north—south basin of Lake Kiantajärvi.

The clearest and most abundant marks of erosion in the area thus have a westerly direction. The orientation of till stones is also mainly westerly, particularly when the material of the till is considered as a whole, and not only its superficial part. The latter has been the primary object of the present investigation. The westerly direction in the Suomussalmi area thus represents the strongest erosion, transport and accumulation of the glacier.

THE MORAINIC HILL ZONE OF SUOMUSSALMI

In addition to the phenomena described in the previous chapters there are some morainic deposits also closely connected with glacial movement. These include the morainic hill zone of Suomussalmi and the drumlins.

As mentioned before (p. 13) an arc containing mainly morainic hills is situated across the central part of the area (Fig. 7). This arc is about 50 km. long, ½—2 km. broad and forms a rather distinctive sort of terrain. The zone, otherwise very continuous, is broken in the region close to and on both shores of Lake Kiantajärvi.

The summit altitudes of the morainic hill zone vary between 240—270 m. The local relief is 2—15 m. The eastern part of the zone slopes gently northward, whereas the slope of the western half is almost the opposite.

The topography of the morainic hill zone is greatly variable and the pattern of small-scale features is rather irregular. In the forest maps this is shown by the small size and complexity of the map compartments, in great contrast to the wide areas over the surrounding ground moraine. The morainic hill zone on the forest map is greatly generalized too, and the terrain is much more irregular than indicated on these maps. Figure 16 is a detailed map of the area west of Lake Kiantajärvi near the farm of Junttila, made on the basis of the forest map and mapped topographically by the writer.

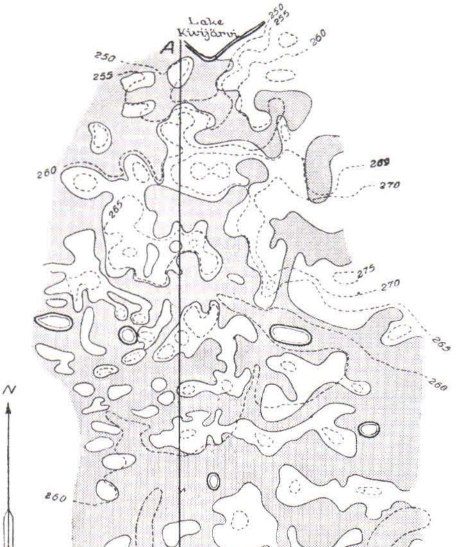

Fig. 16. A topographic detail in the Suomussalmi end moraine west of Lake Kiantajärvi, near the farm Junttila. The line A—B shows the position of the profile in Fig. 18. Numbers indicate height above sea level, gray areas — peat bogs.

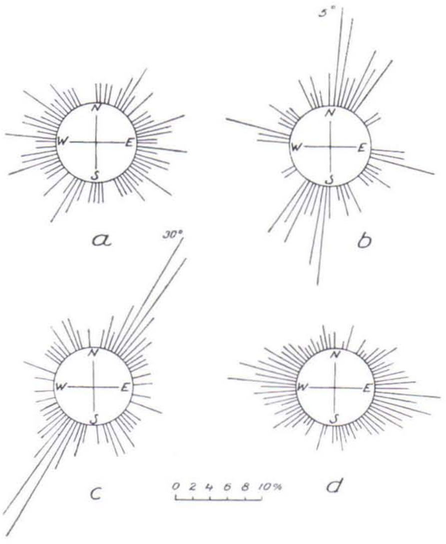

Fig. 17. Results of some fabric analyses of the end moraine, a and b from a hill without orientation, c. from a ridge trending 290°, d. the orientation diagram of the hills and ridges of the end moraine.

The depressions between the morainic hills are covered by peat bogs or ponds and small lakes. Small hills usually 2—10 m. in height, rows of hills or short ridges form dry land. The trend of the ridges is often between west and north-west. There are also numerous ridges with other trends, and sometimes no orientation at all can be detected. The terrain is then composed of short ridges and groups of hills with different directions and no arrangement. The trends of the long axes of 200 hills and ridges were measured in different parts of the morainic zone. The measurements are presented by an orientation diagram like those of the fabric analyses (Fig. 17, d). As is shown in this diagram, a slight orientation maximum can be ascertained in the direction 275°—285°, corresponding to the trend of the main part of the zone.

Parallel ridges and rows of hills are found in some localities in the western part of the zone. If the slope conditions are suitable successive terraces are formed, peat bogs filling the spaces between the ridges and up to the level of the lower ridge; when the peat bog begins to overflow onto a lower level, characteristic, small sloping peat bogs are formed.

As a rule, the morainic ridges are rather short, averaging 100—200 m. in length, and resembling eskers. Sometimes one or another end of a ridge forms a curve, or even a circle. Small depressions like esker kettles are met with here and there among such hills.

Differences in steepness can scarcely be detected on the slopes of the morainic hills, but northward tilting slopes are a little steeper in places. In the cross profile it can be noticed, however, that the northern border of the morainic hill zone is steeper and higher than the part sloping southward (Fig. 18).

Morainic hills also continue onto the slopes of the surrounding higher land covered by ground moraine. These larger rocky hills bordered by morainic hummocks are for instance Kantolanvaara on the eastern side of Lake Kiantajärvi and Pihlajavaara, Hanhivaara and Junttilanvaara in the western part of the morainic hill zone.

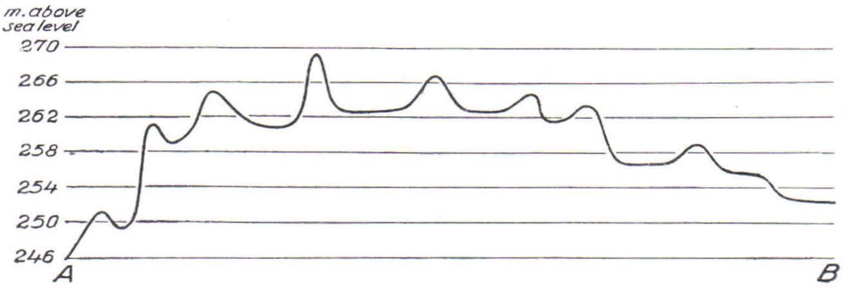

Fig. 18. Profile of the Suomussalmi end moraine along the line A—B in Fig. 16.

The morainic hills are composed of fine sandy till with the little stones characteristic of the whole area investigated. At a depth of 2—3 m. the material changes to a very compact basal till. A little variation can, however, be noticed in different hills. A little sorted drift is found either in separate hills or together with till, sometimes as thin lenses and beds with till forming the main part of the drift, and sometimes forming thicker beds between and under layers of till. The till is in places strongly washed with no fine particles. The upper part of the till then contains considerably more stones than normal. This seems to be true especially in those parts of the zone situated east of Lake Kiantajärvi. Till stones as a rule are angular, but are in places perceptibly rounded. Some grain-size analyses are presented in Fig. 19 from the most typical drift of the morainic hills. As shown in these, grain-size of the unwashed drift of the morainic hills is essentially similar to that of the basal till of the area.

Over ten fabric analyses of till stones in the morainic hills were carried out. The most significant portion of these analyses are shown on the map, Fig. 12. The orientation of the drift is for the most part noticeably

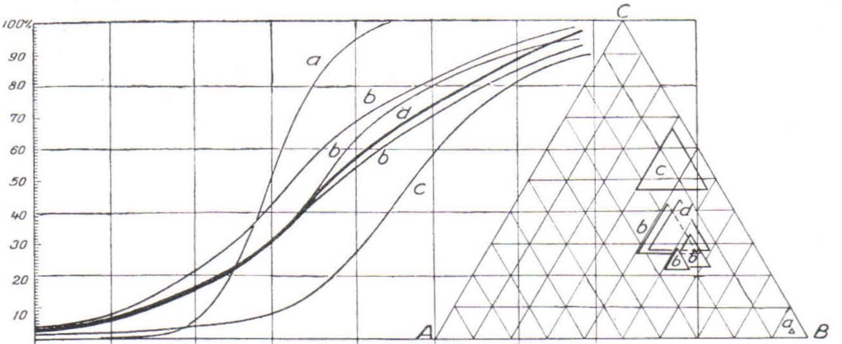

Fig. 19. Some grain-size analyses of the most typical drift of the end moraine, *cf.* Fig. 14, A. clay and silt, B. fine sand, C. sand, the amount of gravel is indicated by the size of the small triangles; a. sand, b. unwashed till, c. washed till, d. the average composition of till in the Suomussalmi area.

weaker and more indistinct than elsewhere in the area. The most distinct trends are westerly and north-north-easterly, but in many fabric analyses it is difficult to observe any orientation maximum. The orientation of the drift seems to be equally weak in spite of the trend of the morainic hills. Relatively distinct orientation is, however, detected in some morainic ridges resembling eskers. The orientation is here at right-angles to the direction of the ridge, and especially when the long axis of the morainic hill is parallel to the general trend of the morainic hill zone. It may be mentioned here that the orientation of the till is northerly even in the north- trending, eastern part of the hill zone. Some typical orientation diagrams of the morainic hill zone are presented in the Fig. 17.

The morainic hill zone of Suomussalmi thus greatly resembles in form, occurrence and composition those deposits which in North America are explained as end moraines originating with the retreat of the ice sheet (Bretz 1939, Leverett 1902, 1917, Leverett and Taylor 1915, Norman 1939, Stauffer, Hubbard and Bownocker 1911, White 1939, Wickenden 1941). This similarity is not changed by the fact that the morainic hill zone of Suomussalmi is originated subaquatic, contrary to the great end moraines in North America, because the water has been in Suomussalmi shallow and of short duration. The end moraines also found in Ireland are very similar (Charlesworth 1928), while the great end moraines in North Germany are of a different kind (Gripp 1929, Scharf 1932, Schott 1933, Woldstedt 1929, 1950). Fredholm's end moraine in North Sweden is also very much like the morainic hill zone of Suomussalmi, as the writer was able to ascertain during the summer of 1949 and as is shown by other investigators (Fredholm 1886, Geijer 1948, Tanner 1915). Similar deposits are also found around existing glaciers, but the orientation of the hills is often much more distinct (Gripp 1929).

The occurrence and especially the form as an asymmetrical arc show, that the Suomussalmi morainic hill zone originated along the margin of an ice tongue, the form of which is reflected in the shape of the end moraine (Rich 1934). The cross profile of the zone is characteristic of typical end moraines. The small-scale relief of the deposit with only slight orientation, and the weak arrangement of till stones, on the other hand, are not typical of such an end moraine, where the thrusting movement of a glacier has been decisive in the origin of the deposit. If the thrusting action of a glacier is powerful enough, the drift should be orientated at right-angles to the direction of ice movement, but in the case of a less powerful movement it should be arranged parallel to the glacier flow.

According to Tarr (1909) unsorted drift in Alaska forms the main part of the knolls of ablation moraine, but sorted drift also is found to some extent within these deposits. The end moraine of Suomussalmi also has features resembling ablation moraine, such as steep, abrupt depressions and hummocks with coarse and washed drift. These have no doubt originated by dumping around the margin of the glacier while dead ice could have been left under the till. The finest debris in the ice was carried away by meltwaters during the deposition of the ablation moraine and accumulated in the immediate vicinity or in holes of the ice margin where it was mixed with the unwashed till.

As a whole, the morainic hill zone of Suomussalmi seems to be an end moraine originating at the ice margin where the accumulation of drift from the melting ice terminus was more rapid than could be dealt with by the thrust of the ice. Thus the deposit has many features of an ablation moraine.

The Suomussalmi end moraine thus corresponds, mainly in respect to its origin, to the end moraine type called by Chamberlin (1894) a lodge moraine, and in it are also found features of the dump moraine (Flint 1940). The Suomussalmi end moraine can be considered according to German literature as »Aufschüttungsmoräne» and »Satz-Endmoräne» (Gripp 1938, v. Klebelsberg 1948, Todtmann 1936) and as »Abschmelz-Moräne» in relation to the general position of the glacier (Milthers 1935, Woldstedt 1929).

DRUMLINS

Drumlins are found scattered here and there over the entire area. Concentration in definite parts of the area can not be observed, and the area does not possess as a rule distinct drumlin »fields». Drumlins do not seem to be situated on the proximal side of the end moraine, nor in such regions where eskers are lacking, as is usual elsewhere (Fairchild 1929, Leavitt-Perkins 1935, Putnam-Chapman 1943, Rich 1934). On the contrary some drumlins are joined to esker chains, especially in those places where an esker is broken or ended, in which case the drumlins form a continuation of the esker chain. Its form then greatly resembles that of an esker, but it is composed of till. Other topographic features of eskers are rare in drumlins. Small but distinct kettles are found, however, in two localities on the slopes of drumlins built of till.

Drumlins are in most cases composed of tough and compact basal till. Lenses of sorted material and layers of sand are relatively common in these, however. There are also instances in the area where the material changes gradually into sorted washed drift. Such is the case for instance at the eastern head of the esker chain no. I (Fig. 7) where a drumlin acquires the features of kame terrain while the till gradually changes at the same time into sorted drift. Ahlmann (1917) has reported corresponding features in some drumlins of South Sweden where drumlins also change gradually into eskers in respect to material and topography (*cf.* also Tanner 1915).

The trend of the drumlins in the area is usually west—east, in the southern part of the area west-north-westerly, and in the northern part, westerly. In two localities drumlins are found in the vicinity of the end moraine. Their direction is normal to the dominant trend of the other drumlins (Fig. 7). The trend of the drumlins does not as a rule differ much from the most common trend of the striations and eskers (Alden 1918, 1924, Hollingworth 1931, Leverett-Taylor 1915, *etc.*). The fact that the main trend of the drumlins is more or less distinctly parallel to that of the end moraine, is a feature which is exceptional in connection with the above mentioned investigations. On the origin of the drumlins of the area is discussed page 45.

WASHED DRIFT

Washed drift is also closely connected with glacial movements. Several investigators have especially emphasized the parallelism between esker chains, striations and glacial movements (Flint 1928, 1947, v. Klebelsberg 1948, Leverett 1899, Wilson 1939).

Deposits built of washed drift in the area are shown on the map, Fig. 7. Washed drift is classified on the map in four groups according to their form: eskers, kames, sand plains and ice-contact terraces. Eskers, kames and sand plains form more or less continuous esker chains, while ice-contact terraces occur independently.

ESKER CHAINS

Most of the washed drift in the area is to be found in long chains which extend discontinuously from west to east. Often it can be observed that the breaks in the eskers have some topographic cause. Esker chains are commonly broken on the watersheds, even on quite inconsiderable ones (*cf.* also Flint 1947, Mikkola 1932). Such gaps are found at the watershed along every one of the esker chains in the area. Rather large lake basins also seem to cause breaks in eskers, or eskers are there so small that they are not visible, at least on the map. Notice particularly how esker chain number V (Fig. 7) runs across the wide Lake Kiantajärvi basin and is broken along the shores of the lake. Steep-sloped and narrow tectonic valleys in the bedrock also cause interruptions in an esker chain. An esker normally ending at the mouth of such a valley (Alden 1924, Hyyppä 1946). The best-known and distinct instances in the area are the following, marked with a cross on the map, Fig. 7: Esker chain no. I is broken by Hiienkirkko of Lake Tervajärvi in Hyrynsalmi, no. III in the western part of the area by the narrow Lake Hiidenjärvi, no. V by the valley between Rakkavaara and Vuorijärvi and by another

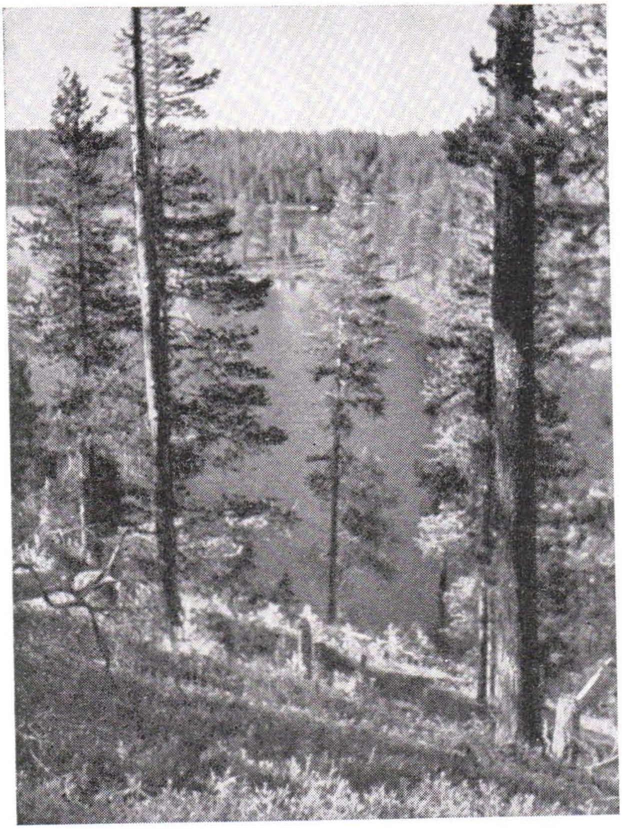

Fig. 20. Typical esker terrain in the north-eastern part of the area, esker chain no. VIII (Fig. 7).

tectonic valley east of Lake Kiantajärvi, no. VI by Kallioinenjärvi on the northern end of Lake Kiantajärvi and Elätinkuru, in the western part of the area, no. VIII by the great valley Porttikuru in the western border of the area and in its eastern part by the valley of Hoiluankalliot. Between the eastern parts of nos. VIII and IX are the well known gorges of Julma Ölkky (Fig. 5), Somerojärvi and Kallioholsi, and between nos. IX and X is the steep-sided valley of Lomapuro. The esker chains of the area agree then, at least partly, with the conception of Hyyppä (1946) which emphasizes their close connection with tectonic valleys of the bedrock.

All topographic irregularities, however, do not, influence esker chains, not even great differences in height. Thus, for instance, the esker chains of the area do not tend to be concentrated in the larger valleys as is often usual elsewhere (Alden 1924, Giles 1914, *etc.*). The esker chains do, however, run more or less perpendicular to the valley systems of Lake Kiantajärvi with its continuation.

The esker chains in the area have a rather uniform trend. The main trend is west—east; in the southern part of the area it is west-north-westerly, while in the north it is west-south-westerly. Rather exceptional are some short parts of nos. VI—X which run south-west, north-west and north-north-east. A comparison between Figs. 9, 15, and 7 shows that the general trend of the esker chains is most often very remarkably parallel to the westerly direction of the striations and fabric analyses which are, in turn, evidence of the strongest and most distinct trend of movement, erosion and accumulation of glacial ice. The main trend of the Suomussalmi end moraine is also more or less distinctly that of the esker chains. Esker chains generally occur at right angles to end moraines (Alden 1924, Leavitt-Perkins 1935, Leverett 1902, Richter 1937, *etc.*), but features such as encountered in the Suomussalmi area have also been found elsewhere (Norman 1939).

The esker is the most characteristic of the forms of washed drift in the area (Fig. 20). Long narrow esker plains, very common in the area, formed through the truncation of eskers by wave action have also been included among eskers in Fig. 7. Esker ridges rise 5 to 50 m. above their surroundings. The greatest esker ridge is Kuusikangas in chain no. IX on the southern shore of Lake Irnijärvi. This ridge reaches an elevation of about 50 m. above the level of the lake. The slopes of the smaller esker ridges are smooth, but the larger ones are irregular. Two or three parallel esker ridges with elongated depressions between them often form chains, but a single esker ridge is the most common form.

Kames consist of irregular hummocks built of washed drift with kettles between them (Fig. 21). The microtopography of such features is rather complex, but differences in height are comparatively small, varying from 5 to 20 m. In the area kames are closely associated with eskers and occur primarily in the vicinity of eskers, between them and transitional to them (see Leverett 1917). In one direction kames may change gradually into eskers, while they grade into sand plains in the other direction. Kames are most numerous in the northern part of the area and particularly in the eastern part of esker chain no. VIII where kames compose the main part of the esker knot of Hossa. Regions of kames are usually parts of esker chains which are greatly widened, indicating a powerful concentration of

Fig. 21. Kames in esker chain no. VIII (Fig. 7).

Fig. 22. Sand plain in esker chain no. VIII (Fig. 7).

drift, great activity of melt waters, and the melting of stagnant or nearly stagnant ice (Ahlmann 1917, Flint 1947, Holmes 1947, Woldstedt 1924).

As mentioned previously, sand plains are very often connected with eskers themselves where they form an even, narrow, but long plateau developed on the top of the esker. They are also common as more independent features usually connected with the marginal parts of esker chains where kames gradually merge into even plains outwards from the eskers (Fig. 22). Sand plains are the result of the action of ancient seas and other great water bodies and they are the surest and most convincing marks of water action in the area (Virkkala 1948).

The ten fabric analyses of the material of the washed drift are most interesting in this connection. Three types of orientation of esker stones may be observed. They are arranged either parallel to the trend of an esker, at about 45° to it or else no distinct orientation can be ascertained. The first type seems to be most common in the area. Stones transported by flowing water usually (Fraser 1935), or at least in some cases tend (Richter 1936), to arrange themselves at right angles to the direction of flow of the stream. Thus we have proof that the direction of flow of the water forming an esker was often perpendicular to the trend of that esker, contrary to what Lundqvist (1948) in Sweden and Schneider (1938) in Germany have ascertained in places. Stone counts however, show, in places that the transport of washed drift has also taken place parallel to the axis of an esker, as Hellaakoski (1931) and Okko (1945) have ascertained in South Finland.

Washed drift in the area is well sorted and strongly washed and it has distinct stratification. The stones for the most part are more distinctly rounded than in till, a difference most evident in the rather big stones and small boulders. Till is never found on the surface of the esker chains or on deposits connected with them, although special attention was directed toward the search for such occurrences and for such localities as seemed promising. It should be mentioned, however, that this thinly settled area has relatively few good sections through eskers, which are sufficiently large to be useful, and conclusions concerning underlying drift can not always be drawn from surface forms. The structure and material of the eskers show that the sorting and washing action of water has played a decisive part in their origin. Ice-contact features are common in deposits of washed drift. Such deposits have thus been formed in the marginal zone of the melting ice and in close connection with the ice (Flint 1930, 1942, Leavitt-Perkins 1935, Woodworth 1899).

ICE-CONTACT TERRACES

Ice-contact terraces of the washed drift are found in two localities in the area. In the north-western corner of the area, within the little valley of Kalajokilaakso they are associated with an esker chain (Fig. 23). They occur here on the slopes of a morainic hill as fairly long projections situated at the same height and limited rather distinctly by the till slopes on the north and by kames on the south. They are composed of sand and fine sand.

More extensive ice-contact terraces are encountered in the north-eastern part of the area along the Hossanjoki valley, but especially on its western side (Fig. 7). Figure 24 shows their occurrence and morphology. On one side the terraces are limited by shore deposits of the river valley and by alluvial sediments. The very pronounced sandy terrace edge is 6—8 m. in height, its irregular course indicating its ice-contact nature. On the other side topographic differences can not be noticed against till, for the ice-contact terraces merges with the gently sloping morainic hills. Low depressions like kettles are found here and there along the edges of the terrace. The terraces are broken in places by small morainic hills or steep-sloped, nar-

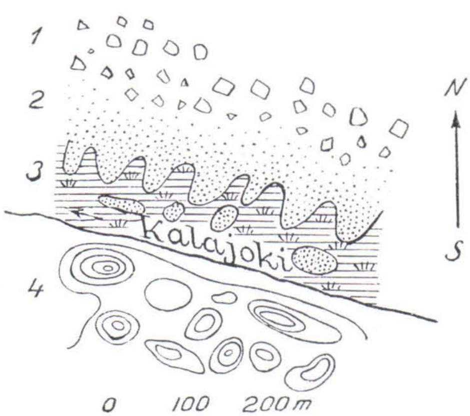

Fig. 23. Ice-contact terraces in the River Valley of Kalajoki, 1. till, 2. ice-contact terrace, 3. peat bog, 4. kames.

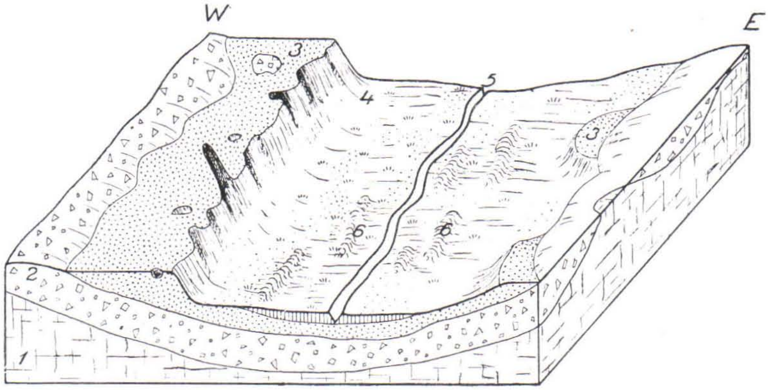

Fig. 24. Ice-contact terraces in the River Valley of Hossanjoki, 1. bedrock, 2. till, 3. ice-contact terrace, 4. peat bog and shore accumulation, 5. River Hossanjoki, 6. dunes.

row ravines. The terraces continue in a west—east direction for not more than a few hundred meters. The surface of the terraces is even and there are three levels: 212, 217—218, and 223 m. above sea-level. The terraces of the different heights are not situated in steps along the sides of the valley, but arranged one after the other, along the valley slope. Terraces are also found as small occurrences east of the Hossanjoki. They are encountered here along two small brooks at 222 m. above sea-level. The stratified structure of the terrace can be well seen here in the sections of the roadway, but in places the layers are deformed (Fig. 25 and Plate I, Fig. 6). They are built of sand and fine sand, and to a lesser extent silt (*cf.* Mikkola 1932).

The ice-contact faces of the terraces indicate that they originated at a time when the Hossanjoki valley was still covered with ice. A narrow zone covered with water was left between the till of the valley slope and a glacier, and in this zone the ice-contact terraces accumulated (Alden 1924, Chapman 1937, Flint 1942, Lougee 1938). Their location at several levels indicates the gradual lowering of water level (Flint 1947).

Fig. 25. Section in the ice-contact terrace of Hossanjoki.

MOVEMENT OF GLACIAL ICE

The rate of flow of an ice sheet, according to recent investigation, is most rapid near the margin of the glacier (Demorest 1942). From this it follows that »beneath a large ice sheet erosion is considerable only near its margin» (Demorest 1943, Flint 1947). Theoretically then the glacier has two opportunities to abrade the underlying surface: during its advance and during deglaciation. Surface melting is the most important factor in the disappearance of the glacier (Antevs 1932), so the shrinkage and retreat of a glacier is, primarily, by thinning (Flint 1942, Sauramo 1929). By this thinning the ice margin loses its energy to move (v. Bülow 1927) and can no longer effectively abrade the bedrock. Therefore the most profound marks of glacial erosion in the area investigated could not have been the result of erosion by a thinning ice margin, but must have been formed during the time the ice sheet was expanding.

The results of glacial erosion are most distinct where the bedrock is broken by tectonic valleys. In this area the trend of the lake basins is mainly parallel to the most pronounced direction of glacial movements represented by striations (Figs. 3 and 9).

The relationship between the striations and the basal till also shows that the former were formed by the advancing glacier. Deposition of till is favored by low temperatures and rapid ice flow (Flint 1947) and so this, too, largely occurred during the advance of the glacier (Alden 1918, Flint 1930), the basal ice gradually becoming richer in rock fragments and losing its capacity for movement with the deposition of a tough and compact basal till (Sauramo 1924). The upper, looser part of the till was deposited when the ice melted later. The loose structure of the surface till of the morainic deposits has been partly caused by later, secondary factors of which washing, solifluction, and frost action have been the most important. However, a true surface moraine must have been very inconsiderable in the area investigated. As only westerly striations are found regulary underlying the westerly orientated till in the area, the striations must have originated at the same time as the basal till. Only a rather small part of the westerly striations can then be considered to have originated during deglaciation. These striations are just those which diverge most from the average trend of the striations, but the number is relatively inconsiderable. The striations of the area can thus be differentiated on the basis of their age into two great groups separated by a considerable time interval. The older, westerly group originated during the advance of the glacier, under thick ice. In the younger group must be included a small part of the westerly striations as well as the south-westerly, north-westerly and northerly striations originating after the maximum extent of the continental ice was attained.

The orientation of till stones continues without change in the drumlins of the area investigated (*cf.* also Alden 1918). The direction of the drumlins as well as that of the striations found in the same places indicates that drumlins have also been formed mainly during the period when the ice sheet was advancing (Flint 1947, Hollingworth 1931).

Thus, the strongest, westerly movement of the glacier is responsible for the erosion of the bedrock, the principal westerly orientation of the till, and the drumlins, and all these were formed while the glacier was advancing over the area from the west. Hence the writer can not agree on the basis of his investigations with the conception that striations (Carney 1910, Granlund 1936, Leavitt-Perkins 1935, Lundqvist 1943, Sauramo 1929, Tanner 1915) and drumlins (Charlesworth 1926, Ebers 1937, Fairchild 1907, 1929, v. Klebelsberg 1948) have been mainly associated with the retreat of a glacier.

The fan-like divergence of the westerly striations in the area indicates that glacial movement occurred in the form of lobes. The mean directions of the striations in the northern and southern half of the area intersect each other in North Sweden near the 65 degree of latitude and 100—200 km. west from coast of the Gulf of Bothnia. This should indicate the area of accumulation from whence the glacial movement in question has derived its origin, if the influence of neighbouring lobes be disregarded.

The south-westerly movement, on the other hand, without doubt must be considered as movement of the ice margin during deglaciation. The melting and thinning ice margin had already lost by that time most of its capacity to move and abrade, and its inconsiderable movements were influenced to a large extent by topographic irregularities (*cf.* Geijer 1948, Lundqvist 1943, Rich 1934). The local relief in most of the area is, however, so small and the individual features so limited in extent that they could not cause great variation in the direction of glacial movement over extensive areas. Only in the vicinity of Lake Kiantajärvi is there an exception. Local relief varies here from 25 m. to 80 m. measured from the level of the lake. The depth of the lake is not known, but it must be supposed that the local relief here is well over 100 meters, at least in places. The movement of the considerably thinned ice margin was influenced locally by these height differences and the ice tended to be diverted to a direction parallel to the trend of the lake basin of Kiantajärvi, where striations have a more or less south-westerly trend. This deviation to the south-west is most distinct just where the relief is greatest along the shores of the lake (*cf.* Figs. 4 and 8) and a gradual swing of the striations to the south-west can be observed when approaching the lake. When the south-westerly striations originated, there must have been stagnant ice in the basin of Lake Kiantajärvi because if a calving bay had been formed here the glacial movement would have been normal to it and would not have turned parallel to the basin (*cf.* Sauramo 1929). The movement of the ice was by this time very weak, however, and the striations are fine and only found here and there. Only in two localities is till found which was deposited during this period. The till here retains in part the earlier orientation from the former westerly movement of the glacier. Transport and re-accumulation of till may thus have occurred to a very limited extent during the south-westerly trend of the glacial movement.

The ice movement from the north-west shows a much more independent trend. It has already been mentioned (p. 19) that the north-westerly movement is younger than the westerly one, but that its age relation to the south-westerly movement cannot be directly ascertained anywhere. As the south-westerly movement is closely associated with the westerly one, while there is a distinct gap between the westerly and north-westerly movements (Fig. 9), the north-westerly movement must be presumed younger than the south-westerly one.

Glacial movement gradually ceased as the ice thinned, but the entire area remained covered by ice. A new movement of the glacier began from a north-westerly direction probably even before the first land areas were uncovered by the ice sheet. In the area being investigated, only the marks of the oldest, westerly glacial movement are found to underlie the evidence of erosion and results of accumulation of the north-westerly movement. If a part of the area had been free from its ice cover before the north-westerly movement, shore features or corresponding deposits would probably have been overlain by till deposited by the north-westerly movement.

The north-westerly movement was rather weak in this area. It has been ascertained that north-westerly movement accumulated till or at least re-arranged drift deposited by the westerly ice flow. The distribution of the striations shows that the north-westerly movement was strongest in the northern half of the area, but weak marks are also found in the southern half. This restriction of the movement to the northern parts of the area finds its most probable explanation in that this part of the area lies closest to the center of the new glacial movement.

The accumulation area of the glacier must have shifted in order for the almost motionless ice to renew its activity. Climatic changes must have resulted in nourishment in the accumulation area of the glacier exceeding the rate of the ablation near the terminus. The climatic change in the accumulation area must have been caused primarily by decreased temperature and increased snowfall supposed that the annual precipitation is not diminished. The growth of the glacier may have occurred along the whole ice divide of the Scandinavian Ice Sheet. The shift in the position of the ice divide readily explains why the more recent movement of the glacier did not appear during the time the ice was advancing from the west. The earlier conception of a stationary Scandinavian ice divide (Frödin 1925) or of only limited changes (Granlund 1936) has gradually given way to the latest viewpoint that there was considerable shifting in the position of the ice divide during the latest periods of the Ice Age (Ljungner 1943, 1945, 1949). At the same time the center of glaciation also moved northwards. It has further been supposed that the ice divide was separated into two parts (Lundqvist 1943). Changes like this have also been ascertained in the glaciated area of North America during the latest stages of the Ice Age (Rutherford 1941).

The Suomussalmi area is situated 600—700 km. east of the ice divide, while the corresponding distance of the ice divide in North-West Scandinavia is only 400 km. Furthermore as mentioned before the area investigated is situated close to the outer limits of this north-westerly movement of glacial ice. If the growth of the glacier was about the same on both parts of the bipartite ice divide, as is to be expected in climatic changes which effect extensive areas, it is evident that the younger, westerly movement of the glacier would not have reached the Suomussalmi area. Instead the direction of glacial movement was from the nearest accumulation area of the glacier. It should be noticed, however, that a thin glacier moves largely in the form of lobes, and that the movement of such lobes was influenced by the movements of the neighbouring lobes. The slope of the terrain, local height differences, small climatic changes *etc.* had a greater influence on the trends of the later glacial movements than on the advance of a thicker ice sheet. Thus the north-westerly movement does not necessarily mean that the accumulation area was in a northwestely direction. This trend in the area under consideration is the result of all the factors affecting the movements of the glacier after leaving the accumulation area.

The increased activity of the glacier from the north-west was not of long duration. It was followed by a new advance of the glacier, this time from a northerly or north-easterly direction. The northerly movement followed immediately after the north-westerly movement or, more probably, after a short period of stagnant or nearly stagnant ice. This is clearly indicated by the fact that the two sets of marks are contained in two distinct groups without intermediate stages (*cf.* Edelman 1951). If the shift in the direction of movement had occurred gradually it should be detected in a transition of the marks of erosion and accumulation. Such transition, however, is absent in the area. The separation of the north-westerly and northerly till, at least partly, into distinct (p. 27) beds shows the independent nature of the northerly movement. The northerly till also is never found in the area overlying such deposits as shore accumulations which might indicate even a local disappearance of the glacier in the area.

The influence of the northerly movement in the area is noticeably stronger and more distinct than that of the north-westerly one. This may be because marks of the northerly movement are latest in origin and so best preserved. Furthermore, the till deposited at this time forms the uppermost part of the land surface and so is most easily observed by the investigator. In addition, this is partly because the northerly movement was the strongest movement since the westerly movement ceased. The northerly movement has accumulated till overlying the westerly and north-westerly till and its influence can be ascertained in the most southern part of the area, where even though its marks are rather weak, they are noticeably more distinct than the north-westerly ones. The northerly movement was strongest in the northern part of the area investigated, and the morainic hill zone or end moraine lying across the area and described previously (pp. 33—37), seems to form the southern limit of the strongest northerly movement of the glacier. Nearly all observations of the striations and the most of the observations of the northerly orientation of till were made north of this limit. Some small drumlins also belong to the deposits of this northerly movement, and they are situated near the end moraine and at right angles to it.

Of the various directions of movement of the ice in the latter part of the Ice Age, movement from the north was strongest. Nevertheless, compared with the strength of movement of ice from the west, it was much weaker. It was not strong enough, even in the northern part of the area, to disturb and modify the westerly marks of the glacier. The amount of northerly till is certainly in places several meters in thickness, but the total work done by the northerly movement is only a fraction of that done by the westerly activity of the glacier.

Climatic factors similar to those causing the increased activity of the glacier from north-west brought about the augmentation of the northern activity. The ice divide evidently was separated into several parts as the end of the Ice Age approached (Lundqvist 1943). The influence of the nearest ice divide can be ascertained in the area, for it was only about 300 km. away to the north. Ice divides situated nearer to the Suomussalmi area have not been ascertained in the Scandianvian glaciated area and the northerly movement is the latest and youngest of the directions of glacial movements found in the area.

The source of the northerly movement is to be sought in the western part of the Kola Peninsula and in the region adjacent to it on the west. Local centers of glaciation occurred in the region Umptek—Lujaur-Urt at the beginning and end of the last glacial stage according to some investigators (Lawrowa 1947, Ramsay 1912). It is not known how long their influence persisted, but it seems probable that the center of glaciation which produced the northerly to north-easterly trending features in the Suomussalmi area was there.

The movement of the ice in the area is the younger, the more northerly it turned, with the exception that the westerly and south-westerly movements are really different phases of the same movement. This phenomenon is readily explained as the result of the breaking up of the accumulation area and ice divide which was caused by the thinning of the glacier. Thus the directions successively gaining predominance have originated from centers of activity situated nearer and nearer to the investigated area and becoming more and more northerly.

DISAPPEARANCE OF THE ICE

After the last, weak advance of the glacier had occurred from the north the ice began to disappear. As shown by Flint (1942) the disappearance of the ice sheet was primarily by thinning, and not so much retreat of a continuous ice front back toward the accumulation area. Thinning occurred either by evaporation or by melting. According to Ahlmann (1936) melting in present glaciers of Spitzbergen is the main mode of disappearance while evaporation accounts for only 3 per cent of the entire ablation. Holmes (1947) concludes from this that evaporation could hardly have been greater even during the Ice Age, while Flint (1935) gives evaporation a larger importance at least in places. Evaporation has been ascertained to be rather noticeable in suitable climates even around present day glaciers (v. Klebelsberg 1948).

The extensive esker chains of Suomussalmi show that melting of ice was more important than evaporation in accounting for the disappearance of the glacier. Evaporation may have been of greater importance in the earlier stages of the deglaciation, while melting played a more important part later. As mentioned above (p. 16) practically the whole area was below water level after the ice disappeared, so calving was also an important factor in the disappearance of the glacier, and this is especially true in the vicinity of the greater basins such as Lake Kiantajärvi, where ice-contact features are lacking. The highest summits may have risen as nunataks over the ice surface at the same time as ice calved in the basins. The ice was in places so rich in rock fragments, however, that it did not begin to calve upon coming in contact with water, but remained frozen at the bottom of the basin. On the other hand, if the amount of debris in the ice was small so that the specific gravity of the ice was less than that of the surrounding water, the ice must have begun to float and calving occurred. The area covered with ice decreased continuously, giving way first to water and finally to dry land. Land upheaval was taking place rapidly and more and more land areas were being uncovered from water. Thus in the area investigated there could

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not have been retreat of an continuous ice margin, but only the gradual shrinkage *in situ* of ice fragments over the entire area.

Wherever ice was buried under a moraine cover or washed drift and thus protected from the sun's rays it could have been preserved for a long time after the main body of ice had melted. The knob and kettle-topography of the Suomussalmi end moraine and of other surface forms resembling ablation moraine originated in this way. The stagnant ice, especially that buried under stratified drift, often played a decisive part in the later development of the topography, as is shown by extensive kame-areas. But dead ice could also have been preserved until later periods under a water cover. In the vicinity of the melting ice, the water was near 0°C even in summer while during the long winters the water froze thus preventing the melting of the ice buried beneath the water (Antevs 1932, Fairchild 1932). Rather large ice bodies could have been preserved in depressions long after the ice under shallower water had already melted. The ice-contact terraces on the western slopes of the Hossanjoki valley provide evidence bearing on this problem. These have originated in the trough between motionless ice in the valley and rather high hill land west of it. The absolute altitude of the lowest ice-contact terraces corresponds in the development of the Baltic to a period which is only a little older than the beginning of Yoldia. Stagnant ice must have been situated a long time after this period in the valley of the Hossanjoki.

Small kettles also occur here and there in the shore deposits. These show that dead ice was preserved, protected by overlying deposits, even after the shore line was lowered.

Thus, the disappearance of the glacier occurred in the Suomussalmi area as superficial thinning and calving, and this caused the ice to become nearly stagnant at a relatively early period. Hence instead of a continuously retreating ice front, there was a broken ice cover, fragments of which could have been preserved for a long time in sheltered localities. The disappearance of the glacier from the area is then very similar to that which occurred in some parts of the eastern coast of North America (Flint 1930, Leavitt-Perkins 1935) where »the ice seems nowhere to have had a well-defined front transverse to the ice motion . . .» (Goldthwait 1938).

DATE OF THE ORIGIN OF THE END MORAINE AND ESKERS

The Suomussalmi moraine has been explained above (p. 33) as an end moraine, during the accumulation of which the activity of the glacier was less decisive than the building up of drift caused by the uneven melting of the glacier. The location of the end moraine at the southern limit of the most distinct northerly movement, as well as the indistinct orientation of part of its till normal to the trend of the end moraine and so parallel to the northerly movement of ice, shows that the end moraine resulted from the youngest, northerly movement of the glacier. Westerly orientation can be observed to a small degree in the till of the end moraine. This means either that the drift of the end moraine overlies the older till in a relatively thin layer with westerly till appearing as »windows» through the end moraine, or that the westerly orientation has been preserved as a relic in the till even during the relatively weak, northerly movement of the glacier. It can be said in every case with almost complete certainty that the end moraine is associated with the northerly movement of the glacier. This statement is rendered no less true by the slight influence of the northerly movement south of the end moraine. The lack of northerly striations and the weak, northerly orientation of till show that the ice south of the end moraine was very thin during the northerly movement and its capacity to move and abrade insignificant. In turn this indicates that the last renewal of the activity of the glacier was very insignificant in the southern half of the area where the ice was then nearly stagnant. Though the Suomussalmi end moraine is very dissimilar in respect to morphology and origin to the great end moraines of North Germany nevertheless similar conditions seem to have prevailed. According to v. Bülow (1925, 1927) and Woldstedt (1925, 1950) the great end moraines of North Germany show the limit between active and stagnant ice which could have been a zone, in places many tens of kilometers broad. Spethmann (1912) has also ascertained in the present glaciers of Iceland an end moraine forming the limit between active and stagnant ice. The end moraine was situated in Iceland on the surface of motionless ice over which the active ice moved.

A comparison between the Suomussalmi end moraine and the esker chain across it (no. V, Fig. 7) reveals interesting evidence of the age of the eskers. As shown in Fig. 7 both deposits are broken in the basin of Lake Kiantajärvi but meet one another on the western side of the basin. The esker here forms a beautiful ridge, 10—15 m. high, the top of which is levelled by water to a little esker plain. Nearer to Lake Kiantajärvi the esker is broken into hilly kame terrain built of well sorted sand and gravel. Morainic hills belonging to the end moraine are encountered in the vicinity of the esker ridge. The end moraine, however, becomes narrower and more indistinct approaching the esker. Its drift is typical till. In no place do morainic hills continue on the surface of the esker, and the difference is sharp between stratified and unstratified drift. This indicates that both deposits are either contemporaneous or nearly so. It seems rather that the end moraine is broken by the esker and so should be older than the latter. Age relations are difficult to ascertain, however, in the absence of sections and borings. Precise contact between the end moraine and the esker is not observed east of Lake Kiantajärvi. In the map, Fig. 7, it can be seen, however, that near the most easterly part of the end moraine, where it turns northward, the esker chain makes a great detour northward avoiding a meeting with the end moraine. This also indicates a slightly younger age for the esker.

No extensive washed deposits are associated with the Suomussalmi end moraine, contrary to the great end moraine areas in North America (Katz-Keith 1917, Leverett 1917, 1928, Leverett-Taylor 1915, Thwaites 1926, *etc.*), in Great Britain and Ireland (Charlesworth 1928, 1929) and in North Germany (Richter 1937). The melting of the glacier was evidently weak during the deposition of the end moraine. This is easy to understand, because the end moraine represents the most active limit of the youngest movement. More active melting of the ice began, instead, in a slightly later period when the latest, northerly movement of the ice had already lost the greatest part of its capacity to move. As a result of melting the esker was built in the immediate vicinity of the end moraine because there was more drift in the ice. This drift had accumulated in the ice since the period of strongest erosion during the westerly movement of the ice, and was added to during the northerly movement. The orientation assumed by the esker chain was partly determined by local conditions, among which tectonic valleys (p. 39), are most important. The importance of such valleys as a primary cause of glacier crevasses and consequently as an influence in the formation of eskers is emphasized by Hyyppä (1946). Gaps in esker no. V occur just where there are tectonic valleys which in turn partly determine the trend of the esker. The trend of the esker has also been partly determined by the general tendency of ice to form crevasses at right angles to the movement of the glacier (v. Klebelsberg 1948). There is reason to suppose that crevasses originated a right angles to the movement, especially when stagnant ice renewed its activity, as in Suomussalmi during the northerly movement. Tarr (1909) ascertained such a case in a present day glacier in Alaska. Lundqvist (1937) has applied the observation of Tarr in North Sweden and similar conditions probably also prevailed in the Suomussalmi area. These conditions determined the general trend of the large features of the esker chain parallel to the end moraine. Thus the esker as a whole assumed the form of a broad arc, like the end moraine, due to the lobate movement of the glacier. Local conditions, however, were important in determining the detailed course of the esker. Thus the relation between the trend of esker and end moraine is quite different from the usual case described elsewhere (*cf.* before p. 40).

It has been emphazised earlier (p. 40) that the general trend of the eskers in the area is often almost exactly the same as the strongest, westerly movement of the glacier. The tendency is then to presume that the eskers are of the same age as the westerly movement of the ice as was ascertained in the case of the drumlins. The relationship described in the previous paragraphs, however, contradicts this. Furthermore, two distinct, independent advances of the ice occurred in the area after the westerly movement. If such movement had occurred since the eskers were formed, it would surely have left some marks on the eskers. Such is the case in numerous localities elsewhere; for instance in the valley of the River Tornionjoki both on the Finnish and Swedish sides, where the younger, westerly movement has accumulated till on the surface of eskers formed during an older northerly movement. Meanwhile the primary forms of the eskers were not completely destroyed (Aurola 1949, Braun 1923, Fromm 1949, Geijer 1916, Hoppe 1948, Hyyppä 1948). Northerly and north-westerly till has likewise been detected on the washed drift in Suomussalmi, but these occurrences are quite local and small in extent (*cf.* above pp. 26, 28). Moreover westerly till has also been located on the surface of washed drift (p. 26). This kind of unusual sequence of superficial deposits is then known in the area, but in no case is it associated with the great esker chains, although attention has been specially directed to this problem in field investigations. Since north-westerly and northerly movements have left clear erosion marks in the bedrock and transported and accumulated till in the area, it seems strange that those ice movements have left no marks on the esker chains. For they are composed of drift, very easy to abrade and such steep-sloped, long ridges ought surely to have resisted the last, relatively weak advance of the glacier. We are consequently led to believe that all eskers in the area originated during and after the last, northerly ice movement and formed parallel to the ice margin. The prevailing conception of eskers originating since the last movement of the ice (*e. g.* Flint 1947, v. Klebelsberg 1948, Korn 1913, *etc.*) seems valid here in Suomussalmi. Most the eskers are, however, disposed parallel to the last movements of glacial ice. Nevertheless, in North Karelia the author has detected eskers more or less oblique to the last movements of the glacier (Virkkala 1949). Similar observations have also been made in North America, thus proving that eskers are not inevitably parallel to the last movements of glacial ice (Crosby 1902, Leavitt-Perkins 1935, Norman 1939, Stone 1899).

A detailed discussion of the origin of eskers does not properly belong to this investigation. Some possibilities may be summarized, however. The conception that eskers may be formed in various ways seems well established (Flint 1942, 1947, Hyyppä 1946, Leavitt-Perkins 1935, Tanner 1929). The variation in the orientation maxima of esker stones in the area under discussion also points to this direction (*cf.* before p. 41). Decisive significance is given in most cases (except: Gumaelius 1876, Leiviskä 1928) to the activity of glacial meltwaters, the esker originating in an ice tunnel (*e. g.* Giles 1917, v. Klebelsberg 1948, Russel 1893, Stone 1899, Strandmark 1889, Tarr 1909), in the last stadium of the development in open crevasses (*e. g.* Hyyppä 1946), as deltas in front of the ice margin (De Geer 1897, Hershey 1897, Trowbridge 1914) or in superglacial valleys (Crosby 1902, Holst 1876, Sproule 1939, Tanner 1932, 1937). Meltwater without doubt played a decisive part here in Suomussalmi, as well. This is indicated directly by the fact that their origin is associated with deglaciation. Wastage of the ice in the area occurred mostly by thinning during the earlier phases. During that time meltwaters could not have obtained debris within the basal parts of the ice. Eskers began forming only when the ice had thinned sufficiently to allow meltwater to begin to transport and sort the rock fragments in the basal ice.

As mentioned above (p. 38) eskers in the area often are situated with a definite relationship to the topography. Topographic irregularities would have caused crevasses in the thinning ice margin (Okko 1945) with consequent concentration of drift in esker chains (Hyyppä 1946). The ice cover was broken during deglaciation, and since the water level was high above the present sea level during the last stages of Ice Age, it is possible that meltwaters could not always flow in these crevasses, but drift can also be accumulated by marine abrasion, as particularly emphasized by Hyyppä (1946).

In smaller features the forms of the eskers are rather sinuous which often resembles to a surprising degree results of erosion of flowing waters in a soft substance, while the profile of the esker is that of an inverted V-shaped river valley. Thus it is more possible that the esker originated in a closed tunnel where meltwaters have flowed. The direction of such a meltwater stream has been proven, as a rule, to be parallel to the last movements of the ice, but it may also be oblique or normal to it (Stone 1899). The flowing of the meltwater in the tunnels presupposes hydrostatic pressure (Alden 1924, Fairchild 1896, Leavitt-Perkins 1935) and this has been proven in the case of certain present day glaciers too (Russel 1893, Thorarinsson 1939). Topographic conditions in the Suomussalmi district favor an origin of hydrostatic pressure, too, at least in some cases. That is the case especially for short eskers beginning high on the top of a hill and continuing some kilometers down onto lower land. The difference in height is then some ten meters between the beginning and the end of the esker. Similar features can also be noticed along many longer eskers, as for instance the eastern part of esker chain no. I, the eastern part of no. II, the western part of no. III, almost the whole of no. V, and the eastern part of no. IX.

The ice margin could not, however, have been very broken during the deposition of the eskers, because the sea would have penetrated into the ice in such cases and prevented the flowing of the meltwaters (Stone 1899). The tunnels presuppose, on the other hand somewhat broken and crevassed ice. For it has been shown (p. 52) that primary causes of esker formation include topography, and the tendency of ice to form crevasses perpendicular to the movement of the glacier. Meltwater tunnels in this area then probably originated only at a very definite stage of deglaciation. Some tunnels in various parts of the area also originated parallel to the last glacial movements as shown by those short eskers with a northerly direction.

As mentioned before no direct correlation exists between the striking parallelism in the trend of the eskers and the westerly movement of the glacier. This parallelism is caused above all by the fact that the last, northerly movement of the glacier occurred at right angles to the oldest, westerly movement of the glacier.

COMPARISONS WITH THE NEAREST INVESTIGATED AREAS

The writer has had opportunity previously to investigate, although not in so great detail, the glacial geological features in the area of Nurmes south of Suomussalmi (Virkkala 1949). The glacial movements here seem to be partly opposite to those in Suomussalmi. The strongest trend of glacial movement and erosion in the Nurmes area is on the average north-westerly. The northerly movement is here older than the north-westerly and westerly movement. The northerly movements in these neighbouring areas can not then correspond to each other because they are separated by the strongest movement of the ice. As mentioned earlier (p. 48) the yonger, northerly movement probably did not reach further south than the Suomussalmi area. It is possible, on the other hand, that traces of the older, northerly movement can yet be found in the Suomussalmi area, even though no signs of such have been encountered during the current study. If a weaker, northerly movement existed before the strongest glacial erosion in the area south of Suomussalmi, it must have also passed over the Suomussalmi area, although all marks of it are here obscured by younger glacial movements and above all by the strongest advance of the ice. The starting point of this older northerly movement should have been the same region as that of the younger northerly movement, namely the local centers of glaciation in the western part of the Kola Peninsula. While the younger, northerly movement originates from a local center of glaciation during the shrinkage of the ice sheet, the older, northerly movement may have had its origin in a similar center before the great advance of the continental ice (*cf.* Lawrowa 1947, Ramsay 1912).

The youngest, westerly movement in the Nurmes area most nearly corresponds to the youngest, northerly movement in Suomussalmi. Both movements may be practically simultaneous and the westerly movement in the Nurmes area may have prevented further movement of the glacier from the north.

On the coast of the Gulf of Bothnia north-east of the town of Oulu in the parishes of Kiiminki and Ylikiiminki the author has ascertained that the last, weak movement of the glacier was from a north-north-westerly direction while the strongest advance of the glacier occurred from the west-north-west. Similar age relations have been ascertained by Hyyppä (1948) on the coast of the Gulf of Bothnia between Vihanti and Simo, by Okko (1949) in Middle Ostrobothnia, by Mölder (1948) in South Ostrobothnia, by Virkkala (1946) in North Satakunta and by Helaakoski (1940) from the area between Tampere and the coast of the Gulf of Bothnia. According to all these observers the movement of the glacier is the younger, the more northerly it becomes. It should be noticed, however, that the northerly movement in South Ostrobothnia and in parts of North Satakunta represents the strongest erosion of the glacier and is so most comparable with the westerly movement in Suomussalmi. The northerly movement met with in Middle Ostrobothnia bears evidence, however, of weaker erosion than the westerly one (Okko 1949).

The age relationships between ice movements are different from areas further southward in the most northern corner of the Gulf of Bothnia (Hyyppä 1948, Okko 1941). The westerly movement is here distinctly younger than the northerly one which is itself the strongest trend of glacial erosion and accumulation in the area (Okko 1941). The reverse order of age relations between the different ice movements in the Tornionjoki valley makes it difficult to connect observations here with those made in Suomussalmi.

Two northerly to north-westerly movements of glacial ice are found on the Swedish side of the northern coast of the Gulf of Bothnia. They are separated from each other by a west-north-westerly movement (Fromm 1949, Hoppe 1948). The age relations of the glacial movements here surprisingly resemble those found in the Suomussalmi and Nurmes areas. The immediate tendency is, of course, to associate these movements. There is, however, so great an uninvestigated area between, that this correlation would be misleading.

There is relatively little glacial geological informations for the region north of the Suomussalmi area. In the parishes of Kuusamo and Salla, nearly all observations are of striations. A short summary of these is presented in the following paragraph on the basis of field notes preserved in the archives of the Geological Survey of Finland. Date references are to these field notes.

The dominant trend of striations in Kuusamo and Salla is west and west-north-west. Observations concerning this trend, made by different investigators range between 264°—300° (Dillström 1907, 1908, Hyyppä 1935, 1936, Mäkinen 1909, Wilkman 1904, 1906, 1907). Many diverging observations have been made, however. Hyyppä (1935, 1936) mentions the trend of glacial erosion in the region of Sallatunturi (mountain) as 320° with striations in the direction 346°. According to Hyyppä (1935) a broad channel abraded by the glacier exists on the western shore of Lake Tenniönjärvi with a trend of 350°—5°. In South Salla Wilkman (1907) found weak north—south striations, and Brofelt (1901) found similar striations at 3°. The last mentioned observation is probably the same as that published by Tanner (1915) with a direction of N. 3° W. In the vicinity of Lake Paanajärvi, Hyyppä (1936) found nearly north-westerly striations diverging from the dominant westerly direction. In the Paanajärvi region Wilkman (1907) has also found striations diverging from the westerly trend. He found here weak striations with a azimuth of 340° and 34°. These striations are distinctly younger than the westerly ones. In the western part of Kuusamo, near Lake Ylikitka Wilkman (1904) also noted weak striations at 340°, 4° and 5° besides the dominant westerly ones. In the same area Hyyppä (1936) made one observation with a trend of 312°. In South Kuusamo Mäkinen (1909) mentions trends of the striations at 316° and 300°.

The north-westerly movement of the glacier is strongly represented by the drumlins of South Kuusamo. Figure 26 shows a part of South-East

Fig. 26. The drumlin »field» in south-eastern Kuusamo. The strongest movement of the glacier is shown by the west-north-westerly trend of the lakes. The drumlins have originated during the later north-westerly advance of the glacier. Ruled areas—peat bogs, gray—lakes.

Kuusamo a few kilometers north of the limit of the Suomussalmi area. The trend of the lakes is west and west-north-west indicating tectonic valleys in the bedrock cleared by glacial erosion. This trend is distinctly cut by the direction of the drumlins which accumulated during the north-westerly movement of the glacier, so the north-westerly trend is here younger than the westerly one.

These scattered observations indicate that glacial movements similar to those in the Suomussalmi area have also taken place further north. The westerly trend of the striations is the strongest here, too, but north-westerly and northerly, even almost north-easterly striations, are encountered. The south-westerly striations of Suomussalmi seem to be missing, however, north of the area investigated for reasons easily understood. Thus the conclusions drawn for glacial movements in the Suomussalmi area seem so to be confirmed in the region north of it.

It is true that the foregoing comparison between different areas investigated in Finland reveal considerable contradictions. However, the elucidation of these problems must wait a more detailed investigation of the areas situated between them.

SUMMARY

Movement of glacial ice in the area has been ascertained to have occurred in four trends: from the west, south-west, north-west and north. The westerly movement represents the advance of the glacier and its marks are the strongest and most distinct compared with those made by other movements. Most of the westerly striations and till, as well as nearly all the drumlins have originated in this time. The westerly movement of the ice was derived from the great, undivided accumulation area of the Scandinavian Ice Sheet east of the Scandinavian Mountains. A considerable difference in age exists between the westerly and subsequent movements, and their corresponding deposits.

The south-westerly movement originated during the retreat of the glacier, when local topographic irregularities had opportunity to affect the trends of ice movement. The marks of the south-westerly movement are weak and occur only locally.

The north-westerly movement of the glacier was limited to the northern half of the area investigated. It, too, was a weak movement, but its independent nature is shown by its continuation in the region north of the Suomussalmi area. The north-westerly movement originated from the bisected accumulation area of the Scandinavian Ice Sheet when the climate deteriorated and after the glacier had renewed its activity during its final phase.

The northerly movement was the strongest among the movements associated with deglaciation. It is indicated by only a few observations of striations in the regions north of the Suomussalmi area, but fabric analyses of the till showing the northerly trend are more abundant in the area investigated. This northerly movement has been proven over the entire area, though it was rather weakly in the southern half. The southern limit of its strongest occurrence is indicated by the end moraine built of morainic hills and disposed across the central part of the area. The northerly movement transported and re-accumulated till already deposited by the westerly movement of the glacier. In addition the esker chains belong to the deposits of the northerly ice movement. Eskers originated in several ways, partly in open crevasses, partly in closed tunnels and accumulated by glacial meltwaters or sea-waves. They originated in general parallel to the ice margin, and their distribution is partly determined by local topography.

The northerly movement presumably originated in West Kola and the high mountain region west of it, when the ice divide and the accumulation area of the glacier changed its position northwards and eastwards and was gradually divided into smaller and more numerous parts.

The disappearance of the glacier from the area took place by melting, evaporation and calving. There are no indications whatsoever that the ice disappeared from the area even locally in the times between the different movements. The disappearance of the glacier did not take place so much as a retreat of a continuous ice front, but rather as a gradual thinning of the glacier which had already become almost stagnant, during a somewhat earlier period of deglaciation. Then there was a ragged, continually shrinking ice cover, the latest residual of which could have been preserved in sheltered places until relatively recent time. As the ice melted the area was covered by the late-glacial sea connected at first with the White Sea.

EXPLANATIONS TO THE PLATE

Fig. 1. A characteristic peat bog in the area investigated. An eutrophic *Sphagnum* bog with *Molinia*-growing peat banks, Suomussalmi, Hossa, Kukkarosuo. Photo M. Salmi.
Fig. 2. Crossing striations and friction cracks by the side of the Hossa road, 9 km. north of Juntusranta village. The pencil is parallel to the younger, north-westerly (321°) striations, and the compass parallel to the older, westerly (271°) striations.
Fig. 3. Till overlying washed drift at locality 20, Fig. 12, Laaja.
Fig. 4. Till overlying washed drift on the Raate road, locality 12, Fig. 12.
Fig. 5. Unwashed till overlying washed till in the cutting of the old military railway of Taivalkoski. The till has a northerly orientation, and the underlying bedrock has westerly striations, locality 52, Fig. 12.
Fig. 6. Structure of the ice-contact terrace by the side of the Hossa road.

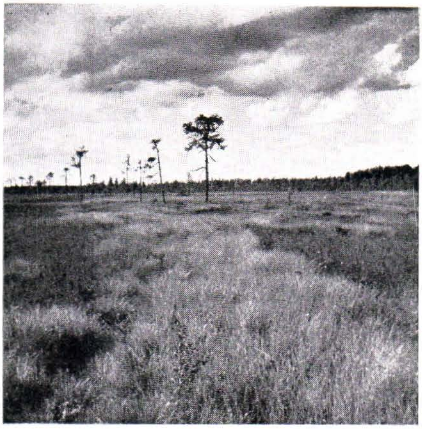

Fig. 1

Fig. 2

Fig. 3

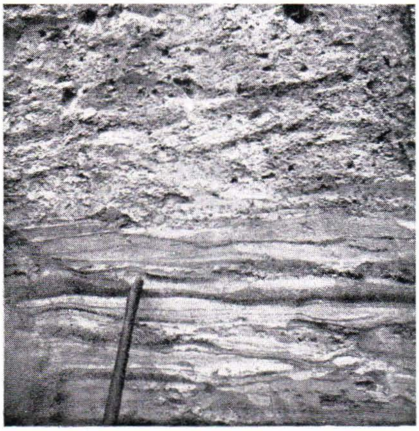

Fig. 4

Fig. 5

Fig 6

K. Virkkala: Glacial geology of the Suomussalmi area, East Finland.

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