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by Pentti Lindroos

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ON THE DEVELOPMENT OF LATE-GLACIAL AND POST-GLACIAL DUNES IN NORTH KARELIA, EASTERN FINLAND

BY

PENTTI LINDROOS

WITH 60 FIGURES AND 4 TABLES IN THE TEXT AND ONE APPENDIX

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Pentti Lindroos

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In the ice-marginal formations of Salpausselkä II and Jaamankangas, in the region known as North Karelia, Finland, transverse, parabolic, longitudinal and barchanoid fossil dunes were investigated.

The sand composing the dunes is fine in grain: Md = 0.16 mm, $S_o = 1.36$ and $S_k = 0.93$. Owing to the short duration of the eolian process, the quartz grains of the dune sand are only slightly rounded. The dark minerals and the rock fragments are distinctly more rounded than the corresponding grains of the source material.

The layers composing the ridge-shaped dunes generally dip parallel to one or the other flank. Cross-bedding occurs especially in the parabolic dunes.

The dunes situated on the distal side of Salpausselkä II originated under periglacial conditions in approximately 8 000 B.C. At that time, the prevailing winds blew from between the northeast and the northwest. The youngest dunes in the region are shore dunes, which date back to about 6 800 B.C. Four C^{14} -datings were carried out from peat samples taken from interdune bogs.

The dunes have undergone deflation. Their tops have at times been exposed and at other times almost completely covered with vegetation, as is at present the case.

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INTRODUCTION

In Finland, active dunes occur on the present seacoasts, while dunes covered by vegetation are to be found farther from the shore line (see Leiviskä 1905 and 1907, Häyrén 1914, Ilvessalo 1927, Lemberg 1933, Lumme 1934, Mattila 1938, V. Okko 1949 and 1964). Vegetation-bound accumulations of eolian sand, mostly fossil dunes, are also met with at considerable distances from present shores (see Virkkala 1948, 1954 and 1956). Leiviskä (1920) and later M. Okko (1962) have described fossil dunes in the Salpausselkä belt. Dunes are associated with glaciofluvial formations, from which their material originally derived (Leiviskä 1905, 1907 and 1928, Tanner 1915, Okko 1954). Aartolahti (1967) is of the opinion, however, that dunes are also apt to occur in moraine tracts, where the dune material has originated from till deposits sorted by wave action.

Eolian sands occurring in North Karelia are briefly mentioned in studies published as early as the end of the last century (e.g., Rosberg 1892 and 1899). Mapping of the Quaternary deposits was done in the region at the beginning of the present century, and in the same connection attention was also drawn to fossil dunes (Wilkman 1912; Frosterus and Wilkman 1915). In Högbom's (1923) view, the dunes occurring in North Karelia are shore dunes, which formed during ancient shore stages. North Karelian dunes are also listed in Lumme's (1934) compilatory paper.

The fossil dunes met with in the interior of the country show that conditions there were at some time favorable to eolian action (cf., Seppälä 1971), but changed later to the extent that the ground between the dunes has turned boggy.

The region of North Karelia has yielded significant studies dealing with the postglacial development of the local climate and vegetation (Hellaakoski 1922, 1932, 1934 and 1936; Sauramo and Auer 1928; Hyvärinen 1966 a and b; Repo and Tynni 1967; Tolonen 1967; Saarnisto 1970). The present paper deals with an area in North Karelia where, in association with glaciofluvial formations sorted material has accumulated in conspicuous abundance. Relatively little research has been done up to the present in Finland on the conditions that prevailed following the deglaciation but prior to the spread of vegetation. It is the genesis of the dunes that formed during that time in the region as well as their morphology and development that the present paper seeks to elucidate.

DESCRIPTION OF THE STUDY AREA

The study area is situated in the region of North Karelia (Fig. 1) between 62°10′ and 62°50′ N. Lat. and 29°15′ and 30°45′ E. Long. The western part of the area is on the whole low-lying and dominated by large lakes, and the differences in elevation in the relatively flat terrain seldom exceed 20 meters. The water level of several lakes, including Pyhäselkä, which are linked to great Lake Saimaa, is under 80 meters (75—77 m above sea level). The water level of other lakes is higher, that of, for example, Höytiäinen and Kuorinka being nearly 90 m above sea level. The elevation of the ground in the western part of the area varies in general from 80 to 110 meters, rising gradually from the lake shores inland. In this western section, the following places can be clearly distinguished from the rest by being higher and also topographically more uneven: the area on the southwestern side of Höytiäinen as far as Vaivio, the vicinity of Jakokoski, the area on the western side of Kiihtelysvaara and a small piece of land to the northwest of Tohmajärvi.

The eastern section of the study area has a hilly landscape, where the differences in elevation vary between 40 and 80 meters, or even more. The boundary of the hilly country runs, starting from the place called Mönni, in the northeastern corner of the study area, across Selkie and Kiihtelysvaara to Saario. The lakes of this eastern section have small basins, owing to the unevenness of the terrain. The altitude of the water level in these lakes varies from 100 to 120 meters. The hills rise to elevations of slightly less or slightly over 200 meters.

The bedrock of the area investigated is likewise characterized by a distinct bipartition. The boundary line from Mönni to Saario (Appendix I) divides the area in

FIG. 1. Location of the study region in North Karelia. I Ss = Salpausselkä I; II Ss = Salpausselkä II; Jk = Jaamankangas.

such a way that the western section consists of a schist zone and the eastern section of a basement gneiss zone. In places in the schist zone, plutonic rocks penetrate the schists, their most prominent occurrences being in the surroundings of Vaivio and Enonkoski (Appendix 1). In the last-mentioned areas, the topography, moreover, varies and is marked by considerable differences in elevation. The schist zone is comparatively low-lying and flat, and its principal varieties of rock are mica schist and phyllite (Frosterus and Wilkman 1916). In this zone, amphibolite and diabase as well as quartzite and arkosite are met with in some places. These occurrences generally lie on a distinctly higher level than the surrounding ground, as in the case of the amphibolite area situated northwest of Tohmajärvi. On the eastern margin of the schist zone there occur amphibolite and quartzite, of which the latter, in particular, forms long and narrow ridges clearly visible in the terrain. The eastern part of the study area is a zone of basement gneiss. The component rocks are mainly granitic gneiss, gneissose granite and granite (Hackman 1931).

The Quaternary deposits of the study area consist for the most part of till. Quite a substantial portion is nevertheless sorted material, deposited as eskers and ice-marginal formations, e.g. Salpausselkä II and Jaamankangas (see Appendix I). In the area investigated, Salpausselkä II extends from Piimäjärvi in the south as far as Kiihtelysvaara and Heinävesi. From there toward the northeast, the marginal formation is represented by the ice-marginal complex situated northeast of Keskijärvi. On the other hand, the author regards the sequence running northwest from the line of Kiihtelysvaara-Heinävaara as having formed out of successive deltas. Deltas and delta sequences are quite distinct features on the northern side of Jukajärvi (see Sauramo 1928) and the eastern and northeastern sides of Kulho (cf., Fig. 6). Toward Paihola from this point, the formation narrows, turning into a very steep-sloped ridge, which has been one of the feeding eskers of the Kulho deltas, the other having come via Utranharju (Utra esker).

The location of the Jaamankangas ice-marginal formation is indicated by Fig. 1 and Appendix I. In addition to the two major ice-marginal formations, the numerous ridges and other glaciofluvial accumulations of the study area have been important sources of sorted material. Of significance from the standpoint of this study is the sandur delta of Eno, the distal portions of which extend to the banks of Pielisjoki, at the very northern end of the area investigated. Another noteworthy glaciofluvial sequence lies on the northeastern side of Tohmajärvi. As early as the stage of their formation as well as during later shore stages, on the distal sides of marginal formations and deltas and along the edges of eskers, extensive sand fields developed (cf., Figs. 3 and 6 and Repo 1957, 1960, 1969).

RESEARCH METHODS

The field work was done in the study area in connection with the mapping of Quaternary deposits undertaken by the Geological Survey of Finland. In determining the occurrence of dune fields, aerial photographs were also examined. Such photographs were used in the drawing of detail maps (Figs. 11 and 17) of localities of which no topographic maps were available. During investigations in the terrain, not only the location of dunes but also their form, size and the angles of their slopes were studied. Moreover, barometric measurements and levellings were performed in the terrain to determine the level of the ground underlying the dune material and the heights of the dunes. In certain instances, the determination of an elevation was carried out by consulting available topographic maps.

The ground underlying the dunes has been considered to correspond to that of the immediate surroundings; sections extending down to the bottom of a formation have been dug in the area only in rare instances (see p. 61). The wind conditions prevailing at the time of the dune action were analyzed on the basis of the structure and shape as well as orientation and location of each given dune field.

Measurements of the angles of the slopes of dunes and the dips of layers were further performed in the terrain by using a hand clinometer. The measurements of dips of layers are more accurate than the values registered for slopes, for the layers are generally quite straight (see Figs. 34 and 35). The accuracy of the measurement of the dip of the layers is 1—2° while the angle of slopes can be determined to an accuracy of 2—5°.

Samples were taken of both the dune and source material for the determinations of grain properties. In addition, samples were taken from the peat layers between and along the edges of dunes. These samples were taken with a piston drill, the length of the pipe of which was 100 cm and the diameter 5 cm.

The grain composition of the dune and source material was determined by sieving. The square apertures of the screens used were 2.0, 0.6, 0.2 and 0.062 mm. The amounts of material used were 200 grams.

The sieving results are presented as triangular diagrams (Figs. 25—28) and a summary in the form of histograms (Fig. 24). In addition, use was made of a 10-sieve series (ASTM), in which the corresponding apertures of the sieves were 1.410, 1.000, 0.710, 0.500, 0.350, 0.250, 0.177, 0.125, 0.074 and 0.037 mm. In these sievings, too, the amount of material was 200 g. The sieving results were marked on semilogarithmic paper as cumulative curves, whereby it was possible to calculate the parameters S_o (sorting) and S_k (skewness) (see, e.g., Köster 1960, p. 141).

The fractions separated by sieving were studied to determine the roundness of the grains and the petrographic composition. From the different fractions, from 100 to 200 grains were counted and their S- and R-values (S = sphericity, R = roundness) determined visually through a binocular microscope according to Krumbein and Sloss (1963, p. 111). In the petrographic analysis, three categories were distinguished: light minerals, dark minerals and rock fragments (cf., Shepard and Young 1961).

The classification by peat types of peat samples is based primarily on laboratory determinations done microscopically. The pollen preparations were done by the

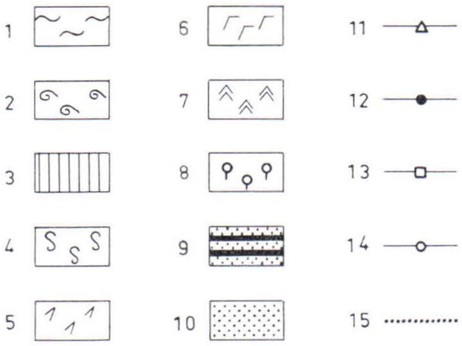

FIG. 2. Symbols used in pollen diagrams: 1 *Sphagnum* peat, 2 *Bryales* peat, 3 *Carex* peat, 4 *Eriophorum* peat, 5 *Scheuchzeria* peat, 6 *Equisetum* peat, 7 *Phragmites* peat, 8 peat with remains of trees, 9 sand and peat, 10 sand, 11 *Picea*, 12 *Pinus*, 13 *Alnus*, 13 *Betula*, 15 *Salix*.

KOH method. The sand-bearing samples of the lower parts of the series were prepared by the HF method (cf., Faegri and Iversen 1964). One hundred AP grains were counted from the samples. The findings are presented as pollen diagrams, the different symbols of which are shown in Fig. 2.

LOCATION AND MORPHOLOGY OF THE DUNES

Morphological classification used

In North Karelia, eolian sand forms morphologically varying types of dunes. Their classification was carried out for the purposes of the present study mainly on the basis of the ground plan of the dunes. Thereby, the following dune types were distinguished:

Dune mounds (cf., e.g., McKee 1966, p. 10). The shape of these dunes at their base is oval or oblong. The mounds vary in height from one to three meters and in length from 50 to 150 meters. They occur in association with larger dunes (e.g., 16, 34 and 48; Appendix I and Figs. 3, 9 and 11), but single mounds are likely to be met with, too (8 and 30 Appendix I).

Barchanoid dunes are crescentic in form at their base, with the horns of the crescent extending downwind (cf., Sokolow 1894, Ohlson 1957, Cooper 1958, Finkel 1959, McKee 1966). These dunes are highest in their middle portion, diminishing in height toward the horns. They are likely to occur separately (e.g., 2 and 21, Appendix I), but most often barchanoid forms are met with in association with sand ridges (e.g., 48, Figs. 11, 14 and 15; cf., also Ohlson 1957).

Sand ridges. The shape of these dunes at the base is long and narrow. The length is many times greater than the width. A sand ridge is seldom altogether straight. Most of them bend somewhat, in places even sharply (Fig. 17). *Transverse dunes* represent their most prevalent form. These ridges are oriented at right angles to the direction of the wind that produced them (cf., e.g., Hörner 1927, Kádár 1938, Galon 1959, McKee 1966). The cross profile is asymmetric. The difference in slope between the windward and lee sides is generally marked enough to be noticeable. The inclination of the windward side of the dunes in the study area varies on the average between 10° and 18° and that of the lee side between 18° and 32° (cf., e.g., Laulajainen 1914, Högbom 1923). The windward side is also always distinctly longer than the lee side.

Typical transverse dunes are, for example, shore dunes, the lee side of which faces away from the open water (e.g., 5, 9 and 11, Appendix I and Fig. 3). Transverse dunes are met with in other places, too, without any clear connection with a shore (e.g., 41 and 42, Fig. 18). *Longitudinal dunes* (Kadar 1938, McKee and Tibbits 1964) represent another type of sand ridge. In cross profile, they are nearly symmetrical. Such forms have evolved through the action of winds blowing from varying directions. Longitudinal dunes occur most commonly in association with parabolic dunes and in the marginal parts of dune fields (e.g., 27 and 48, Figs. 5 and 16; cf., also Hörner 1927).

Parabolic dunes. The form of these dunes at the base resembles a U or a V (cf., e.g., Kádár 1938, Landsberg 1956, Jennings 1957, Odynsky 1958, Galon 1959, Cooper 1967). Their middle part is highest and has moved forward in relation to the arms on either side, which point windward. The arms of the parabolic dunes in the study area range in length from 100 to 500 meters. Parabolic dunes are in many instances asymmetric with respect to their ground plan; that is, one of the arms is appreciably longer than the other. Typical parabolic dunes occur particularly in the area of Tohmajärvi (e.g., 55, 56 and 57, Figs 17 and 23) and at Mönni (e.g., 34, Fig. 9).

The dunes of the area investigated will be described regionally:

Liperi area, dunes 1—18, Appendix I and Fig. 3.
Joensuu area, dunes 19—30, Appendix I and Figs. 4 and 6.
Mönni area, dunes 31—35, Appendix I and Fig. 9.
Tohmajärvi area, dunes 38—58, Appendix I and Figs. 11 and 17.

In addition, two separate dune fields, 36 and 37, were investigated.

Liperi area

The ice-marginal formation of Jaamankangas is the most important source of dune material in the area of Liperi. The material deposited on the distal slope of its middle and western portions is relatively fine in grain and well sorted. Later shore stages further sorted it and transported it greater distances (Fig. 3).

Dunes of the distal part of Jaamankangas

The transverse dune, 1, on the western side of the area is about 400 meters long and 2 to 3 m high. Dunes 10 and 15 are irregularly shaped sand ridges (Fig. 3). Their

FIG. 3. Position in local terrain of dune fields of Liperi area (see Appendix I, area I). Profiles are presented in Figs. 44 and 45 1 = till, 2 = glaciofluvial material, 3 = dune, 4 = peat, white = sand, 95-meter contour line marked with broken line, space between other contour lines 10 meters.

thickness is only between 1 and 4 meters and they are underlain by glaciofluvial coarse sands.

The largest dune in the area is transverse dune 9, which is nearly 1 km long and runs in a northeast-southwest line. It is in many places 6 or 7 m high, but the dune loses height toward the southwest. The northeastern part of the dune is more than 100 m broad, constituting an undulating dune complex. It evidently consists of numerous concurrent sand ridges and mounds. The northwest flank of the ridge is the windward side; its inclination at the highest point is from 14 to 18° and at low portions in the southwestern part from 12 to 16°. The corresponding inclinations on the lee side vary between 23 and 30° and in the low stretches between 22 and 27°.

Dune 14 is a transverse dune with respect to the asymmetry of the inclination of its flanks, but its longitudinal plan is curved. It resembles the »star dune», described by McKee (1966, pp. 65—66) as having been piled up by winds blowing from different directions. The northern part of the dune for a distance of 100 meters has a north-south orientation, after which follows the highest part of the formation, a ridge in a NNE-SSW line measuring about 300 m in length. Extending from this ridge for 300 m more is a lower portion that runs northwest-southeast. At the southern end of it, there extend a couple of parallel ridges, which run in an NNE-SSW line (Fig. 3). The northwest flank of the dune is the windward side, which has an average inclination of from 14° to 18°.

The southernmost dune in dune field 16 is a sand ridge nearly a kilometer long, the overall orientation of which is NNW-SSE. Since there is no appreciable difference between the angles of the slopes, this is one of the typical longitudinal dunes.

Dunes of the vicinity of Kuorinkajärvi

The surroundings of Kuorinkajärvi consist of fields of sand, which has derived from Jaamankangas through post-glacial marine and lacustrine wave action.

On the western side of Kuorinkajärvi, there occur a couple of isolated dunes, 2 (Appendix I). One of them takes the form of a mound, with a length of some 100 m. The other is a barchan-like dune, the concave side of which faces south.

On the north side of Kuorinkajärvi, there are dunes in two separate places. The southernmost dune, 3, is an isolated dune mound (Fig. 3) from 3 m to 4 m high. Dune 11, located east of Kokinniemi, was at its initial stage a shore dune approximately 800 m long; its orientation was the same as that of the present shore of Kuorinkajärvi, or NNE-SSW. What is now left of it is two successive ridges, situated along the line of the former continuous shore dune. The longest continuous part now is over 300 m. Deformation appears to have taken place as early as the end of the primal stage of the dune's evolution. Indicative of this is the dune mound on the northeast side of the ridge as well as, further, the longitudinal dune extending from it for a distance of about 200 meters (Fig. 3). The inclination of the windward flank, facing the lake, is from 12° to 18° and that of the lee side from 20° to 30°.

Dunes between Riihilampi and Pyhäselkä

Slightly over a kilometer from the shore of Riihilampi to the northeast, there occur a pair of shore dunes, 4 and 5, running parallel to the northeast shore of the pond (Appendix I). The dunes are almost linked to each other by several mounds situated between them. The more southern dune is over 1 300 m long and from 3 m to 6 m high. At its southeastern end, it broadens out into an undulating complex nearly 100 m wide. The southwestern flank of these shore dunes facing the pond is the windward side, which slopes from 10° to 15°. The inclination of the lee sides varies between 15° and 25°.

To the northeast from the foregoing locality, there is a narrow, winding longitudial dune, 6. Varying in height from 1 m to 4 m, the dune breaks up at some points almost into separate mounds.

There are two dune fields, 7 and 8, on the north side of Maisonvaara (see also Frosterus and Wilkman 1915). In the dune field 7 there are three separate, narrow shore dunes, oriented NNW-SSE. The largest of the dunes is 500 m long and 2—5 m high. The flanks facing Pyhäselkä are the windward sides, which dip between 12° and 18°. The corresponding values registered for the lee sides are from 22° to 27°. At the highest point of the crest of the dune, the lee side dips 30°—32°.

The length of dune complex 17, on the western side of Mattisenlahti, is nearly 600 m, its width being in places over 100 m (Appendix I and Fig. 3). It consists of small mounds and non-oriented ridges, and hollows between them, resulting in a chaotic relief. The length direction of the whole complex is northwest-southeast, and its northwest portion constitutes a single transverse dune for about 100 meters. On the basis of the slopes, the windward and lee sides can be clearly distinguished. The dip of the northeast flanks of the single dune is approximately 11° and that of the southwest flank 18°.

Some two kilometers to the south of the foregoing dune complex, eolian sand occurs in the shape of mounds and small ridges, 18. The low mounds are so arranged that they form ridges from 1 m to 3 m high and oriented northwest-southeast. This direction corresponds to the ancient shore of Lake Pyhäselkä in this locality (Fig. 3).

Salokylä dunes

Somewhat over two kilometers to the north from Salokylä, there is a bipartite sand ridge, 12 (Fig. 3). The part farther north constitutes a transverse dune. It is about 400 m long and the direction is northeast-southwest. The part more to the south consists of a chain of dome-shaped accumulations. Its ground plan is slightly curved, but the prevailing orientation in northwest-southeast.

On the northwest side of Salokylä, there are two separate parallel sand ridges, which belong to one dune complex, 13 (Fig. 3). They are oriented southwest-northeast. The ridge more to the north is the larger, being about 500 m long and from

1 m to 4 m high. The southwest part of the dune is the highest. There the northwest flank dips 10—12° and the southeast flank 20—25°. The flanks of the lower northeast portion are nearly symmetrical, having an inclination of about 15°. The other dune is a ridge only from 1 m to 2 m high but with a length of nearly 600 m. At its southwest end, there is an extension 100 m long running toward the northwest (Fig. 3).

Joensuu area

In the Joensuu area, there is an abundance of sorted material. On the north side of town, there is Jaamankangas, and on the east side, extensive series of deltas. These are joined together by Utranharju (Appendix I). Relatively fine-grained material was deposited primarily along the margins of these accumulations. Subsequently the quantity of sorted fine material was substantially increased by littoral forces, which deposited fine sand over broad tracts.

Dunes of Utranharju

The most prominent dune complex, 20, in this area (Fig. 4) is situated west of Lehmo. Oriented northeast-southwest, this complex is some 1 400 m long. In addition, to its southwest end is linked an extension nearly 500 m long, which runs in an east-west line. Its northeast portion consists of two parallel ridges, both measuring about 500 m in length. The height of these parallel ridges varies from 1 m to 4 meters, but their middle portion reaches heights of from 8 m to 10 m. The slopes do not differ in degree appreciably. At the low points, the inclinations vary between 15° and 18°, and at the highest points, between 25° and 30°. The complex falls into the class of longitudinal dunes (Fig. 5).

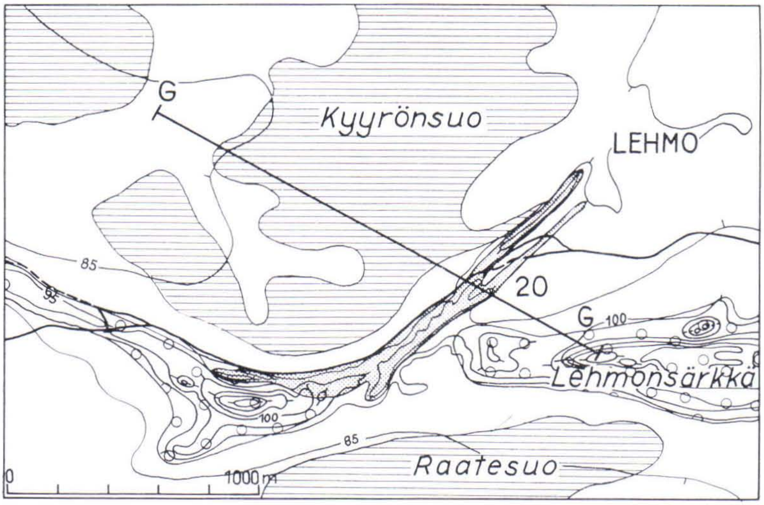

FIG. 4. Location of longitudinal dune 20 at Lehmo at margin of esker (area II). Profile is presented in Fig. 45 and symbols in Fig. 3.

FIG. 5. Low northeastern portion of longitudinal dune 20 at Lehmo.

FIG. 6. Dunes of Joensuu area in surroundings of Utra and Aittolampi (area III). Profiles presented in Fig. 45. Symbols same as in Fig. 3. Spaces between contour lines are 10 meters.

On the east side of Utranharju, there occurs a transverse dune 22 (Appendix I), which is over 600 m long and is oriented northwest-southeast. It varies from 2 to 6 meters in height, which diminishes toward the southeast.

The dune complex, 23, on the south side of Utranharju (Appendix I and Fig. 6) consists of two parts. Its main portion forms a transverse dune oriented northwest-southeast and with a length of about 500 m. From its southeast end, there turns off toward the northeast a longitudinal dune nearly 400 m long. The dune complex spreads out at the bend into an undulating feature about 100 m broad. At this point, the dune also rises to its greatest height, over 10 m (Fig. 7). The inclination of the windward side of the transverse dune in the high southeastern portion varies from 13° to 17° and that of the lee side from 26° to 34°. In the low northwestern section, the corresponding values are 12° and 14° on the southwest flank and 18° and 21° on the northeast flank (Fig. 8).

FIG. 7. Highest point of dune 23, situated on south end of Utranharju. Surface of dune has become exposed in spots because its top is criss-crossed by footpaths.

FIG. 8. Rather low northwestern portion of dune 23. Note the asymmetric form of dune.

Dunes of the Aittolampi vicinity

Along the margins of the great deltas, there occur some dune mounds or irregular ridges with slightly sloping sides, 30 (Appendix I). In some instances, only a couple of meters of dune sand have been observed to overlie the glaciofluvial material, 24. The most prominent dunes are located in the surroundings of Aittolampi (Fig. 6). Closest to the glaciofluvial deltas, one meets with barchan-like dunes, 26. Their convex sides dip on the average 12° and the concave sides from 20° to 24°. The largest of these dunes is the one farthest south, and it rises to a height of from 5 to 7 meters.

At a greater distance from the deltas, the dunes are generally parabolic in form, as witness 28 and 29. Their basic pattern is asymmetric, for one arm is in many cases twice as long as the other. The height of the parabolic dunes is greatest at the point of the nose (from 5m to 8 m), diminishing toward the arms. Furthermore, the larger arms (e.g., 28, Fig. 6) contain small parabolic extensions.

On the south side of Aittolampi, there is a longitudinal dune, 27, which lies somewhat apart from the rest and measures more than 300 m in length. It varies between 5 m and 7 m in height, and there are scarcely any differences between the flanks with regard to their pitch.

Scattered occurrences

In the Joensuu area, dunes standing apart are to be met with, too, occurring on till mounds thrusting up out of the sand fields. The sand ridge, 19, (Appendix I) is 200 m long and oriented in a northeast-southwest line. Dune 21, on the eastern side of the city of Joensuu, is barchanoid in form. Its convex west side dips from 12° to 15°, and its concave east side from 22° to 24°.

The dune located on the south side of the Utra canal, 25 (Fig. 6), is a low ridge about 200 m long and oriented in a nearly north-south line. The dune has gentle slopes and is between 1 and 3 meters high.

Mönni area

On the northwestern side of the Jakokoski canal, there occurs an extensive field built up by glacial meltwaters (Appendix I). Its northwestern section is a sandur and its southeastern section a delta. Because the Pielisjoki (= river) wore down its channel across the delta, the sands have been subjected to diverse sorting and provided susceptible material to the winds for transportation.

Southwest of Mönni, one meets with a transverse dune, 31, which is 600 m long. In this locality, eolian sand is also present as cover-sand, 32 (Appendix I).

North of Mönni, typical shore dunes occur close to the banks of Pielisjoki. The orientation of the dunes varies, being either north-south or northeast-southwest,

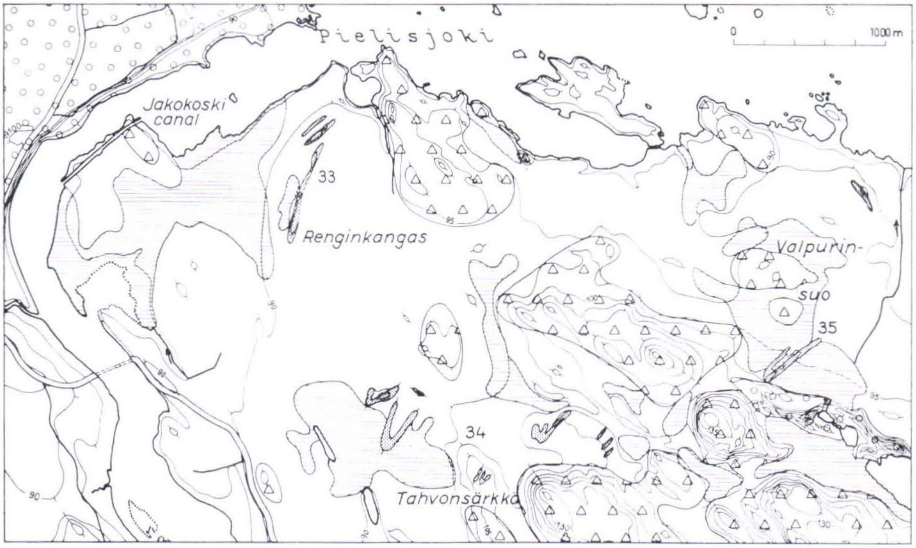

FIG. 9. Dunes of Mönni area (area IV), symbols explained in Fig. 3.

and it conforms to the direction followed by the shore (Fig. 9). The longest dunes stretch for distances of about 700 m, and their crests rise to from 1 m to 4 m. The area also has fairly well developed parabolic dunes, 34, which lie slightly farther from the river. The lengths of the arms of the parabolic dunes vary between 100 and 300 m, and the basic pattern is generally fairly symmetrical (Fig. 9). In height, the dunes vary from 1 m to 4 m. Farthest to the northwest, there occurs the largest dune of this area, 35. A symmetrical longitudinal dune, it has a length of more than 500 m. The crest rises in places above 5 m, but there is a levelling off toward the northeast.

Tohmajärvi area

The ice-marginal belt of Salpausselkä II extends past the western sides of Heinävaara and Kiihtelysvaara to Onkamo. Around Heinävaara and Kiihtelysvaara, no dunes, however, occur (Appendix I). This area is lacking in flat, level stretches of ground where meltwaters from the ancient continental ice sheet could have deposited material suitable for wind transportation. The primary material of which Salpausselkä II is composed is in places in this area, too, quite coarse (e.g., Repo 1957, p. 113 and Figs. 71—77). Signs of eolian activity are to be noted here and there, as, for example, on the south side of Palojärvi and the north side of Haarajärvi.

Overlying the mounds and ridges, 36, consisting of sorted material on the south side of Palojärvi, there is eolian cover sand from 1 m to 2 m thick. On the north side of Haarajärvi, cover sand lies on top of till mounds, 37, as well as on their western slopes to a thickness of between one-half and one meter (Appendix I).

North of Tohmajärvi, in the area of Vatala and Murtoi, there spreads out a broad and fairly level tract marked by the presence of abundant sorted material. Having been reworked by littoral forces, its most important sources are Salpausselkä II, the esker situated between Valkealampi and Karhunpäälampi, and the smaller, fragmentary esker sequence on the northeast side of Muskonlampi (Appendix I and Figs. 11 and 17). Also, at the bottom of bogs, for example the broad Valkeasuo, fine sand is commonly met with (cf., Tolonen 1967, Appendix III, Profiles A, D and N). Fine sand occurs in the area so abundantly and uniformly that its exact relation to glaciofluvial material is exceedingly difficult to determine with respect to genesis.

Rouanaho dunes

In the area of Rouanaho, there are extensive occurrences of fine sand, which may have derived from different sources. In the northern part of the area, there is a continuous sandy stretch that reaches as far as Jylmänvaara (Appendix I, Fig. 11). In the west, the area is bounded by bogs, but sand occurs underneath all the way to the distal portions of Salpausselkä II. The fragmentary esker chain in the southwest (Fig. 11) has also provided sand.

East of Jylmänvaara, there is an isolated dune complex, 39. It is made up of a longitudinal form about 100 m in length and oriented northeast-southwest and another one linked to it transversely, being of the same length and running in a northwest-southeast line (Fig. 10). The dune complex is on the whole between 2 and 3 m high but at the bend nearly 5 m. Southwest of Jylmänvaara, there occur several transverse dunes, 38, which are oriented northwest-southeast (Fig. 11). They vary in length from 200 to 400 meters and in height between 2 and 4 meters. On the northeast side of the transverse dunes, there are dune mounds and ridges, which may generally be designated as longitudinal dunes or rudimentary forms in the same class.

FIG. 10. Dune 39 on eastern side of Jylmänvaara. Dune's highest point visible at left margin of picture. Auto stands atop transverse ridge.

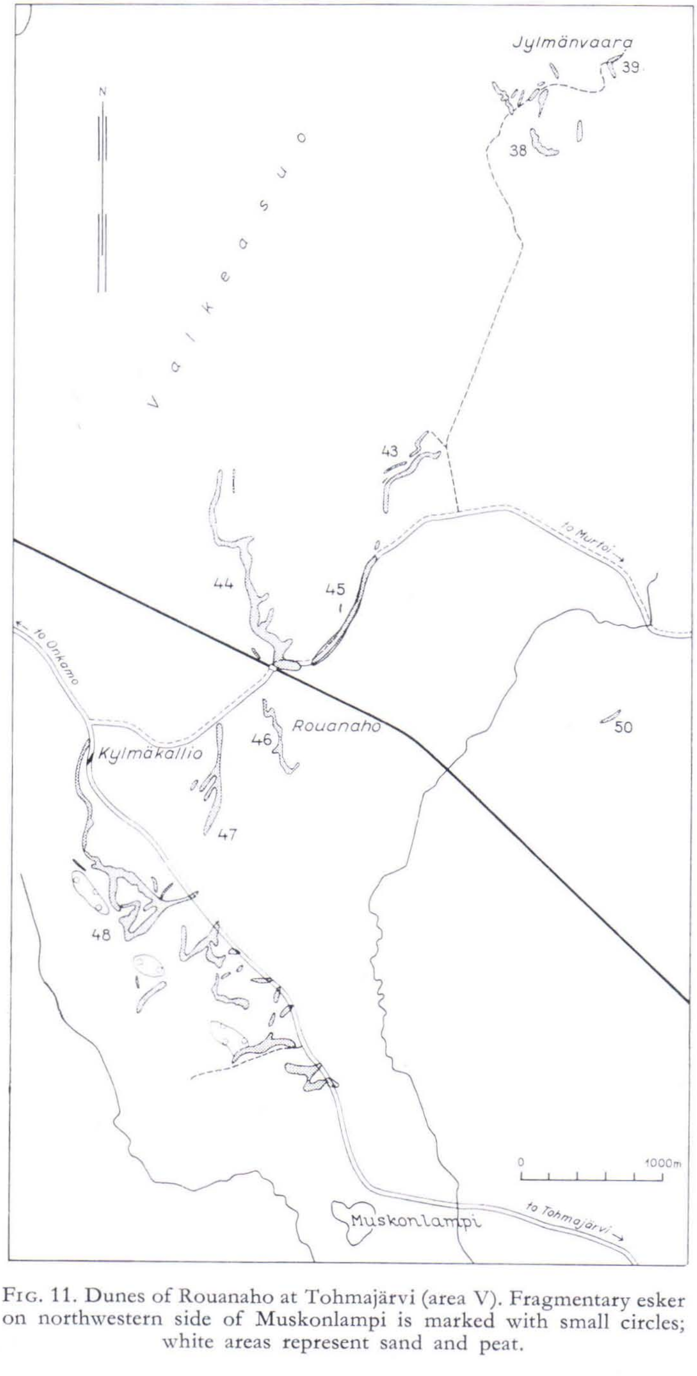

FIG. 11. Dunes of Rouanaho at Tohmajärvi (area V). Fragmentary esker on northwestern side of Muskonlampi is marked with small circles; white areas represent sand and peat.

On the north side of Rouanaho, there is a dune complex that possibly was originally a large parabolic dune: the remnants of its former NNE-SSE-oriented arm now lie separated from the rest (Fig. 11). Farthest to the northeast, there occur three separate ridges of eolian sand, 43, of which the largest is about 500 m long and from 2 m to 5 m high. It winds considerably and its flanks slope at varying angles on different sides (cf., Fig. 43).

Along the road to Murtoi, there is a sand ridge a kilometer long, 45. Its crest rises toward the southwest, to the nose of the original parabolic dune. (Fig. 11). At most, the height of the ridges reaches from 6 m to 9 m. The flanks of the formation are distinctly asymmetric. The slope of the northwest flank varies between 10° and 17° and that of the southeast flank between 20° and 30° (Fig. 12).

On the site of the other arm of the former parabolic dune, there now stands a ridge nearly 1.5 km long. It is a continuous and conspicuously winding sand ridge, 44, with small extensions (Fig. 11). The ridge is oriented NNW-SSE and its long profile is very sinuous (Fig. 13). The northern portion of the dune is a ridge between 1 m and 3 m high and running in a north-south direction for a distance of some 500 m. The east-west and northeast-southwest bends and extensions are small parabolic arms. The side of the sand ridge facing east and northeast is on the whole slightly gentler of slope than the opposite flank, and all the extensions as well as detached ridges are located on that side. The western flank is bordered sharply by a bog.

On the south side of Rouanaho, one meets with a couple of detached, sinuous sand ridges, 46 and 47 (Fig. 11). They vary in height from 1 m to 4 m, and here and there they consist of almost separate chains of dune mounds. The interdune area is filled with peat; the bog borders sharply on the ridges. There is no note-

FIG. 12. Road leading to Murtoi runs across summit of dune 45. More gently sloping northwestern flank of formation appears at left in photo.

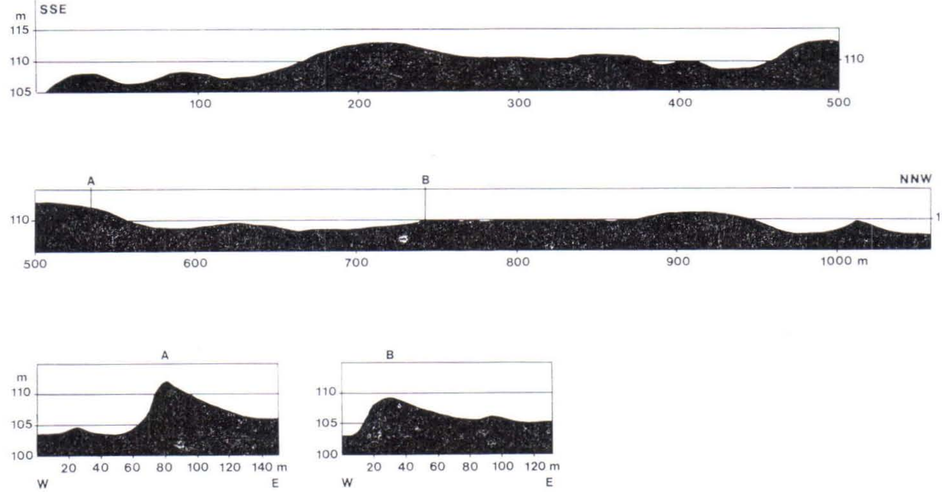

FIG. 13. Long profile and two cross sections (A and B) of dune 44 at Rouanaho. Peat profiles were taken from site of latter cross section B, the pollen diagrams being given in Figs. 50 (west side) and 53 (east side).

worthy difference between the slopes of the dunes, but at the bends the ridges are asymmetric (cf., Fig. 43). From the south end of the eastern ridge, 46, there extends a projection 100 m long to the northeast. It is conceivably a remnant of one arm of a parabolic dune. By contrast, the western ridge, 47, is a combination of a longitudinal and a parabolic dune.

The broadest dune field of the study area, 48, is some 3 km long and it varies between 100 m and 600 m in breadth (Fig. 11). In this field there are sand ridges varying in shape and orientation and separated by ground that has turned boggy. The general orientation of the dune field is from northwest to southeast, but the separate sand ridges are by and large situated at right angles to this line. In the northwestern part of the field, there is a sand train measuring about 800 m in length and running in a nearly north-south line. It has quite a serpentine form, however, and is made up of, in places, almost detached barchanoid portions (Figs. 14 and 15). This sand train varies from 1 m to 5 m in height, and its south end is joined to a ridge oriented northwest-southeast. This large ridge, like a hogback in places, has a length of over 600 m and the highest points rise almost 10 m above the surrounding ground.

In the middle of this extensive dune field, there occur parabolic dunes with arms stretching out an average of between 300 m and 400 m. Downwind they are joined by longitudinal dunes from 100 m to 300 m long. In the southeast part of the dune field, there are sharply winding ridges between 200 m and 500 m in length. Their profile along the top is conspicuously undulating. The highest points of the ridges are from 8 m to 10 m. There are no marked differences in pitch between the opposite flanks of the dunes (Fig. 16), which fall into the category of longitudinal dunes.

FIG. 14. Dunes consist in some instances of barchanoid parts, (northwest portion of dune field 48).

FIG. 15. Concave side of barchan shown in preceding picture has turned boggy. Sinuous part of a formation appears in the background.

FIG. 16. Longitudinal dune, nearly symmetrical in shape, of broad dune field 48 at Rouanaho.

Dunes of Vatala

The numerous sand ridges of Vatala are situated on the whole in the proximity of the esker running between Valkealampi and Karhunpäälampi, in many instances at its very margin (Appendix I and Fig. 17). It is from this esker that the dunes of Vatala have evidently derived their material. It is somewhat harder to explain the derivation of the material contained in dunes 41 and 42, which are situated to the south of the esker. With respect to elevations, the area on the north side of Vatala deviates from the other places. Dune field 42, on the southwest side of Honkalampi, rests on approximately the same level as the rest of the dunes of Vatala. On the other hand, the northernmost dune field, 41 (Fig. 17), lies distinctly higher than the rest. In the surroundings of the dune field, there are occurrences of fine sand over fairly wide stretches of ground, but its origin is not very easy to determine.

On the two dune fields, 41 and 42, situated on the north side of Vatala, there occur mainly transverse dunes, which in general are oriented northeast-southwest (Fig. 17). In both places, the dunes on the southeast side of the field are the largest (Fig. 18 and 19). They are from 600 m to 1 000 m long and, at the highest points, from 7 m to 10 m high. The long profie of the dunes is highly undulating (Fig. 18). In each place, on the northwestern windward side of the largest dune, there occur parallel sand ridges. In the latter place, 42, they are only short and low mounds. By contrast, in the former field, 41, there are from 2 to 4 ridges varying in length from 300 m to 800 m and from 1 m to 5 m in height. All the dunes are transverse forms. Their northwest flank is consistently the more gently sloping windward side, the

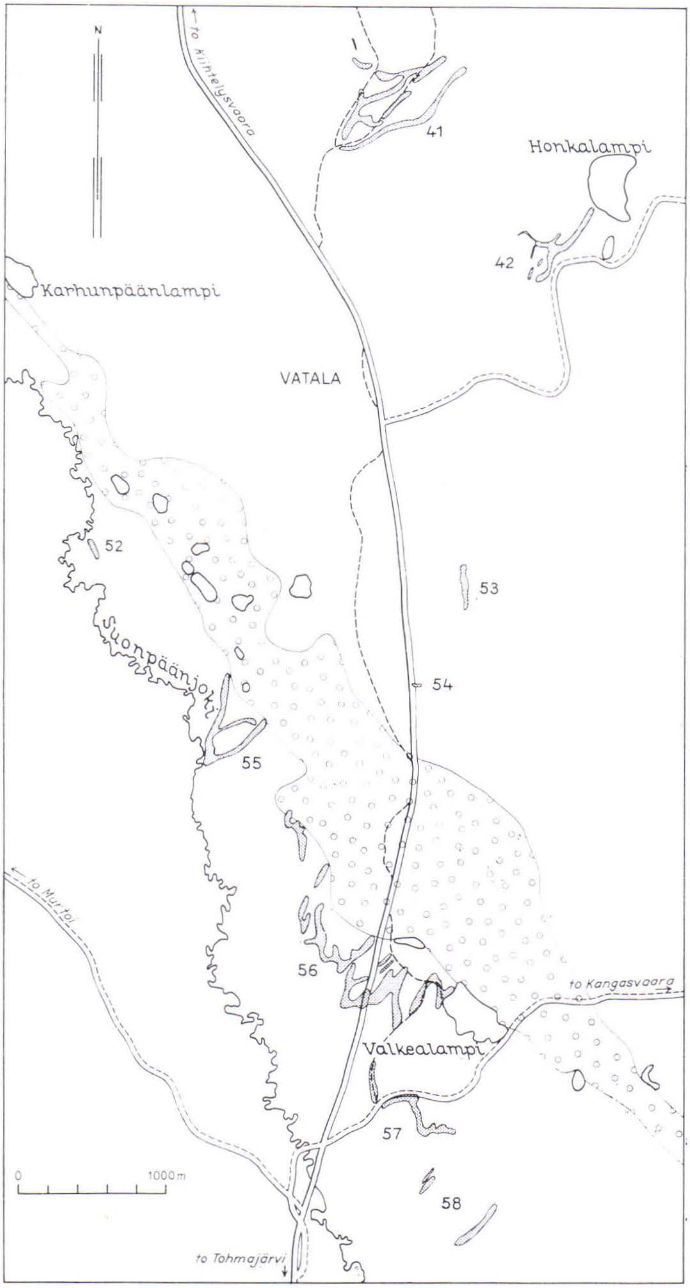

FIG. 17. Vatala dunes in Tohmajärvi area (area VI). Extensive esker sequence between Valkealampi and Karhunpäälampi is marked with circles. White areas denote sand and peat.

FIG. 18. The largest transverse dune, 41, at Vatala is rolling in shape. Photo was taken from windward side; bog in foreground.

FIG. 19. Surface of dune is mantled by sparse but continuous *Calluna* and *Cladonia* vegetation. Photo from summit of transverse dune 42, situated on southwest side of Honkalampi, with lee side on left.

inclination of which varies, depending on the height of the formation, from 10° to 18°. At the highest points of the dunes, the lee side has a pitch of from 25° to 32°. The interdune areas have turned boggy (see Fig. 18). Similar paludification phenomena of dune areas have been observed elsewhere, as, for example, in Poland (Chmielewska and Wasylikowa 1961, Kobendzina 1961, p. 386).

In the northwestern part of Vatala, there is an isolated parabolic dune, 40 (Appendix I). It is quite regular in its ground plan, and the arms are about 200 m long.

On the south side of Vatala, there occur a couple of transverse dunes, 52 and 53 (Fig. 17), from 200 m to 300 m long and 1 m to 4 m high. In addition, on the edge of the esker, there is a parabolic dune, 54, which never developed past a rudimentary stage.

On the northwest side of Valkealampi, there is a broad area covered with eolian sand (Fig. 17). Farthest in the northwest, one meets with a very highly developed parabolic dune, 55, the lengths of the arms of which are 500—600 m (Fig. 20). The arms are only from 2 m to 4 m high to start with but rise to a height of from 4 m to 7 m toward the nose. The inner flanks are slightly gentler of slope than the outer ones, which dip 18—20°. The arms of the dunes reach out partly on the lower flanks of the esker.

Near Valkealampi, there are numerous parabolic dunes situated side by side on dune field 56, and in between them longitudinal dunes. The lengths of the arms of the most prominent parabolic dunes are about 500 m. In the middle of the field

Fig. 20. Arm of parabolic dune 55 and in background part of its nose.

Fig. 21. A dune in dune field 56 extending to the slope of the glaciofluvial formation visible in the background. The ground vegetation on the surface of the dune is almost exclusively *Cladonia.* Boggy ground on both sides of the dune.

FIG. 22. Gently winding longitudinal dune of dune field 56 on slope of esker northwest of Valkealampi.

FIG. 23. Parabolic dune 57, on southwest side of Valkealampi. Photo was taken from summit of opposite arm, so that the highest point of the parabola, the nose, appears at the left and the road runs atop the other arm. The ground between the arms has turned boggy.

is the biggest parabolic dune, which is intersected by the highway connecting Kiihtelysvaara and Tohmajärvi. At the point of the road cut, the height of the dune is between 10 and 12 meters. In this dune field, some sand ridges are slightly asymmetric. The dunes are sharply bounded by a bog (Fig. 21) and they extend partly on the flanks of the nearby esker (Fig. 22).

Dune complex 57, situated on the southwest side of Valkealampi, is built up of two parabolic dunes (Figs. 17 and 23). The arms have grown together, and the nose of one of the parabolas is a blow-out. On the south side of Valkealampi, there is dune field 58, to which belongs a transverse dune measuring some 400 m in length. To the northwest from this point, there occur a couple of parallel transverse dunes (Fig. 17) about 100 m long. They are all oriented northeast-southwest, and their northwestern flanks slope gently windward.

Scattered occurrences

In addition to the afore-described dune fields, there are some small isolated occurrences in the area of Tohmajärvi (Appendix I). About 2.5 km to the southwest from Kylmäkallio, there is a transverse dune, 49, which is 200 m long and oriented northeast-southwest. Its southeast flank slopes gently.

On the south side of the village of Murtoi, there occur transverse dunes 50 and 51. The former is less than 200 m long and has a northeast-southwest orientation. In the latter place, there are a couple of parallel transverse dunes, which are 250 m and 400 m in length. They vary in height from 1 m to 4 m. Besides the transverse dunes, there is a small dune mound downwind (Appendix I).

THE MATERIAL OF THE DUNES

Grain size and sorting

Several dozen samples were taken from the dunes in the study area, and they were subjected to a total of about 100 grain size analyses (p. 10). Insofar as several samples were investigated from the same dune, the average value obtained was taken to represent the grain composition of the dune.

The material of the dunes of North Karelia consists predominantly of highly sorted sand. It contains only the following fractions:

2.0—0.6	mm (coarse sand)
0.6—0.2	» (fine sand)
0.2—0.062	» (very fine sand)
<0.062	» (silt)

No grains have been met with in the samples collected from the dunes of the area investigated that have exceeded 2 mm in diameter. Also in Högbom's (1923, p. 137) data, over 2-mm grains are exceptional. Only five dunes, 5, 12, 13, 20 and 30 (Appendix I) have yielded grains measuring between 1.41 and 2.00 mm in diameter. Even so, the diameters are near the lower limit. In the Tohmajärvi area, only a few dunes contain grains exceeding 0.71 mm in diameter (cf., Fig. 28).

In the different dune areas, the grain size of the material depends not only on the composition of the source material but also on the strength of the wind. According to different investigators, the minimum velocity of the wind capable of blowing sand varies from 3.5 to 4.5 meters per second (e.g., Anderson 1926, Land 1964). Constantly blowing winds of a velocity between 5 and 8 m per sec. play a bigger part in the transportation of sand than do sporadic gales. The afore-mentioned velocity suffices to put grains into saltation movement.

According to Sokolow (1894, pp. 12 and 288) and Land (1964), the relation between wind velocity and grain size is as follows:

Wind velocity	Maximum grain size	Motion of sand
< 3.4 m/s		Scarcely any effect
3.4—6.7 m/s	0.25 mm	Light minerals: continuous saltation; heavy minerals: slow saltation
6.7—8.4 m/s	0.5 »	Sand flies through air for some distance
9.8—11.4 m/s	1.0 »	Rain often falls in conjunction with heavy winds, preventing movement of sand
11.4—13.0 m/s	1.5 »	

Severe gales, with velocities over 9.0 m per sec., tend to deform dunes by causing deep blow-outs and other deflation forms. According to Land (1964), dunes form mainly when the wind velocity is sufficient; this observation applies also to the formation of the North Karelian dunes, for their material is quite fine.

The wind velocity increases, according to the research done by Anderson (1926), above the surface of the ground as follows:

At the surface	Wind velocity	4.5 m per sec.
30 cm above	» »	5.0 m per sec.
3 m »	» »	9.2 m per sec.
40 m »	» »	16.3 m per sec.

The median grain size (Md) of the dune sand in North Karelia varies in general between 0.13 and 0.18 mm, and the arithmetic mean is 0.16 mm. The lowest values, 0.09—0.11 mm, were yielded by the samples from dunes 3, 16, 17 and 21. The highest values, 0.24—0.25, were registered by the samples from dunes 1, 5, 12 and 15. These findings represent very small variations in the Md values. Its value is likewise low, which proves the material to be quite fine-grained. Also Högbom (1923) and Hörner (1927) reported occurrences of eolian sand of similarly fine composition.

One reason for the fineness of the dune material can be discovered in the character of the source material, grain-size analyses of which prove it to be quite fine-grained, too. The eolian sand is still finer of composition than the source material (cf., e.g., Hörner 1927, Giles and Pilkey 1965). Comparisons between the source material and the eolian sand proper have produced consistent results with respect to the grain size. The following pair of samples come from the area of Liperi, between Riihilampi and Pyhäselkä. The composition of the sample from the windward terrain of dune 4 is marked A and that of the dune sample, B.

	A	B
2.0—0.6 mm	2.7 %	0.5 %
0.6—0.2 mm	35.1 %	22.4 %
0.2—0.062 mm	59.0 %	72.7 %
<0.062 mm	2.2 %	4.4 %

Dune material (B) contains a distinctly smaller quantity of coarse fractions than source material (A) does. In the dune material the fine fractions have become enriched at the expense of the coarse fractions.

In the Joensuu area, samples were taken from the southwest side of dune 29 (A, 0.3 m depth and B, 0.6 m), from the dune itself (C) and from the ground on its windward side (D, comp. Fig. 6). The proportions of the different fractions were as follows:

	A	B	C	D
2.0—0.6 mm	0.3 %	6.2 %	—	2.0 %
0.6—0.2 mm	13.1 %	46.7 %	2.7 %	59.8 %
0.2—0.062 mm	82.5 %	45.7 %	91.8 %	36.8 %
<0.062 mm	4.1 %	1.4 %	5.5 %	1.4 %

The composition of sample A corresponds closest to the composition of dune sample C. Quite apparently, the surface layer of well-sorted material 30—50 cm thick occurring in this area has been transported and sorted by the wind, whereas sample (B) represents waterlaid material. Sample (D), taken from the northeast side of the dune, is distinctly coarser.

Similar results have been obtained also from the Tohmajärvi area. Here is an example, A denoting the source material and B the material from dune field 42 (comp. Fig. 17):

	A	B
2.0—0.6 mm	4.1 %	—
0.6—0.2 mm	15.5 %	5.6 %
0.2—0.062 mm	77.6 %	90.2 %
<0.062 mm	2.8 %	4.2 %

In this case, too, the dune material is noticeably finer than the source material. The dune contains no coarse sand whatsoever — any more than do the dunes of Tohmajärvi in general. The quantity of fine sand, too, is only about one-third of the corresponding amount of source material.

Although the dune material throughout the study region is visually very much alike in composition and sorting, the average grain composition varies considerably from place to place. In individual dunes, these values differ even more. In histograms A, B, C and D of Fig. 24, the average grain-size composition of the dune material in different areas is shown.

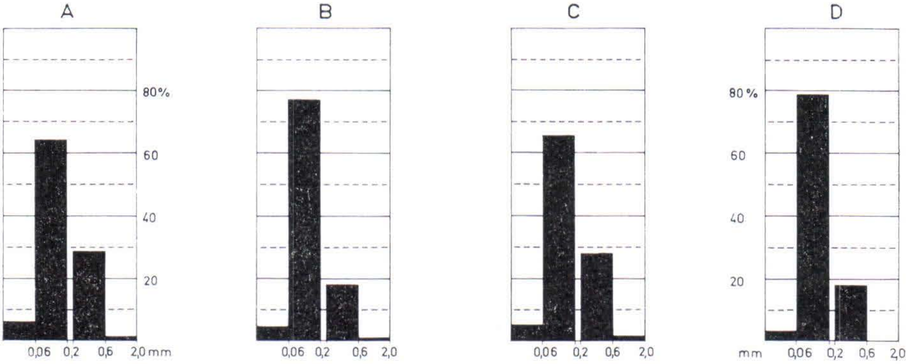

FIG. 24. Histograms showing the grain compositions of dune sands in study region: A = Liperi, B = Joensuu, C = Mönni and D = Tohmajärvi.

The dune material of the Mönni area is the coarsest of all (histogram C). Material coarser than 0.2 mm accounts for more than 30 per cent of the total, and in individual dunes the proportion is even greater. Correspondingly, the very finest grade (< 0.062 mm) occurs in the smallest amounts, on the average 5 % (Fig. 25). The material of the dunes of this area is also sorted best according to Sindowski's (1961, p. 173) classification. The S_0 value averages 1.31. The material sorted best was met with in a parabolic dune situated in dune field 34.

The dune material in the Liperi area is likewise quite coarse (histogram A). An average of nearly 30 per cent of the material is of a coarseness exceeding 0.2 mm in diameter (Fig. 26). Dunes 12 and 13 of Salokylä deviate clearly from the other

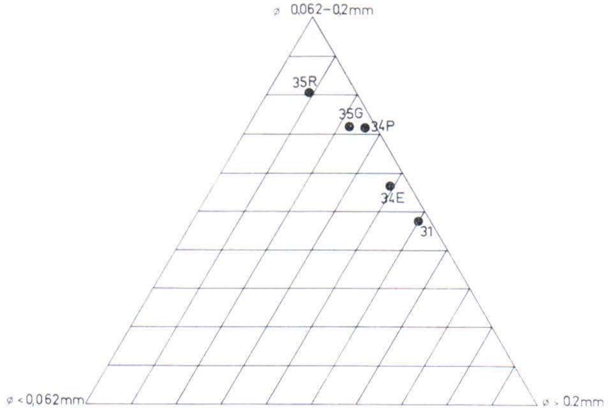

FIG. 25. Grain composition of Mönni dune sands.
34 E = small ridges of east side of dune field 34
34 P = parabolic dunes of dune field 34
35 G = dune of dune field 35, situated alongside esker
35 R = shore dune in dune field 35 (comp., Fig. 9).

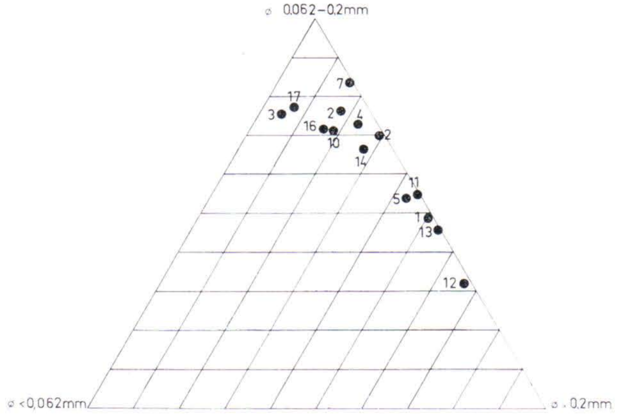

FIG. 26. Grain composition of Liperi dune sands.

dunes of the Liperi area, for over 50 per cent of their material consists of coarse fractions, measuring > 0.2 mm, while the finest fraction, < 0.062 mm, accounts for only 1 per cent of the total (cf., Fig. 26). The material of the Salokylä dunes is quite well sorted, for the average S_0 value is 1.35, whereas the corresponding figure for the Liperi area as a whole is 1.37. The most poorly sorted material occurs along the margins of Jaamankangas, where the S_0 value is 1.40; elsewhere it varies from 1.34 to 1.37.

The dune material of the Joensuu area and the Tohmajärvi area is highly similar (histograms B and D, Figs. 27 and 28). Grains coarser 0.2 mm in diameter make up slightly less than 20 per cent of the total, with coarse sand comprising less than

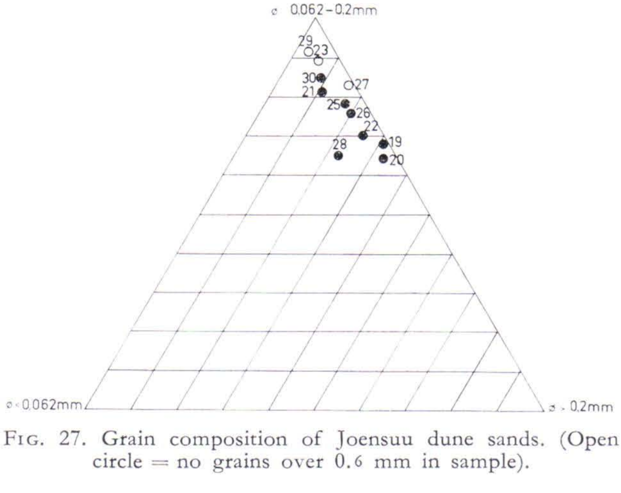

FIG. 27. Grain composition of Joensuu dune sands. (Open circle = no grains over 0.6 mm in sample).

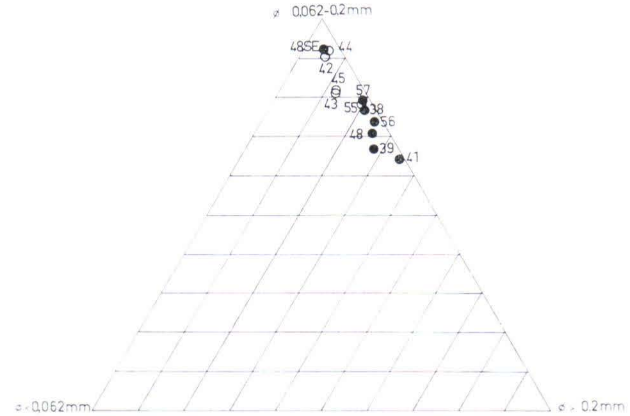

FIG. 28. Grain composition of Tohmajärvi dune sands (open circle = no grains over 0.6 mm). Sample 48 SE = southeastern part of dune field 48.

1 per cent of this content (Fig. 24). The dune material of the Tohmajärvi area is the finest of all. The content of grains over 0.6 mm in diameter averages 0.1 per cent, but this size is lacking altogether from many samples (Fig. 28). The finest fractions (< 0.062) do not occur in these dunes, however, any more than in the dunes of the other localities; the silt content varies between 3 and 4.5 per cent. In the dunes of the Joensuu and Tohmajärvi areas, the 0.062—0.2 mm grain size accounts for almost 80 per cent of the total. In the case of individual dunes, this size is apt to register as much as 90 per cent (Fig. 28, Nos. 44 and 48).

The average sorting value of the Joensuu dunes is 1.38, and of the Tohmajärvi dunes 1.33. The best sorted material of the former area occurs in scattered dunes, where the S_0 value averages 1.34. The lowest value, 1.28, was yielded by dune 25. The most poorly sorted material occurs in the dunes of the Aittolampi area, their S_0 value being on the average 1.41. In the Tohmajärvi area, the material of the Vatala dunes is on the average better sorted ($S_0 = 1.32$) than the material of the Rouanaho dunes, the S_0 of which is 1.38.

The skewness values vary between 1.01 and 0.85 in the different dune fields. In the Mönni and Liperi areas, the skewness values are close to 1. The highest value registered in the entire study area, 1.02, occurs in dunes 12 and 13 of Salokylä. This signifies that in these dunes, the finest fractions are better sorted than the coarse ones (cf., eg., Köster 1960, p 141, Molnar 1966, pp. 138—139).

The average skewness value measured in the Joensuu area is 0.92. The lowest value, 0.87, occurs in the dunes of the Aittolampi vicinity. There in individual instances, the S_K value is likely to be on the 0.80 level. These values distinctly under 1 reveal that the coarse fractions are the best sorted ones.

The average skewness value registered for the Tohmajärvi area, 0.88, is one of the lowest known in the study region. The lowest value, 0.78, was yielded by dune 43 at Rouanaho. In the light of the skewness values, it may be said that the coarsest fractions have been sorted best as a result of wind transportation, even though the material might be very fine.

An examination of the material of the dunes of North Karelia as a whole reveals that an average of 25 per cent contains grain sizes exceeding 0.2 mm in diameter. The silt content is less than 5 per cent of the total, and over 70 per cent of the rest ranges from 0.062 to 0.2 mm in diameter. Taking the average figures for all the dunes in the area investigated, $S_0 = 1.36$ and $S_k = 0.93$. The values cited do not deviate in general from those reported for eolian material from other countries (cf., Klemsdal 1969, p. 63). The dune material in North Karelia is slightly finer of grain, however, than that for which values are given in other studies (cf., e.g., Högbom 1923, pp. 137—138). The material is on the average well sorted. Besides the fineness of the material, the lowness of the S_k values is noteworthy, proving as it does the sorted character of the coarse fractions.

Petrographic composition and grain form

For the investigation of the petrographic composition and grain form of the dune material, 19 samples were selected from different parts of the study area. These samples were analyzed by the methods described on pp. 10. The samples are distributed among the different localities as follows: Liperi area, 6 samples (dunes 5, 9, 11, 12, 13 and 17); Joensuu area, 5 samples (dunes 19, 20, 26, 27 and 28); Mönni area, 3 samples (dunes 31, 33 and 34); and the area of Tohmajärvi, 5 samples (dunes 39, 44, 48 and 57). For purposes of comparison, six samples were chosen, being taken from glaciofluvial material in the following places:

A 37 Liperi, western part of Jaamankangas
A 51 Onttola, Jaamankangas plateau
A 120 northeast side of Joensuu, Utranharju
A 65 south side of Heinävaara, Salpausselkä II
A 121 Tikkala, »
A 100 Onkamo, »

A summary of the analytical results arrived at with the fractions between 1.00 and 0.71 is presented in Table 1. The quantity of light minerals varies from less than 60 per cent to more than 70 per cent. The light minerals are predominantly quartz, besides which feldspar is also present. The dark minerals consist mainly of biotite, in addition to which there are small amounts of hornblende and magnetite.

In the dunes of Liperi and Joensuu, the light minerals are present in larger amounts than the dark ones. The former make up about 70 — and in exceptional instances

TABLE 1

Petrographic composition and S and R values of the dune material and the source material (fraction 1.00—0.71 mm)

area	light min.	dark min.	rock frag.	sphericity	roundness
Liperi	71%	5%	24%	0.77	0.34
light minerals				0.78	0.33
dark »				0.74	0.50
rock fragments				0.77	0.38
Joensuu	69%	3%	28%	0.73	0.34
light minerals				0.72	0.33
dark »				0.71	0.50
rock fragments				0.73	0.38
Mönni	66%	8%	26%	0.71	0.31
light minerals				0.68	0.26
dark »				0.74	0.53
rock fragments				0.75	0.36
Tohmajärvi	57%	6%	37%	0.70	0.31
light minerals				0.72	0.26
dark »				0.63	0.47
rock fragments				0.65	0.47
All the dunes, mean	67%	5%	28%	0.74	0.33
light minerals				0.73	0.30
dark »				0.71	0.50
rock fragments				0.73	0.39
Source material	60%	4%	36%	0.70	0.22
light minerals				0.73	0.21
dark »				0.62	0.22
rock fragments				0.65	0.22

as much as nearly 80 — per cent of the material. The dark mineral content varies between three and five per cent, on the whole, but it may be lacking in some samples. Rock fragments account for roughly a quarter of the total composition.

Rock fragments account for more than one-third, however, of the total content of the dune sands of Tohmajärvi. It is the content of dark minerals that varies least from locality to locality. It is in the Tohmajärvi area that dark minerals occur in the largest amounts; compared, for example, to the Joensuu area, their content is twice as large. The difference is due largely to the nature of the local bedrock, for in the Tohmajärvi area there are occurrences of hornblende schist.

A comparison of the average petrographic composition of all the dunes (fraction 1.00—0.71) with that of the glaciofluvial material reveals that the content of dark minerals is nearly the same. The share of the light minerals has increased in the dunes by less than 10 per cent and that of rock fragments has decreased by the corresponding amount.

In the fractions investigated, the effect of the wind abrasion is evident most distinctly with respect to roundness. According to Carrol (1939, p. 22) roundness lessens drastically in the finest fractions. The values for the roundness of grains vary in different localities within narrow limits: R = 0.31—0.34. The mean value for all the samples is 0.33. The corresponding value for the source material is 0.22. With respect to the light minerals, the difference between the values is still smaller — 0.30 for the dune material and 0.21 for the source material (Table 1). Quartz grains predominate among the light minerals. The roundness of quartz grains as a result of wind action has been studied by, among others, Cailleux (1942 and 1952), Kuenen (1959, 1960 and 1964), and Kuenen & Perdok (1962).

As will be shown in a later chapter (pp. 74), the dune material of North Karelia has been exposed to the action of winds for only a short time. Accordingly, the difference between the dune material and the source material with respect to the roundness of the light minerals is so slight that it is liable to be concealed by the margin of error involved in the analytical method. For this reason, the present author is of the opinion that also the roundness of other than the quartz grains ought to be investigated. In his recent studies, Seppälä (1969, pp. 176—177, and 1971, p. 56) has, however, used only quartz grains. Also according to Cailleux (1942, p. 109), quartz grains must be subjected to recurrent eolian processes for a very long time before most of the grains become fully rounded. Accordingly, grains less resistant to wear should show the rounding effect of eolian action over a short time more distinctly. It must be taken into consideration, moreover, that the sand occurring in the study region — even though deriving from glaciofluvial material — was subjected to the abrasive action of quite powerful littoral forces before being exposed to the action of the wind. The effect of the afore-mentioned factors on the roundness of the sand grains has not been analyzed in this connection, but it cannot be ignored, either.

Distinct differences can be detected in the roundness of the dark minerals and rock fragments of the dune material as compared to those of the source material. The roundness of the dark minerals, particularly biotite, varies in the dune material from 0.47 to 0.53, being on the average 0.50 (Table 1). The corresponding figure for the source material is 0.22. The difference is made quite plain also by Figs. 29 and 30. As for the rock fragments, the difference is also clear, although smaller than in the preceding instance. The average roundness of the dune material is 0.39 and of the source material 0.22. The S values, representing sphericity, registered for the dark minerals and the rock fragments differ in the dune material and the source material. The S values of the dark minerals and the rock fragments vary between 0.71 and 0.73, the corresponding values obtained from the source material being 0.62 and 0.65. With respect to the S values of the light minerals, no appreciable differences exist between the dune material and the source material.

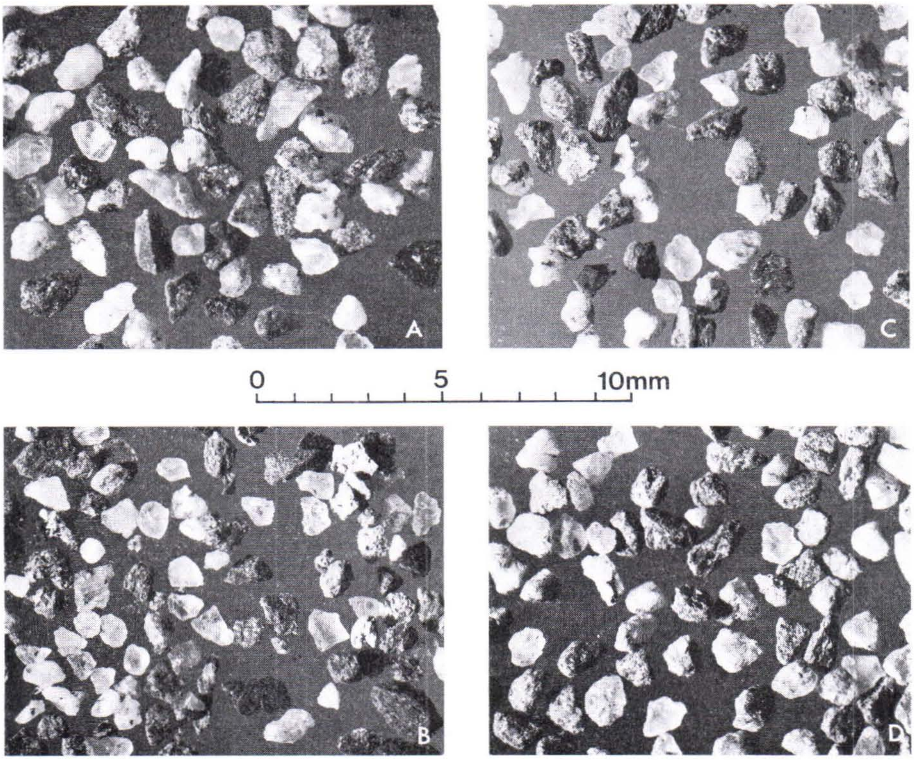

FIG. 29. Primary glaciofluvial material, from which material of dunes derived. Samples were taken from following places: Utranharju (A), Jaamankangas, Onttola (B), Salpausselkä II, Heinävaara (C), and Salpausselkä II, Onkamo (D). Grains are fairly angular, as are rock fragments and dark minerals, too. Photo: E. Halme.

The variations in the petrographic composition and roundness of the different fractions of the dune material are illustrated by Table 2. Samples from six dunes situated in different parts of the study area were selected for analysis, while five samples from the glaciofluvial material were used for the making of comparisons.

With a diminishing of the grain size, the proportion of light minerals present increases at the expense of the rock fragments, as does that of the dark minerals, too. The amount of light minerals is larger in all the fractions of the dune material than of the source material. The proportion of dark minerals in the fine fractions of the source material seems to be larger than in those of the dune material. The explanation probably lies in the selective sorting effect of the littoral and the eolian processes.

The proportion of the rock fragments decreases with diminishing grain size, and in dune material their content is always smaller than in the source material. The finest fractions of half the samples of the dune material contained no rock fragments whatsoever, whereas there were invariably some to be observed in the source material.

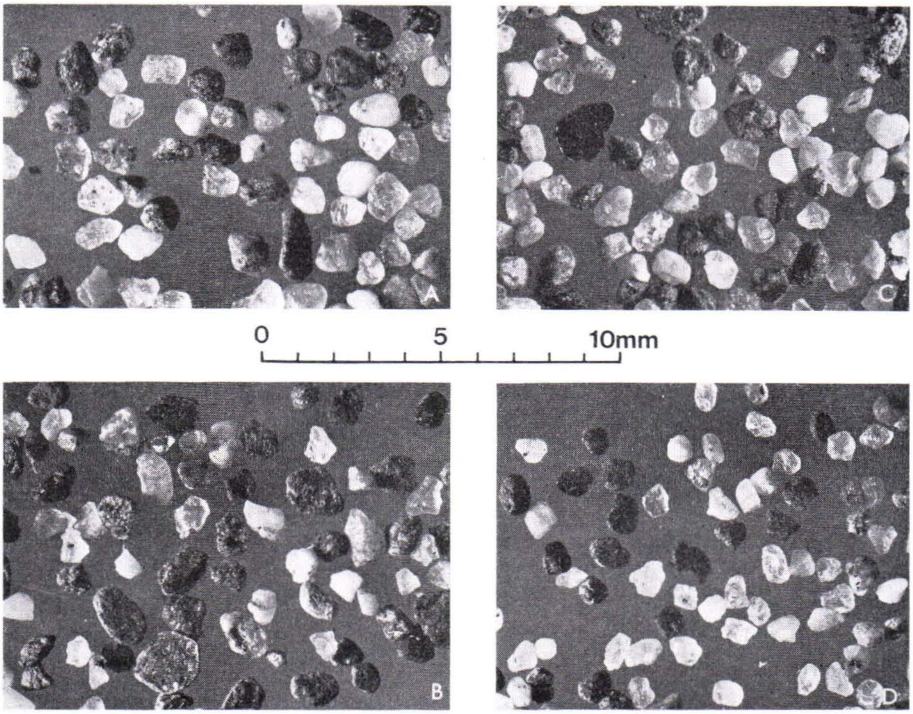

FIG. 30. Dune material from various parts of study region: from Liperi (A), Tohmajärvi (B), Joensuu, east side (C), and Joensuu, north side (D). Especially rock fragments contained in dunes as well as dark minerals are distinctly more rounded than corresponding components of source material. Photo: E. Halme.

TABLE 2

Petrographic composition of the dune and source material and the S and R values of the grains in different fractions.

	light min.	dark min.	rock frag.	sphericity	roundness
Dune material					
2.0—0.6 mm	66%	5%	29%	0.70	0.36
0.6—0.2 mm	81%	9%	10%	0.65	0.32
0.2—0.062 mm	89%	9%	2%	0.67	0.28
Source material					
2.0—0.6 mm	59%	3%	38%	0.70	0.23
0.6—0.2 mm	76%	10%	14%	0.66	0.22
0.2—0.062 mm	80%	17%	3%	0.65	0.20

With respect to the sphericity values, no noteworthy variations occur in either material. The roundness of the dune material lessens, however, with diminishing grain size; and it appears to be slightly greater also in the fine fractions than in the corresponding portions of the source material. The difference in roundness is due to the greater

TABLE 3

Relation of S and R values of grains to petrographic composition.

Dune material				Source material		
fraction	S	R	composition	fraction	S	R
2.0—0.6 mm	0.72	0.32	light	2.0—0.6 mm	0.72	0.22
	0.66	0.51	dark		0.62	0.28
	0.61	0.41	stones		0.66	0.23
0.6—0.2 mm	0.71	0.32	light	0.6—0.2 mm	0.72	0.24
	0.62	0.47	dark		0.60	0.24
	0.61	0.38	stones		0.67	0.24
0.2—0.062 mm	0.70	0.27	light	0.2—0.062 mm	0.69	0.21
	0.68	0.40	dark		0.66	0.19
	0.60	0.32	stones		0.65	0.20

roundness of the dark minerals and rock fragments contained in the dune material as compared to the source material. Notably in the case of quartz grains, particularly in the fine fractions, no apreciable differences exist (Table 3).

The increase in the proportion of light minerals in the dune material at the expense of the rock fragments, in comparison with the source material, is probably due to the shattering of the rock fragments into separate minerals during transportation. The increase in the proportion of dark minerals in the fine fractions, too, may be attributed to the same circumstance.

Surface texture of quartz grains

The quartz grains were divided into the following categories on the basis of surface texture: dull, or »mat», grains, semi-mat grains and brilliant grains. The dull grains are lusterless on all sides, and they are typical of eolian material (cf., Cailleux 1942, 1952). The semi-mat grains represent an intermediate kind, with both dull and nearly bright portions.

The variations in the surface texture of the quartz grains contained in the dunes of North Karelia are shown in Table 4.

Blown by the wind, the coarser grains of sand are propelled into rolling motion over the surface. As a result, the edges become rounded and the surface simultaneously loses luster (Cailleux 1942, Kuenen and Perdok 1962). As it was indicated in the foregoing, the dune material proved to be more rounded than the original material. However, the degree of roundness of the light minerals, which are relatively resistant to wear, did not appear to differ appreciably from that of the corresponding minerals in the source material. It is therefore understandable that the surface texture of quartz grains, in particular, exhibited no distinct differences. The dune material

TABLE 4

Surface texture of quartz grains

area	mat	semi-mat	brilliant
Liperi	14%	48%	38%
Joensuu	12%	42%	46%
Mönni	11%	36%	53%
Tohmajärvi	16%	52%	32%
Study area as whole	14%	48%	38%
Source material	12%	43%	45%

contains on the average slightly more grains with a mat or semi-mat surface than does the source material; but these differences are apt to be obscured by the margins of error implicit in the method of determination. On the other hand, brilliant grains are more abundant in the source than in the dune sand. Among the individual dunes, the greatest abundance of mat-surfaced grains were met with in dune 12, situated in the Salokylä area, where the figure arrived at was 29 per cent. A typical feature of this dune — just as of dune 13 in the same area — was the small amount of brilliant grains. The extent to which the dullness of the grains contained in these dunes is due to weathering or to earlier sedimentation processes is a question to which no answer can be given within the framework of the present study. This difference, too, must nevertheless be taken into consideration in comparing the Salokylä dunes with the rest of the dunes of Liperi (see, pp. 60 and 74).

Eolian cover-sand

Along the edges of the dunes and in the surrounding sand tracts, deposits of sand corresponding in grain size to the dune material occur in thicknesses of between 30 and 50 cm (cf., p. 33). Also along the edges of glaciofluvial formations and in the distal portions of marginal accumulations, there occur in many places well sorted sand in deposits from one-half to one meter thick. This sand differs clearly from the underlying coarser material, and the boundary between them is extremely sharp. The cover-sand of the surface parts is only weakly stratified, but usually there is no stratification whatsoever. The glaciofluvial material of the basal parts is, by contrast, distinctly stratified.

Eolian cover-sand occurs in many places in the distal parts of Jaamankangas in the Liperi area, where it has come to light in, among other places, many road cuts. The average sorting and granular composition of three samples taken from the Liperi area are as follows:

S_o	S_k	2.0-0.6	0.6-0.2	0.2-0.062	<0.062
1.35	1.06	1.2 %	39.5 %	56.4 %	2.9 %

These values run very close to those obtained from the dunes of the Liperi area (see Fig. 26). The greatest difference occurs in the amount of fine sand. The cover-sand contains about 10 per cent more of the fine grains than the dune material does, and the sorting of the cover-sand is even slightly better than that of the dunes. On the other hand, its S_k value deviates considerably from that of the dune sand. The skewness value of the cover-sand indicates that the fine components are more sorted than the coarser ones.

In the Joensuu area, eolian cover-sand is met with at the edges of Utranharju as well as in extensive tracts between Aittolampi and Jukajärvi. From typical points in these areas, five samples were taken, their average sorting and granular composition being as follows:

S_o	S_k	2.0-0.6	0.6-0.2	0.2-0.062	<0.062
1.37	0.95	2.4 %	28.2 %	61.6 %	7.8 %

The composition of the cover-sand resembles the average composition of the dunes situated in the Joensuu area, but it deviates from the latter most with respect to the fractions of medium coarseness (cf., Fig. 27). On the other hand, the sorting and the skewness values are almost exactly the same as those registered for the dune material.

The cover-sand overlying glaciofluvial material is of eolian origin, for the degree of sorting, granular composition and the form of the grains correspond to these properties in the dune material.

Overlying the till mounds situated on the northeastern side of Haarajärvi, 37 — as well as on their flanks — is very fine sand, which smooths over and rounds their original shapes. From one such deposit of very fine sand, a sample was taken, yielding the following granular composition and sorting values:

S_o	S_k	6.0-2.0	2.0-0.6	0.6-0.2	0.2-0.062	<0.062
1.33	0.95	0.1 %	0.6 %	24.4 %	68.4 %	6.5 %

The sample in question is well sorted and its skewness value is equivalent to the corresponding values of the dune material. Also the granular composition corresponds to that of certain of the dunes (cf., Fig. 24). In the light of these circumstances, the present author has concluded that the material under consideration is eolian cover-sand. It is difficult to find any other explanation for its occurrence on top of till deposits. Evidently, in the area in question there was a shortage of the kind of fine and sorted material required for the wind to transport and pile it up into dunes.

Cover-sand is also met with in many places in the Tohmajärvi area. The lower slopes of the amphibolite ridge situated between Muskonlampi and Kylmäkallio (p. 9) are mantled by well sorted cover-sand. Sand has been unearthed in a number of road cuts, and in some places it extends all the way to the crest of the ridge.

FIG. 31. Lower portions of glaciofluvial accumulations overlain by about 50 cm of cover-sand. Surface of sand is in places partly exposed along footpaths.

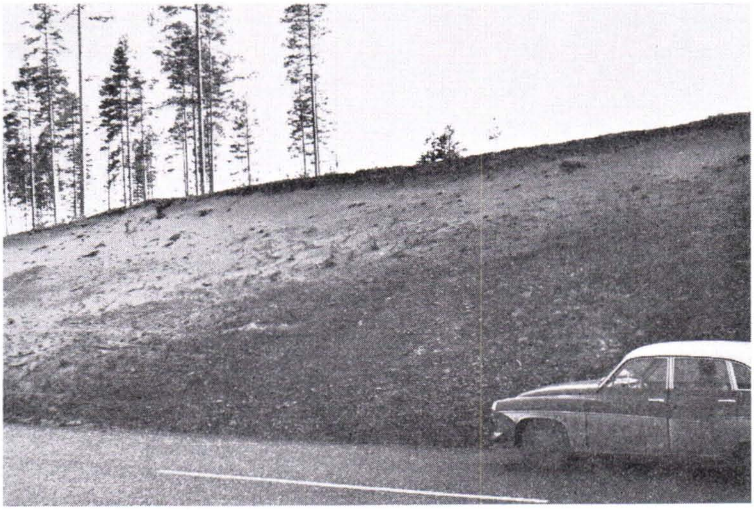

FIG. 32. Eolian sand extends as cover-sand-type of deposit down to lower slopes of glaciofluvial accumulation.

The edges and low-lying stretches of the extensive glaciofluvial formation in the Vatala area (Fig. 17) are in some places overlain across broad stretches by cover-sand to a thickness of between 30 and 100 cm. Three samples were taken from the sites shown in Figs. 31 and 32, and their average granular composition and sorting were as follows:

S_o	S_k	2.0-0.6	0.6-0.2	0.2-0.062	<0.062
1.41	0.87	0.2 %	13.5 %	76.3 %	10.0 %

With respect to the values obtained, the material closely resembles the average composition of the Vatala dunes (cf., Fig. 28), but the finest fractions, in particular, exhibit differences. In his discussion on cover-sands, Maarleveld (1960) points out that the finest fraction of the cover-sand has increased its share at the expense of the fine sand. It is conspicuously less well sorted than the dune material, but the skewness values of each correspond completely (cf., p. 37). The distinctly higher content of the finest fraction in the cover-sand suggests, in the present author's view, transportation by the wind over a longer distance, in addition to which it possesses wind-borne silt properties (cf., p. 52).

The summits of many of the high hills of North Karelia also tend to be mantled with very fine sand (cf., e.g., Mielonen 1965). Without delving deeper in this connection into the origin of the very fine sands of this variety, one might look into the granular composition of a sample taken from Huosionvaara. The sampling site lies approximately 175 meters above sea level, and the sampling depth was about 80 cm.

S_o	S_k	6.0-2.0	2.0-0.6	0.6-0.2	0.2-0.062	<0.062
1.50	0.79	0.2 %	1.6 %	23.7 %	53.5 %	21.0 %

The granular composition of this samples deviates distinctly from the composition of the dune material because of its poor sorting, its skewness value and its high content of the finest component.

STRUCTURE OF THE DUNES

The dune material in North Karelia is well sorted and the variations in grain size are slight. The following pair of samples illustrates how the grain size varies in different strata. The samples were taken from dune field 44 in the Tohmajärvi area. The depth of the coarse layer from the surface is 2.0 m and that of the fine layer 2.2 m.

grain size	coarse layer	fine layer
2.0—0.6 mm	0.1 %	—
0.6—0.2 mm	22.0 %	7.6 %
0.2—0.062 mm	75.7 %	82.1 %
<0.062 mm	2.2 %	10.3 %

The samples could not be obtained altogether pure from the different layers, for material from upper portions of the dune was apt to become mixed in them. Thus the difference in granular composition between the different strata may be even greater. The difference between the layers is further emphasized by the varying mineral composition, as Ohlson (1957) observed in Lapland.

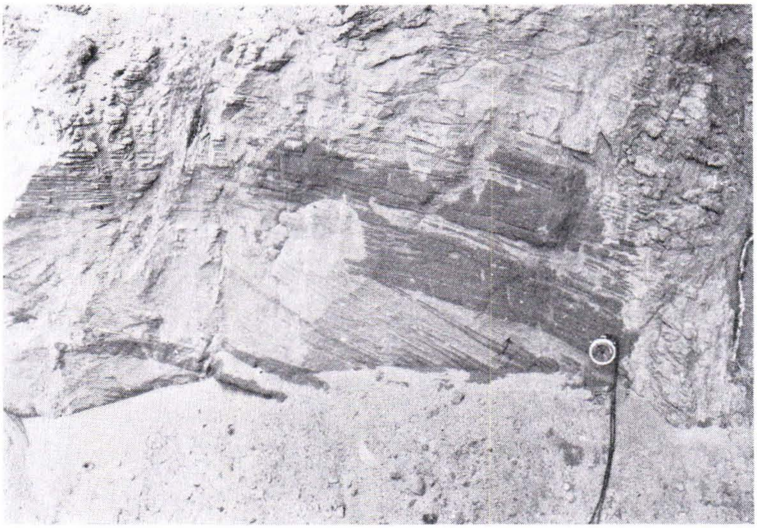

FIG. 33. Typical cross-bedding in parabolic dune of dune field 48. Scale indicated by compass, the diameter of which is approximately 5 cm. Location of cutting is seen in Fig. 21 at the right margin of the picture.

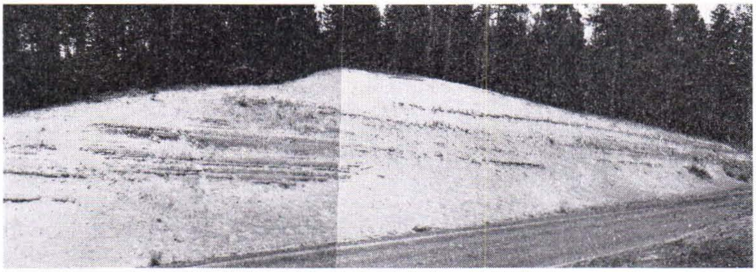

FIG. 34. Windward flank in dune 10 is parallel to even-bedded sand strata.

The thickness of the fine and the coarse layers varies considerably. In some instances, fine and coarse layers a few millimeters thick alternate. Some of them are as much as ten centimeters thick. In many cases, there is no difference detectable to the eye with respect to grain size between layers. The difference in tone between the layers is likely to be due to a variation in mineral composition. The finest material retains moisture longest, and this is the reason for its staying darker than the coarse material (cf., Fig. 33). The greater the difference in coarseness between layers, the greater is the difference in moisture content and, consequently, in tone (cf., e.g., Hörner 1927).

As the material dries, the coarsest portion dries fastest. It loses its cohesion and tends to slide by itself and becomes more susceptible to being blown by the wind.

The result is the appearance of furrows. Retaining its moisture longest, the finest material forms cohesive layers, which frequently gain a fairly durable structure. Such structures in certain cases last for a long time after drying out (see Fig. 34).

On the basis of the structure of dunes, it is possible also to discover facts about the winds that transported and sorted the sand. The laminae are in some cases parallel for distances of many meters (cf., Fig. 34), but in other cases they intersect each other at an oblique angle. This is due to variations in the direction and velocity of the winds.

In the event that deposition of sand takes place on the windward side, gently sloping stratification toward the windward side occurs. A structure of this kind is typical of stationary dunes (cf., Högbom 1923, p. 127; Bagnold 1965). If, again, stratification only in the direction of the lee side occurs in the dune structure, it means that the deposition of sand has taken place exclusively on the steep lee side.

The commonest type of stratification found among transverse dunes of North Karelia is thin, fairly regular even bedding. The different strata run nearly parallel to each other, and they can frequently be followed for distances of several meters (Fig. 35). Among shore dunes, there seems to prevail a stratification running parallel to the windward flank, where the dip of the strata is nearly the same as the pitch of the flank. A structure of this kind is to be observed in, e.g., dune 5, on the northeast side of Riihilampi, the dip of its strata being 10°—12° (Fig. 35). The structure of dune 17 in the same locality is nearly the same. Its layers are thinner, however, but their dip, too, nearly parallels the windward flank (Fig. 36).

FIG. 35. In transverse shore dune 5, the dip of the windward layers and the windward slope is 10—12°. From middle of picture to the right, the layers bend into line with slope of lee side.

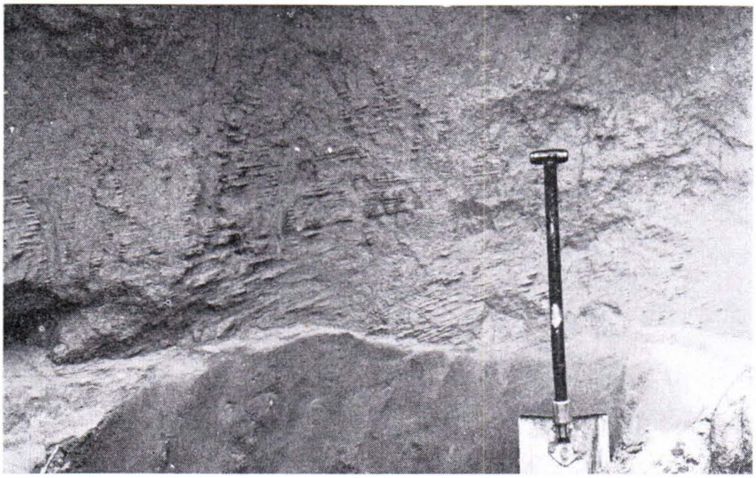

FIG. 36. Dense and low-angle cross-bedding of transverse dune 17 in Liperi area.

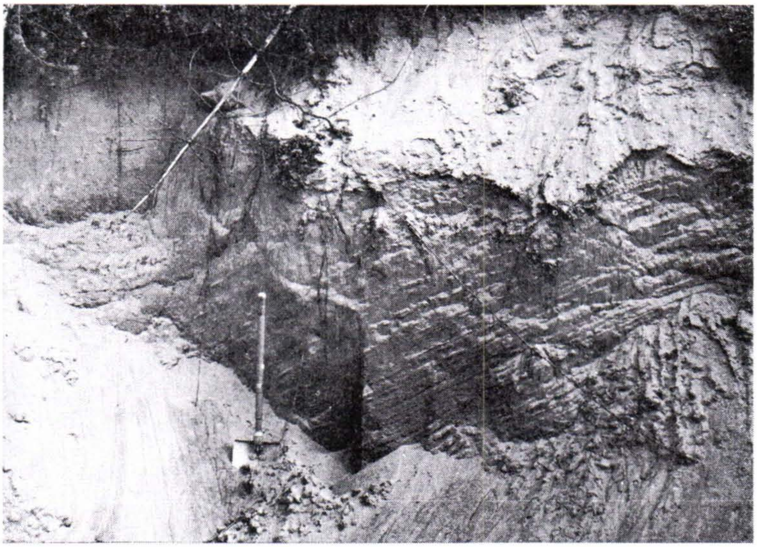

FIG. 37. High-angle strata parallel to lee slope in transverse dune 42 at Vatala. The top layers in upper part of picture are structureless.

Transverse dunes also exhibit stratification running parallel to the lee side flank. This does not necessarily point to a migrating dune (cf., Högbom 1923, pp. 127—128). Steeply dipping layers have been generally observed from the crests of the dunes, for the sections have not extended deeper. On the summit of dune 7 in the Liperi area, for example, a cut 1.5 m deep has been made; from here the layers have registered an average dip of 22° and near the lee side one of as much as 24°—27°.

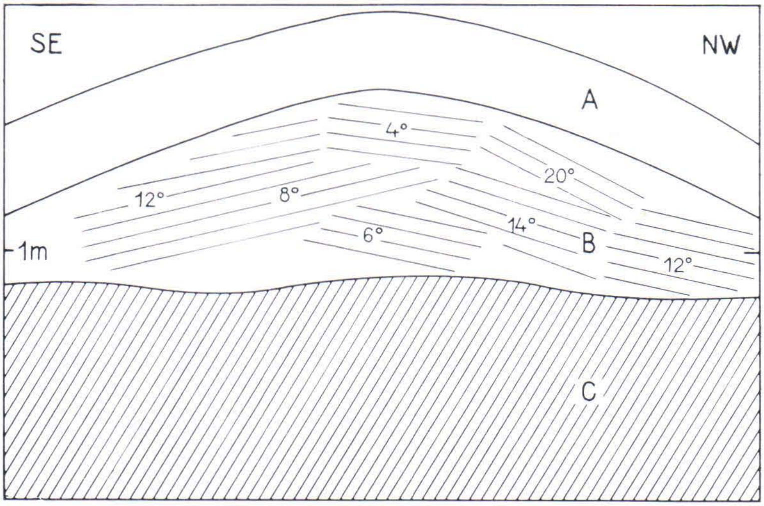

FIG. 38. Structure in cross section of longitudinal dune 13. No bedding was be detected in top layers (A). In middle portions of section, cross-bedding occurs, with layers dipping parallel to one or the other slope of dune (B). Lower portion of section has slumped (C).

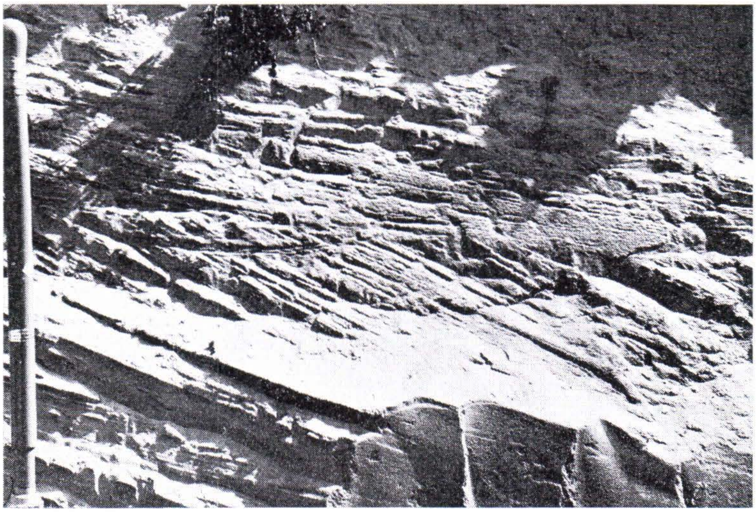

FIG. 39. Cross-bedding in parabolic dune situated in dune field 44.

These values correspond to the inclinations measured on the lee side. Similar readings have been obtained from the transverse dunes of the Tohmajärvi area. The dip of the strata in dune field 42 varies from 28° to 31° (Fig. 37), which corresponds quite closely to the pitch of the lee flank.

On the basis of the observations made from the few sections cut out of the longitudinal dunes of North Karelia, the layers appear to slope in the direction of both

FIG. 40. Structure of parabolic dune of large dune field 48 in Tohmajärvi area.

flanks. Also Urbaniak (1962) has reported similar dips in Polish longitudinal dunes. The structure of dune 13 at Salokylä, in the Liperi area, is represented in Fig. 38. The steepest dip of the layers is approximately 20° NW; but on the whole the slopes incline between 8° and 12°, running both toward the northwest and the southeast.

Cross-bedding has also been observed in many sections. It seems to be particularly characteristic of parabolic dunes. Cross-bedding occurs in the Tohmajärvi area, as in, among other places, dune fields 44 and 48. In the former instance, the observation was made close to the nose of the dune (Figs. 11 and 39). In the latter case, the section was made in the arm of a parabolic dune (Figs. 40 and 41). The cuts extend through the surficial portions of large dunes, and the structure consistently indicates the changing directions of the winds.

In general, the dune forms are in full agreement with their structure. Dune 16 in the Liperi area, however, is an exception to this rule. The pitch of the northeast flank of the dune is in places from 26° to 30° and that of the southwest flank from 16° to 20°. This evidence would seem to indicate that the southwest flank was the windward side. But the section showed the dip of the layers to be between 8° and 10° NE. Accumulated upslope (Fig. 44, profile D—D), the dune has received an asymmetric form. In certain instances, the windward flank cuts the layers running parallel to the lee side.

Another exception to the usual dune structure occurs in the lower portions of dune 4. It is a transverse dune, in which a section has been made in its longitudinal direction. To a depth of about three meters, the strata are nearly horizontal, which is a typical feature of transverse dunes (e.g., McKee 1966, pp. 31—39). Beginning

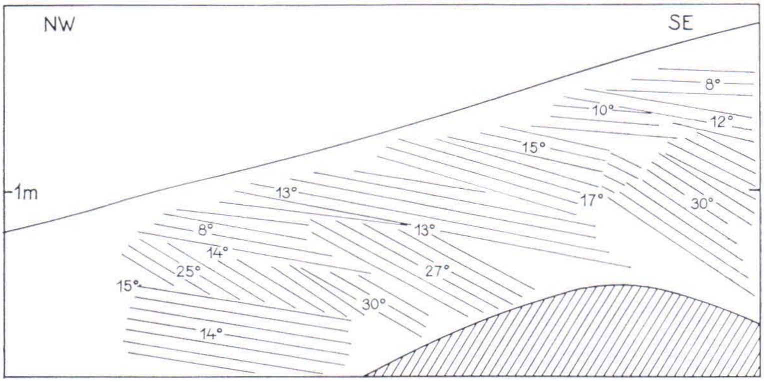

FIG. 41. Bedding structure of preceding figure as schematically represented. In lower portion, slumped material (marked by lines).

at a depth of about three meters, there first occur thin layers, in which the material is distinctly finer than the dune material in general. The number of layers of fine material increases downward; and from a depth of about four meters, the material begins to be grayish and distinctly finer than the yellowish brown normal dune sand of the surficial portion. The following pair of samples shows the difference in granular composition. Sample A is from a depth of about 3 m and B from about 4.5 m:

grain size	A	B
2.0—0.6 mm	0.4 %	0.5 %
0.6—0.2 mm	15.5 %	2.8 %
0.2—0.06 mm	82.1 %	40.7 %
0.6—0.02 mm	2.0 %	39.0 %
<0.02 mm	—	17.0 %

The composition of sample A corresponds to the general composition of the dune sand in the area investigated (cf., Fig. 24) whereas sample B deviates from it fundamentally. The latter sample was not observed to contain diatoms, which do not occur in the dune material in general, either. This need not prove that it is eolian by origin. Hörner (1927), among other researchers, mentions that, in conjunction with formations built up of wind-blown sand, there occurs very fine material considered by him to have an eolian origin. V. Okko (1957, p. 40) and Agrell and Hultman (1971) have described similar material, which they regard as being eolian.

For the sake of comparison, here is a summary published by Keilhack (1920) of the composition of different varieties of loess:

2.0—0.5 mm	0.0—0.5 %
0.5—0.2 mm	0.5—3.0 %
0.2—0.1 mm	1.0—7.0 %
0.1—0.05 mm	8—40 %
0.05—0.02 mm	50—65 %
<0.02 mm	16—36 %

The afore-mentioned sample B resembles to a certain extent the average composition of loess, but it is better to speak only of loess-like material on the basis of a single sample. It is probable, though, that the fine material in question may be windborne silt.

DEVELOPMENT OF THE DUNES

Sand accumulation

Dunes arise wherever sand of suitable fineness and winds capable of effectively transporting it are present. These basic conditions are fairly easy to ascertain and demonstrate to be right. On the other hand, the initial cause proper, which leads to the accumulation of sand, is a harder problem to work out. Different researchers have expressed differing views on this matter. The problems relating to the formation of dunes have been investigated in deserts as well as experimentally in laboratories and wind tunnels (cf., Sokolow 1894, Free 1911, Cornish 1914, Solger 1920, Exner 1921, Bagnold 1965). Under conditions of this kind, it is possible to observe the initial stages in the genesis of formations and analyze the processes. The formation and structure of a living dune is difficult to study because the material is dry and susceptible to being blown by the wind, besides which it is apt to slump upon being dug. For these reasons, making a section in a recent dune field is laborious. In fossil dunes bound by vegetation, studying the internal structure is easier, for their moist material remains longer in place. On the basis of the structure of fossil dunes, it is thus also possible to draw conclusions regarding their formation and mode of origin.

There must be some primal cause underlying the accumulation of sand and thereby the formation of dunes. It is quite commonly understood that dunes form in connection with some obstruction (Free 1911, Bagnold 1965). Many investigators take the view, however, that dunes can develop without any direct contact with obstacles (e.g., Solger 1920, Exner 1921). In addition, there are modifications and combinations of these points of view.

The obstacle causing sand accumulation may be some clearly observable thing, such as a rock or a rise in the ground. Vegetation may be regarded as forming a similar obstacle. The upper portions of plants continue to grow upward while their lower portions are buried in sand (cf., e.g., Fontell 1926, pp. 172—174). Inasmuch as many investigators (e.g., Bagnold 1965), have observed dunes to form because of visible obstacles, such a mode of sand accumulation must be considered as having been proved true.

In many instances, the formation of well-developed dunes would not appear to be dependent on obstacles; but even their occurrence, too, may be explained on the basis of the existence of obstacles (e.g., Free 1911). The original obstacle might have been, for example, some little clump of vegetation that disappeared later. It might at first have been covered with sand, which formed a small mound; then, under favorable circumstances, it might have grown into a large dune.

Although the theory involving obstacles in sand accumulation has been fairly generally accepted, it has also been criticized and attempts have been made to find other causes, too, for the formation of dunes (cf., e.g., Högbom 1923, Hörner 1927). One explanation is based on the wave motion produced by the wind (e.g., Cornish 1914). Also Potter and Pettijohn (1963) connect sand-waves with the development of dunes. Attention has been drawn to the circumstance that in many fields of eolian sand, dunes occur in the same kind of sequence as waves on the surface of bodies of water. Traveling over even a slightly uneven tract of sand, the wind is forced into wavy motion. In places where air currents move close to the ground, the velocity and the transport capability of the wind increase. In such places, the wind carries sand forward, and it begins to accumulate in spots where the force of the wind is slight. At first, there form shield-shaped sand drifts (Mattila 1938). Later, they evolve into other dune forms.

According to certain researchers, wave systems of quite different magnitudes are apt to occur simultaneously (e.g., Solger 1920). On the surfaces of living dunes, ripples are quite commonly observed, just as on the surface of waves in water, too. Ripples have also been produced in wind tunnels (e.g., Bagnold 1965), and they are apt to appear even on fossil dunes insofar as sand for any reason becomes exposed to the action of the wind.

Ripple marks are likely to vary considerably in form. Depending on the grain size of the material and the velocity of the wind, ripple marks also vary in length and height. Some researchers, e.g., Exner (1921), who reject the idea of comparing dunes and waves with each other nevertheless regard ripple marks in sand as rudimentary dune forms, as embryonic dunes. Observations have been reported from deserts of fairly sizable ripple marks with a wave length of as much as 20 meters and a height of over 60 cm (Bagnold 1965, p. 155). Vanoni and Kennedy (1961, Table 3; as cited by Potter and Pettijohn, 1963) have proposed that in the event of the occurrence of waves of two different sizes, the larger should be called dunes and the smaller ripple marks.

The angle of rest of plastic matter, like water, is 0°, but that of sand about 30°. Thus it is rather bold to speak of waves as applied to non-plastic matter like sand. Ripple marks may be produced in sand as a consequence of wave movement, but dunes are in altogether a different order of magnitude and can therefore be regarded as sand-waves only in a figurative sense (see, e.g., Högbom 1923, Hörner 1927).

Whatever the primal cause of sand accumulation might be, the deposition of sand continues once it has started. The result is the creation of dunes of varying shapes. Quite a typical feature of dunes is a slip-face. The wind transports grains of sand either by saltation or over the surface of the ground; but after the crest has been passed, the force of the wind weakens and the grains are deposited on the lee side. The pitch of the slip-face is such, in the ideal case, that the sand grains just barely stay put. Depending on the grain size of the material, the angle of the slope varies between 30° and 34° (e.g., Bagnold 1965, McKee 1966).

Dune forms and, in particular, the inclination of the slip-face have been studied in living dune areas, where these properties occur nearest to perfection. Even fossil dunes retain their characteristic features quite well. Despite possible erosion and the smoothing effect of vegetation, the windward and the lee sides of the transverse dunes in North Karelia are generally distinguishable on the basis of differences in slope. The lee side does not, however, occur as a slip-face proper; it has become gentler of slope to some degree. The steepest inclinations of the lee side vary between 26° and 32°. The steepest lee slopes have been measured on the highest dunes, whereas on low ones the slopes are considerably gentler. It appears to be nearly the rule for the angle of the slope on the lee side to diminish with decreasing height of the dune.

The height of the dunes in North Karelia varies a good deal from locality to locality. In many places, relatively gently sloping lee sides in the low portions of dunes show that they are poorly developed. As Hörner (1927, pp. 150—151) sees it, dunes could hardly grow beyond certain limits through the action of winds prevailing at any given time, although sand might be in available supply and the time of growth of the dunes might be limitless. The highest dunes of North Karelia are between 10 and 12 meters high. It is difficult to estimate whether this is the greatest possible height they could have achieved in the area under unchanging conditions of formation. On recent coasts, there occur migrating dunes apt to be several tens of meters high (e.g., Mattila 1938). The largest dunes in deserts reach heights of from 100 to 200 meters (Bagnold 1965).

On the basis of different dune forms, conclusions might also be drawn regarding the evolutionary stage of the eolian process. Transverse dunes are commonly considered to be poorly developed, and they are therefore taken as evidence of the initial stage of the eolian process. According to Bagnold (1965), transverse dunes are not enduring forms — not, at least, under desert conditions — for they end up as blowouts, which in turn develop into independent barkhans. In deserts, Bagnold contends, only barkhans and longitudinal dunes last.

The development of inland dune forms is schematically represented in Fig. 42. The scheme is based on papers by Kádár (1938, pp. 169—171), Landsberg (1956; p. 177) and Galon (1959, p. 98). Dunes frequently originate as transverse dunes (A), but as the eolian process advances, their form changes (B). An intermediary form in the evolution of dunes must be considered to be the parabolic dune (C), the final form being the longitudinal dune (D). The transverse dunes of North Karelia thus represent, like many shore dunes (e.g., 4, 5, 9 and 11), the initial stage in the evolutionary process. The dunes of the Liperi area have generally remained at this stage. The parabolic dunes, particularly the almost V-shaped ones, represent a fairly far-advanced form. They are to be met with mostly in the Tohmajärvi area.

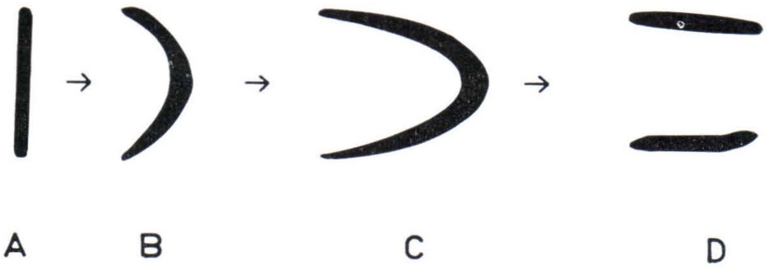

FIG. 42. Development of various dune types as schematically represented, after different researchers (see text p. 55). Wind direction is from left to right.

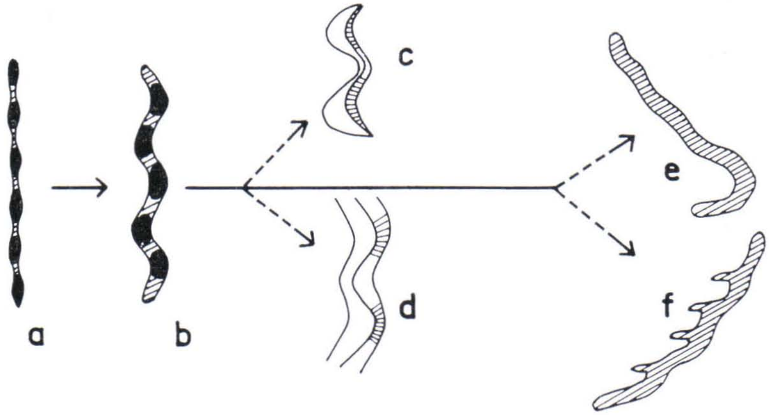

FIG. 43. Development of different dune forms in North Karelia, schematically represented. Wind direction is from left to right. Highest point of ridge marked in black (a and b). More detailed explanation in text p. 57.

Although the longitudinal dunes may represent the terminal evolutionary stage, this need not, in the author's opinion, signify that all the longitudinal dunes of North Karelia had undergone the afore-mentioned developmental process. Longitudinal dunes are also apt to be built up as original forms, just like transverse dunes, as Enquist (1932, p. 20) has noted. Otherwise, it would be hard to explain their occurrence in conjunction with the transverse shore dunes of Liperi (e.g., dunes 6 and 9).

On the basis of measurements and observations relating to the form and location of dunes, the author has drawn up a diagram, reproduced in Fig. 43, which illustrates the special features of the dunes of North Karelia. During the initial stage, a transverse dune forms out of a chain of sand mounds (a). An example of this stage is the zone between dunes 4 and 5. At the next stage, the dune grows larger and its ground plan becomes serpentine (b). The highest points of the dune are at the bends (e.g., dune 9). In places, there are distinct differences between the flanks of the dune with respect to the angle of slope. Sometimes they appear to consist of barkhanoid parts (c), with the result that the steep slope is on the concave side; but in other instances, it may be on the convex side of the dune (d). An example of the former is a dune situated in dune field 48, dune 46 being an example of the latter.

As the dune form continues to develop, the accumulation of sand turns into a parabolic dune in the manner represented in Fig. 42 (C). But the parabola need not be regular in shape. In North Karelia, the final product in many instances is a highly irregular parabolic dune, one branch being conspicuously shorter than the other (e) (e.g., dune 29, Fig. 6). In certain cases, again, one of the arms of the parabola is apt to be replaced by several small extensions (f) (e.g., dune 44, Fig. 11).

In the dune areas of North Karelia, the question is also apt to come to the fore of the possible migration of dunes, even though all the dunes are nowadays dead and bound to the ground by vegetation. In the map (Appendix I) depicting the distribution of dunes, it is seen that they occur commonly in the vicinity of sorted glaciofluvial material. Many of the dunes of the Liperi, Mönni and Joensuu areas run parallel to ancient and, in quite a few instances, also present-day shores, and they should, in fact, be regarded as shore dunes by origin. The main part of the dunes of the areas mentioned may, thus, be regarded as fairly stagnant. In the Tohmajärvi area, however, there are certain dunes that are situated at quite a long distance from the original sources of their material (e.g., dunes 41 and 42), and they deviate in form, too, from the rest of the dunes in the area. These and certain other dunes of the Tohmajärvi area may be presumed to have migrated for some distance — at most, however, only a few kilometers.

Location of the dunes in the terrain and the winds effecting their formation

Among the most important preconditions of an eolian process are suitable materia and wind. The best conditions are met with in deserts and on shores, where there is an abundance of fine sorted material and winds blow forcefully. Favorable conditions for eolian activity sometimes occur also inland, in which case the material is mainly of glaciofluvial origin. Littoral and fluvial processes may have further sorted fine and previously sorted material and transported it across extensive tracts. For these reasons, Högbom (1923) and Rickert and Tedrow (1967, pp. 250—252) consider it justified to speak of river, shore and inland dunes.

In studying the location of dunes in Finnish terrain, their relation to the source material must be established. It is on this basis that one can also ascertain the general direction of transport. Furthermore, when the absolute level at which dunes formed is known, it is also possible to determine their relative age: since the Ice Age, land uplift has taken place in the study region and caused displacements of the marine and lacustrine shore levels. The relation of the dunes to the underlying ground may

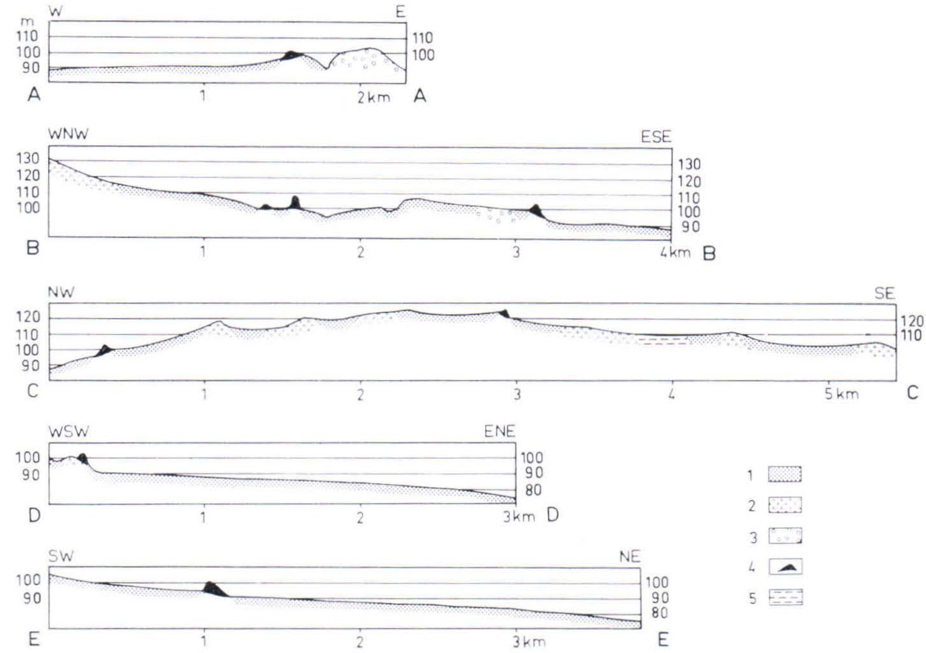

FIG. 44. Profiles from Liperi dune field (Fig. 3). 1 = sand, 2 = till, 3 = glaciofluvial gravel, 4 = dune and 5 = peat.

cast light on their mode of formation and age. When, in addition, the form and structure of the dunes are taken into account, it may be possible to determine the wind conditions during the formation of the dunes.

There is an abundance of sorted material in the study area. In most instances, it is easy to determine where the dune material originated. The material composing the dunes of Liperi can be traced to Jaamankangas. The northernmost dunes of the Liperi area (9, 10, 14, 15 and 16) are situated at the distal margins of Jaamankangas and to some extent even on its distal flanks. The source material of these dunes has undergone several sorting stages, partly during the initial stage of deposition, partly during subsequent littoral stages.

In the main, the dunes of the Liperi area are located about 95 m above sea level (cf., Fig. 3; also Frosterus and Wilkman 1915). Only a few are situated distinctly on a higher level, examples being dunes 12 and 13 (Fig. 3), which lie on elevations between 115 and 120 m. The dunes often tend to run in a particular direction. At the time the water level in Liperi was at 90 m to 95 m, the dunes lay in the shore zone and they ran mostly parallel to the shore line (see Figs. 3, 44 and 45).

Of the dunes of Liperi, the majority formed directly on a sand field. This is only natural, for sand fields cover extensive tracts there. The following nine dunes

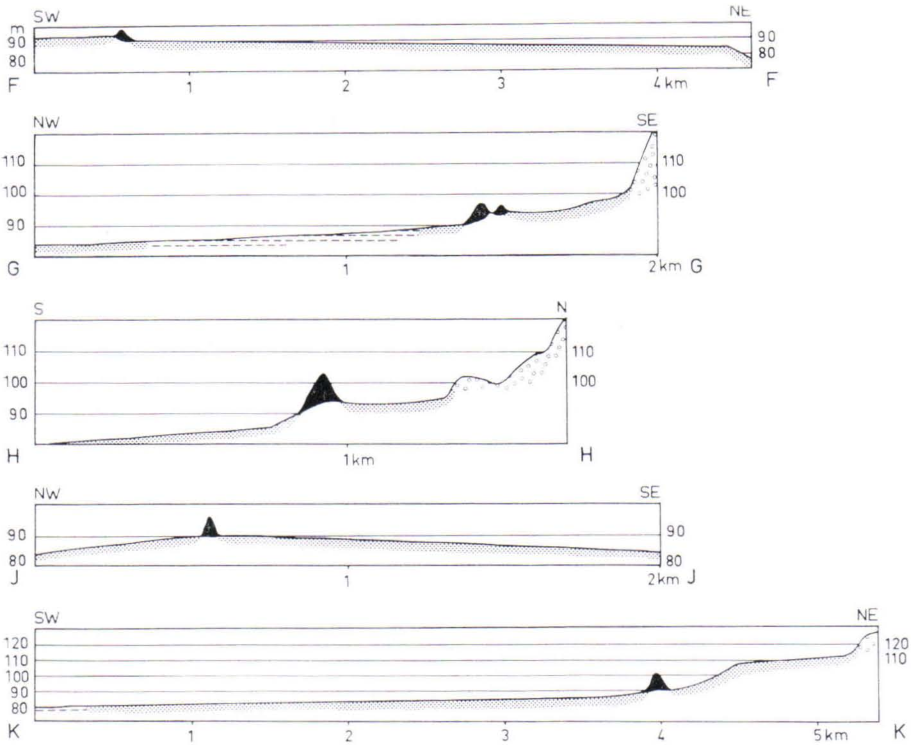

Fig. 45. Profiles from dune fields of Liperi and Joensuu (Figs. 3, 4 and 6). Symbols explained in Fig. 44.

were deposited on top of a sand field: 3, 5, 9, 11, 14, 15, 16, 17 and 18. In two instances, the base of the dune consists partly of coarser glaciofluvial material (9 and 15), and in one instance, partly of till (16). Dunes 1 and 10 were deposited wholly on top of glaciofluvial material. The rest of the dunes in the area formed on top of a moraine. These dunes are 2, 4, 6, 7, 8, 12 and 13. The relation of the dunes to their surroundings and base is shown by profiles A—F in Figs. 44 and 45.

On the basis of the location of the Liperi dunes and the form of the ridges as well as of previously reported structural data, conclusions have been drawn regarding the wind directions. Eighteen dunes of the locality were formed through the action of different winds as follows:

NW winds	5 dune fields	2, 9, 11, 14 and 15
SW—WSW winds	4 » »	3, 4, 5 and 6
NE winds	3 » »	16, 17 and 18
SE—ESE winds	2 » »	8 and 10
E winds	1 dune field	7
S winds	1 » »	1

The winds that produced dune fields 12 and 13, which are located higher than the rest, are somewhat difficult to interpret. Their windward and lee flanks cannot be determined on the basis of the angles of slope of the sides. The dunes formed either *in situ* or in process of migration. The latter alternative is improbable, however, for dune material should become the finer, the farther it travels (see Finkel 1959, pp. 620—625) and the material of these dunes is nearly the coarsest of any existing in the entire study area. Inasmuch as the cross section of dune 13 is nearly symmetrical, it probably represents a longitudinal dune according to McKee's and Tibbits's (1964) classification. The wind direction must therefore have been from the northeast, a conclusion supported also by the orientation of certain dunes in field 12.

With the exception of three scattered occurrences (19, 21 and 25), the dunes of the Joensuu area are located at the margins of glaciofluvial formations. The elevation of the dunes, 92—95 m above sea level, corresponds to that of the Liperi deposits. The isolated dunes mentioned have been deposited on top or on the flank of a moraine. The rest of the dunes in the Joensuu area have been deposited on a sand field. About one-half of them are partly situated, in addition, on glaciofluvial material: 20, 23, 24, 26 and 30. The relation of the dunes of the Joensuu area to the surrounding terrain and to the underlying ground is depicted by profiles G—K (Fig. 45).

The wind conditions responsible for the formation of the dunes were determined on the basis of their form, location and structure. Ten dune fields evolved through the action of the following winds:

W winds	four dune fields	19, 21, 22 and 24
NE winds	three » »	27, 28 and 29
SW winds	two » »	20 and 23
NW winds	one dune field	26

With respect to dunes 25 and 30, determining the wind direction proved so difficult that they were left out of account in this connection altogether.

The location of the dunes of the Mönni area gives clear indications of the source of the dune material. The material of the westernmost dunes of the area, 31 and 32, derive from the distal sands of the easternmost portions of Jaamankangas. In the main, however, the dunes of Mönni are situated on the distal side of the sizable sandur-delta of Eno. The Mönni dunes are generally situated on a level slightly above 90 m (see Fig. 9). The small parabolic dunes of dune field 34, however, lie on an elevation of about 105 m.

Judging by the location of the dunes, all were deposited on a sand field, with the exception of the small parabolic dunes, which are to some extent underlain by till. In most of the area, the prevailing winds had been westerly, varying in direction between southwesterly and northwesterly. The parabolic dunes of dune field 34, however, formed as a result of northeasterly winds.

The determination of the location of the Tohmajärvi dunes was greatly hampered by the outdated and deficient map material. Thus the maps proved of scarcely any use in ascertaining the elevations at which the dunes were located. On the basis of levellings and barometric readings done in the area, the dunes may be estimated to be generally situated at or slightly above the 100-meter level. On the north side of Vatala, however, there lies a dune field, 41, which lies distinctly higher than the rest. There eolian sand has been deposited close to the 120-meter level.

The material of the Tohmajärvi dunes has two unmistakable sources: Salpausselkä II and the sequence of eskers between Murtoi and Vatala (Figs. 11 and 17). The distance of the Rouanaho dunes 38—58 from the distal edge of Salpausselkä varies between 3 and 5 km. The Vatala dunes are situated right along the edges of the esker sequence referred to. Farthest from the distinct and large primary glaciofluvial accumulations are dune fields 41, 42, 51 and, perhaps, 38 and 39, too (Appendix I).

The Tohmajärvi dunes have been deposited on the whole on the extensive sand fields met with on the distal side of Salpausselkä II. Some of the dunes also lie partly on top of till: 39, 41, 42, 48, 50, 51 and 54. Certain of the Vatala dunes extend in part on the lower flanks of the esker, as in the case of 55 and 56 (Fig. 17).

For the determination of wind conditions, fewer cuts shedding light on the structure of the dunes have been available in the Tohmajärvi area than in other parts of the study area. The conclusions concerning the winds that formed the dunes were reached largely on the basis of their form and location. With respect to the different dune fields, the winds are distributed as follows:

NW winds	11 dune fields	38, 39, 43, 44, 45, 46, 48, 52, 55, 56 and 57
NW winds	5 » »	41, 42, 50, 51 and 58
N winds	2 » »	40 and 54
W winds	1 dune field	53
SW winds	1 » »	47
SE winds	1 » »	49

In the entire study area, it was possible to study the relation of the dunes to the underlying ground only in dune fields 4, 21, 25, 34 and 56. In the first three instances, the base of the dunes was till, in the next instance a sand field and in the fifth glaciofluvial sand and gravel. In not one instance was any trace of vegetation found on the contact surface of the eolian sand and the primary base. No signs of weathering or humus could be detected on the surface of the ground, either (Fig. 46). In Fig. 47, the dune material and the underlying ground is depicted schematically. At the base is till (C). The sand overlying it reflects the stage at which the region was inundated after deglaciation. On top of this shore deposit, there began to accumulate typical eolian sand, which soon began to exhibit the cross-bedding characteristic of dune material. The circumstance that the granulometric composition of the dune

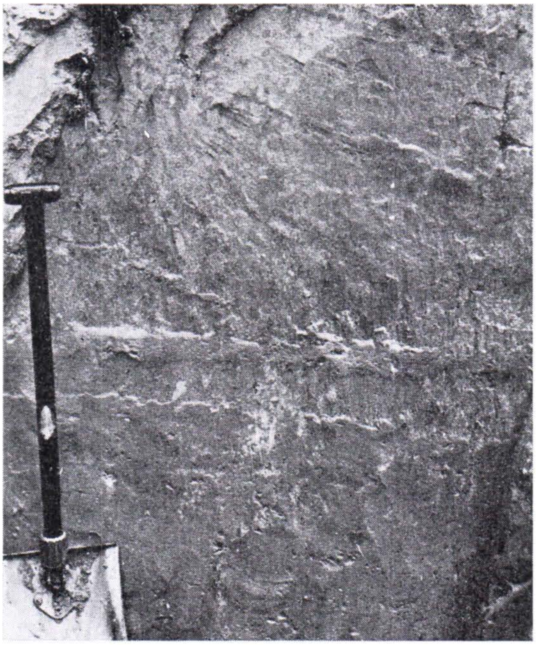

FIG. 46. Cutting dug through dune into underlying deposits (dune 25).

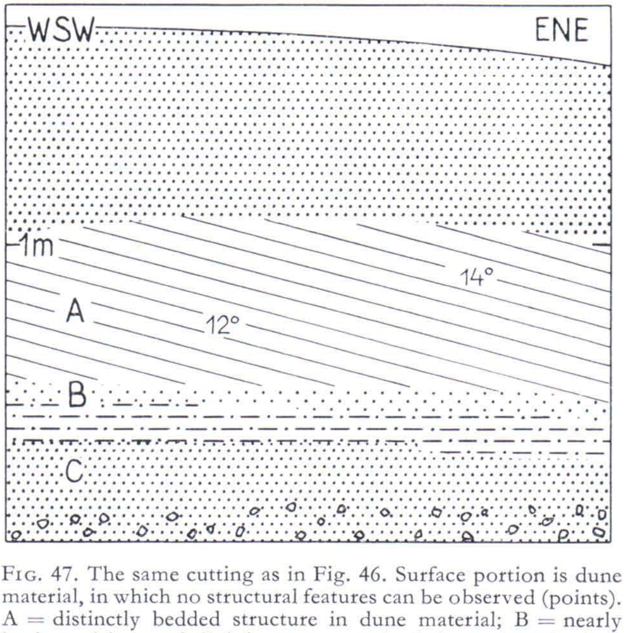

FIG. 47. The same cutting as in Fig. 46. Surface portion is dune material, in which no structural features can be observed (points). A = distinctly bedded structure in dune material; B = nearly horizontal layer of slightly coarser-grained shore deposit; C = fine sand grading into till without clear boundary.

material and the shore deposit is alike indicates that the dune was deposited on a sand field, just as were the great majority of the dunes found in the study area. The stratification of the shore deposits at the base of the dune is generally almost horizontal, whereas the dune is characterized by dipping strata (Fig. 46) or cross-bedding.

It has been pointed out in the foregoing that the wind direction causing dune development has varied considerably in the study region. In the vicinity of Tohmajärvi, the winds have blown mainly from between the northeast and the northwest. This, in the author's view, clearly shows that during their development the proximity of the ice sheet had a significant effect on local climatic and wind conditions. Several researchers, e.g., Högbom (1923, pp. 140—170), Hörner (1927, pp. 170—173), Lundqvist (1943, p. 142), Poser (1948, 1950), Sundborg (1955), Hjulström, Sundborg and Falk (1955), Tolonen (1967, pp. 354, 364), Aartolahti (1967, pp. 116—119, and 1968, pp. 88—89) and Seppälä (1971, pp. 62—63 and 75) have expressed similar views. By contrast, the winds causing dune development in other localities blew from between the southwest and the northwest. The last-mentioned conditions closely resemble the present-day wind conditions in the study region.

The development of dunes in the foreland of Salpausselkä II

The maximal time since the formation of the dunes is fixed by the deglaciation of the study area and the displacement of the shore. The dunes formed during that relatively short time after deglaciation before the land started to sprout vegetation. Efforts have been made to fix the time of the deglaciation as accurately as possible.

If Sauramo's (1918) varve chronology is compared with that arrived at in Sweden, as has been done, among others, by Hyyppä (1963, p. 47), Donner (1964) and Nilsson (1968), the age of Salpausselkä I may be estimated at approximately 8 900—8 700 B.C. From there the ice margin retreated to Salpausselkä II in 200 to 300 years. Thus the age of Salpausselkä II would be around 8 400—8 200 B.C. (see also Niemelä 1971).

A clear-cut delay in deglaciation is further evidenced by the marginal formation of Jaamankangas (Frosterus and Wilkman 1915. Okko and Peltola 1958, Repo 1960). In places, it may be compared in form and structure as well as in size and location to the Salpausselkä formations. Repo (1957 and 1960,) however, regards Jaamankangas as contemporaneous with the Salpausselkä II substage. It is quite probable that the glacier margin remained at Jaamankangas for between 100 and 200 years, as it did in the Salpausselkä II belt. If the time consumed in the recession of the ice sheet from Salpausselkä II and in the advance of the ice to Jaamankangas is considered, the conclusion seems justified that the glacier margin still stood in the vicinity of Jaamankangas around 7 900—8 000 B.C. The proximity of the ice sheet had a significant effect on the climate and, especially, the wind conditions in the adjacent regions, as it was pointed out in the foregoing.

After deglaciation, the region of North Karelia was inundated by the Baltic Ice Lake. After its damming-up during the Salpausselkä I substage (Donner 1969), this glacial lake was strongly regressive; hence, its development is divided into two (Hyyppä 1966) or three »B stages» (Donner 1969). The ages obtained by different researchers for the different B stages vary considerably, as do the levels arrived at for the corresponding shores. This is due, in the author's view, to the methods applied. For example: it is not reliable to draw parallels with certainty between the ancient shores of different areas far apart on morphological evidence alone. Similarly, dating by the pollen method can reach back only to the time when the region investigated had become covered with vegetation or when the ground there had begun to turn boggy.

During its highest stages, the Baltic Ice Lake extended into most of the areas in which the dune fields investigated formed. The uppermost shore of the lake, B I, according to Hyyppä's (1966, Fig. 13) estimate, is between 110 m and 115 m above present sea level in the Tohmajärvi area and from 130 m to 140 m above sea level in the Liperi and Joensuu areas. Because the dune fields lie below these elevations, the uppermost shore lines of the B stage have not very great significance from the standpoint of the present study.

As the study region is situated mainly in the zone of Salpausselkä II, the discharge of the Baltic Ice Lake was an extremely important event from the standpoint of the genesis of the dunes. In conjunction with this discharge, extensive areas of land emerged out of the water. The discharge of the Baltic Ice Lake took place near Mount Billingen in central Sweden. As a result, the water level sank between 25 and 30 meters. In Finland, this event has been observed as a corresponding difference in esker plateaus (e.g., V. Okko 1957, pp. 12—13, 24—25, Sauramo 1958, pp. 83 and 114, Virkkala 1961, pp. 229—230 and pp. 239—240, 1963, pp. 44—45, 1969, pp. 23 and 57, M. Okko 1965, pp. 19—21, Aartolahti 1968, pp. 71—74, Saarnisto 1970, pp. 25—26). The sinking of the water level can be detected to a slight extent on the proximal side of Salpausselkä II. The glacier margin had been close to the proximal part of Salpausselkä II in North Karelia, too, during the time of the discharge of the Baltic Ice Lake. In the light of varve-chronological studies, the time of the discharge is 8 300—8 200 B.C. (Nilsson 1960, 1964, 1968; Hyyppä 1963, 1966): The figure 8 213 B.C. is generally used. Especially along the margin of glaciofluvial and large marginal formations, broad sand fields became then exposed, and this material was further sorted to some extent by littoral forces.

In view of the general direction of the recession of the ice sheet from southeast to northwest and owing to land uplift (see Kääriäinen 1963), it was the most southeasterly and highest areas in the region covered by the present study that were lifted up above the water level first. The Tohmajärvi area is situated in the foreland of Salpausselkä II (Appendix I) and its dunes are probably the oldest in the study region. When the Tohmajärvi sand fields on the distal side of Salpausselkä II emerged, the glacier margin lay probably close to the proximal parts of Salpausselkä II. The sand fields recently exposed from underneath water thus afforded exceedingly favorable targets for the wind blowing down the glacier.

On conspicuously higher ground than the rest lies the Vatala dune field 41 in the Tohmajärvi area (comp., p. 61 and Fig. 17). Accordingly, this field may be considered the oldest site of dune development in the whole study region. The Vatala terrain probably emerged as early as the regression of the Baltic Ice Lake before its final discharge (see Hyyppä 1966, Fig. 13). The location of the Vatala dune field 41 is exceptional, compared to the other fields, for it lies at quite a distance away from glaciofluvial formations. If the point of departure be the assumption that the water level was still at the height of the B stage at the time the Vatala dunes originated, great tracts of glaciofluvial material still had to be submerged. This raises the question as to the source of supply of sand for these dunes. Two alternative answers to this question suggest themselves first: 1— the material derived from ground free of vegetation in the vicinity of the dunes; 2— the material originated directly from the marginal ice. The latter alternative does not seem likely, for the material composing the Vatala dunes corresponds to that of the rest of the dunes in the Tohmajärvi area. In the event that the material had traveled all the way from the ice sheet, it should have proved finer, on account of the long transportation distance, than it did. The dunes of dune field 41 at Vatala were built up through the action of northwesterly winds, which points to periglacial conditions and the proximity of the glacier. The components of the dunes would appear to have derived from material sorted by glacial meltwaters. The meltwaters produced a distal deposit, which accumulated on the lee side of a long rock outcrop.

The interdune areas of dune field 41 at Vatala are now covered with peat (cf., e.g., Berghell 1916). Some exceptionally great change in climatic or other external conditions must have taken place in order for the spaces between individual dunes to begin paludifying. The sand accumulation taking place as a result of wind action reveals, at least to some degree, dry climatic conditions. The paludification, again, is due to a general change of climate that brought with it higher humidity, as in this case seems to have happened. As such opposing phenomena as the formation of dunes and the paludification of the dune field are involved, the events must surely be separated by a considerable time span. The probability is that the gradual change to a humid climate and the increase in the density of plant life caused the formation of dunes to cease.

Two series of samples were taken from the peat beds situated between the dunes in dune field 41 at Vatala in order to shed light on the evolution and time of genesis of the dunes. One series was taken from the northwest side of the largest dune and the other farther away, from an area between smaller dunes (Fig. 17). The pollen diagram, 1, drawn from the former series is presented in Fig. 48, and that drawn from the latter series in Fig. 49. Diagram 1 (Fig. 48) reveals that the process of paludification started at the end of the pre-Boreal period, in the forest-historical zone IV. Judging by the arboreal pollens, the birch was then the principal species

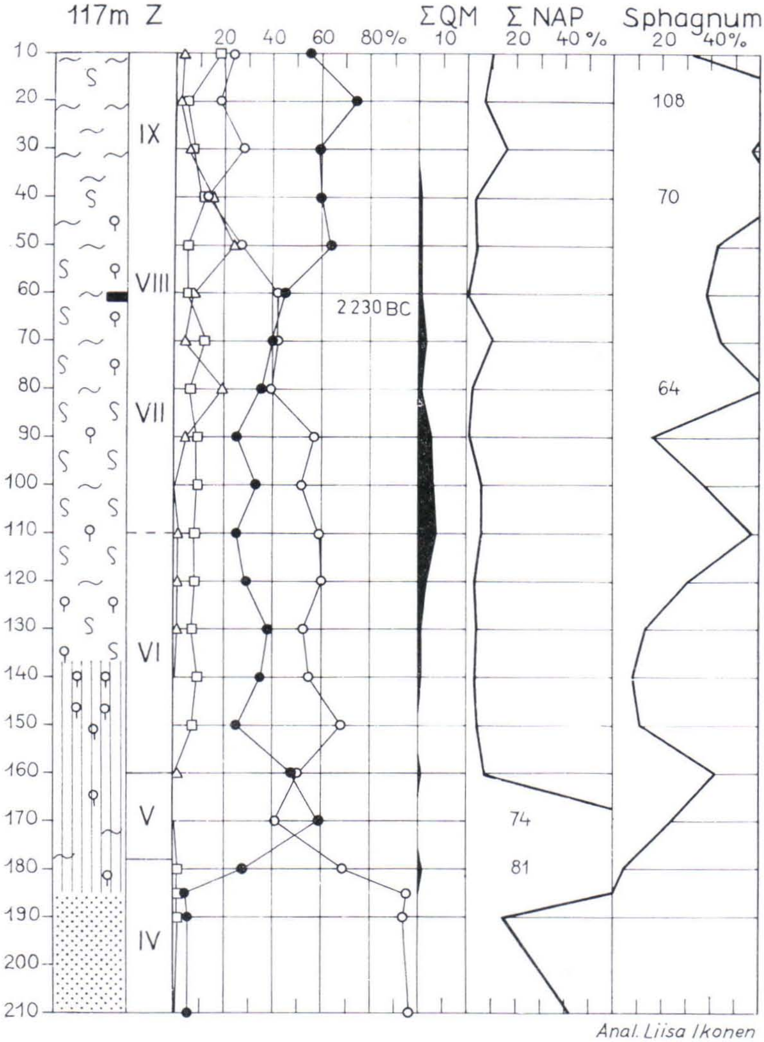

FIG. 48. Pollen diagram 1, from northwest part of dune field 41.

of tree. Before the growth of forests in the locality, there was a stage, however, at which vegetation had been sparse. It was a favorable time for the eolian action. Later on, toward the end of the period, forests spread over wider tracts and paludification got underway. Vegetation gained the upper hand over the eolian processes, and this spelled the end of eolian accumulation.

On dune field 41, the process of paludification advanced gradually from the margins of the field. This is clearly shown by the pollen diagram constructed from the peat profile taken from the middle of the field, 2 (Fig. 49). The middle portions

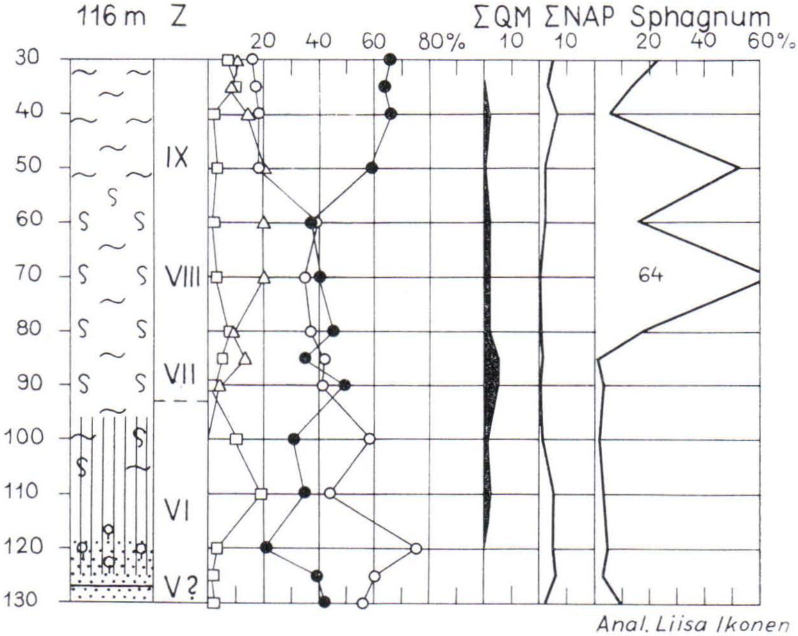

FIG. 49. Pollen diagram 2, from middle of dune field 41.

of the dune field began to turn boggy, according to the diagram, at the turn of zones V and VI, or slightly before the beginning of the Atlantic period.

The rest of the dunes of the Tohmajärvi area are situated on nearly the same level, 100—105 meters above sea level. From these dune fields, a number of series of samples have been taken from peat beds toward determining the time of formation of the dunes. A sample series was taken from the west side of a large parabolic dune situated in dune field 44 (cf., Figs. 11 and 13). The sample series was taken at a distance of two to three meters from the flank of the dune to verify that the dune material continues at the site underneath the peat. The dune had thus formed before the peat appeared along its edges. The pollen diagram for the sample series, 3, is presented in Fig. 50. Correspondingly, a sample series was taken from dune field 56 (Appendix I, Fig. 17) about seven meters from the flank of the largest parabolic dune (see, p. 30). Its pollen diagram, 4, is given in Fig. 51. In this series, too, the material at the base was identified as wind-blown sand, signifying that the dune is older than the peat situated along its edges. On dune field 41, there is an old cut across the dune, and it shows the contact between the dune material and the peat to be uneven: a tongue of sand projecting from the ridge overlies the peat in some places (Fig. 52). In the lower parts of the peat profiles, the phenomenon appears most distinctly in diagram 3, where the transitional zone from pure dune sand to pure peat is nearly 25 cm thick. In diagram 4, it is over 10 cm thick. For the purpose

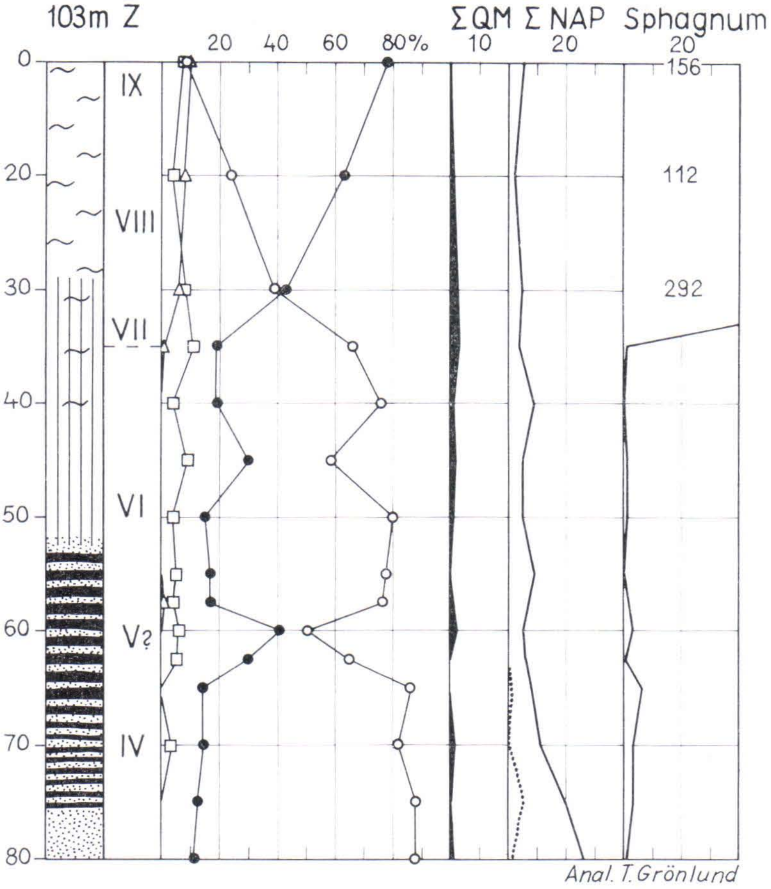

FIG. 50. Pollen diagram 3, from west side of dune field 44.

of C^{14} age determination, a sample was taken from the series of dune field 56 at a point where the peat is uncontaminated (Fig. 51), inorganic mineral matter having a tendency to cause discrepancies hard to explain in C^{14} ages (see, among others, Hyvärinen 1966 a, diagrams 11, 15 and 16).

On the basis of both diagrams (Figs. 50 and 51), it could be ascertained that paludification along the margins of the Tohmajärvi dunes got underway during the pre-Boreal stage. The C^{14} dating made from the peat of the latter series (Fig. 51) yielded an age of 7 250 ± 100 B.C. This is likewise the age of the pre-Boreal *Betula* maximum in Finland (cf., Salmi 1962, p. 198; Hyyppä, Hoffren and Isola 1962 SU-8 and SU-13; Donner 1964, 1965; Tynni 1966, pp. 58 and 69, Fig. 45; Virkkala 1966, p. 238; Tolonen 1967, pp. 264—365).

In view of the fact that an age of approximately 7 250 B.C. was obtained for the peat and that the dune material begins to appear 20 cm deeper down (Fig. 51),

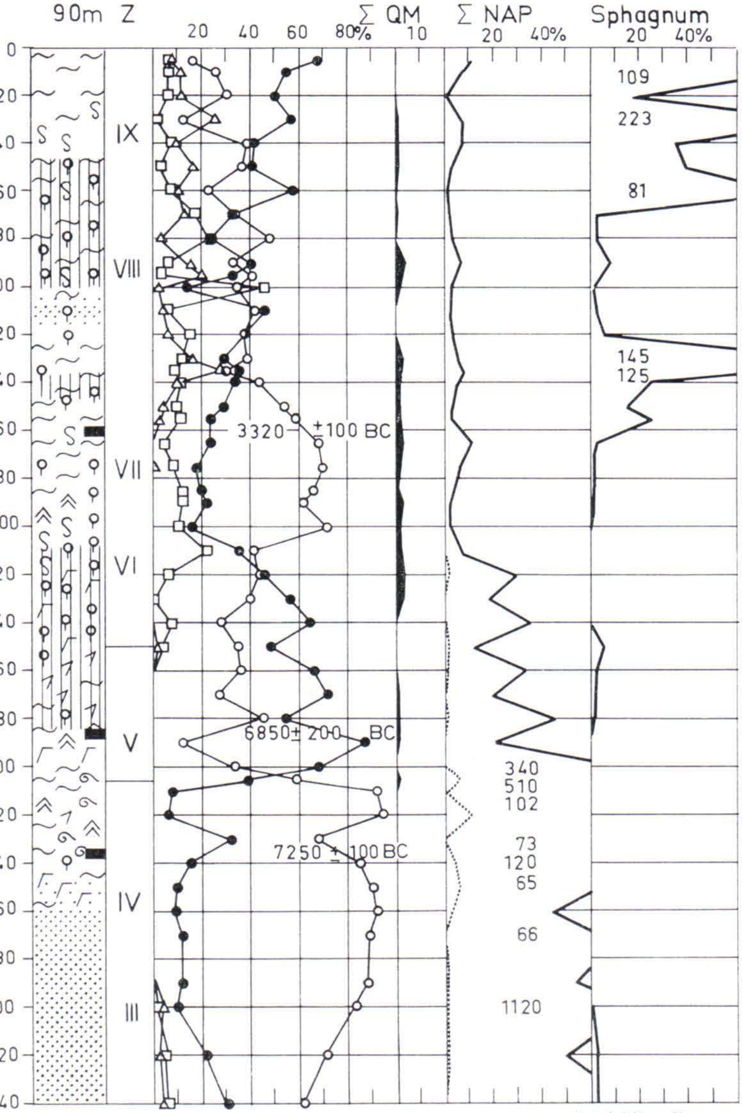

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FIG. 51. Pollen diagram 4, from dune field 56.

it may be concluded that the formation of the dunes ceased in the Tohmajärvi area at the latest around 7 500 B.C. Considering, on the other hand, the circumstance that the dunes could have formed only subsequent to the discharge of the Baltic Ice Lake (8 200 B.C.), one obtains for the theoretical length of time of the formation of the dunes approximately 700 years. This theoretical time was actually still shorter,

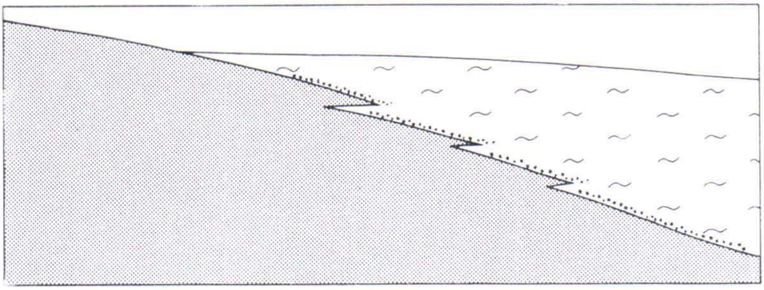

FIG. 52. Contact between peat and dune sand (points). Charcoal occurs sparsely at boundary between dune sand and peat (dune field 41).

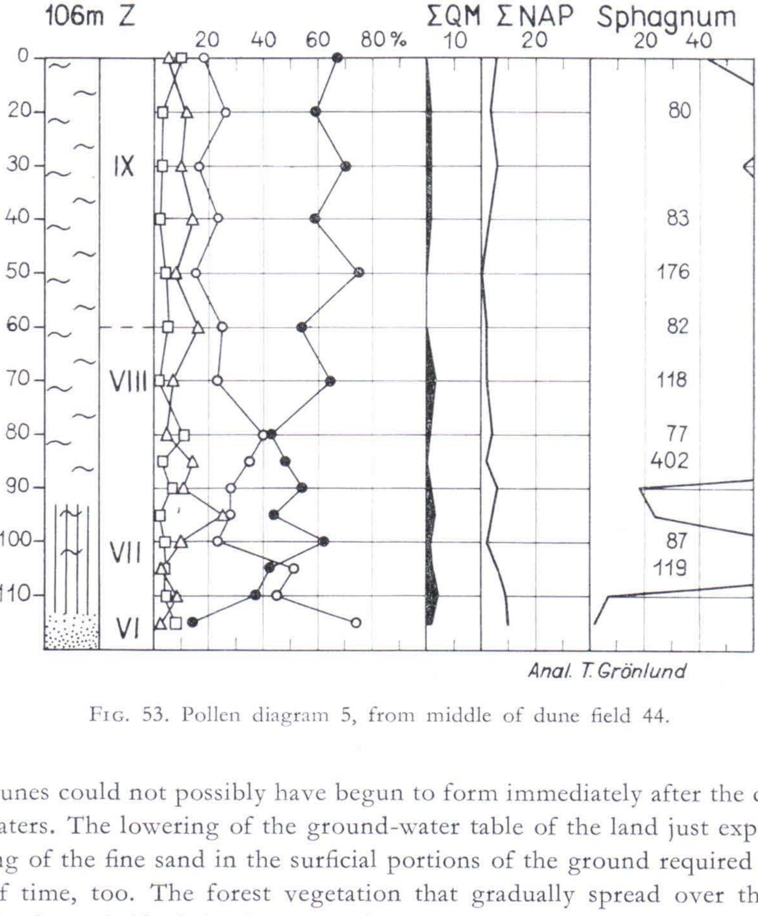

FIG. 53. Pollen diagram 5, from middle of dune field 44.

for the dunes could not possibly have begun to form immediately after the discharge of the waters. The lowering of the ground-water table of the land just exposed and the drying of the fine sand in the surficial portions of the ground required a certain length of time, too. The forest vegetation that gradually spread over the region during the latter half of the formational stage of the dunes, which is revealed by the diminishing of the NAP, caused a shortening of the period of formation. As evidence of the early occurrence of herbaceous plants, there is the abundance of

NAP in lower part of the diagram 4 (Fig. 51). If both these factors working to shorten the formational time of the dunes are taken into account, its very probable length turns out to be roughly 500 years. The period of formation of the dunes would thus appear to have been at its optimum between 8 100 and 7 600 B.C. At the end of this stage, the forests and vegetation in general were growing so vigorously as to prevent the formation of new dunes. The vegetation first spread across the areas from which the dune material originated. When the supply of material was cut off, dunes were no longer able to arise. The vegetation was not at first able to strike root in the dune fields themselves, however, or to bind the dunes finally, as will be shown later on.

For the investigation of the development of the Tohmajärvi dunes, series of samples were also taken from the middle portions of dune fields 44 and 56. The series taken from dune field 44 (pollen diagram 5, Fig. 53) is from a hollow between dunes (comp., p. 23 and Fig. 13). At the bottom of the peat deposit is dune sand, which changes within a distance of less than 10 cm into *Carex* peat. The pollen composition of this series as well as of diagram 3 indicates that forests had grown in the vicinity of the dune field at the time of the zone boundary V/VI. Possibly, however, during the dry Boreal stage, the dunes had still been bare. The damp, though warm, Atlantic stage nevertheless signified the end of transport of sands even in the middle parts of the dune field.

Diagram 6 (Fig. 54) depicts the pollen composition of the series taken from the boggy interdune area in dune field 56. At the bottom of the series, dune sand is met with, but it changes fairly sharply into peat. Paludification began slightly after the general spread of the spruce in zone VII. The beginning of the continuous pollen curve representing the spruce was dated by the C^{14} method (Fig. 51) and the figure arrived at was 3 320 ± 100 B.C. (cf., Tolonen 1967, pp. 359—360). Also Auer (1928), Aario (1965) and Aartolahti (1966) have discussed the general spread of the spruce. During the Atlantic stage, the climate was relatively humid, judging by the fact that in the large dune fields even the interdune areas started to turn boggy. The dampness of the climate is further reflected by the powerful swelling of the *Sphagnum* curve — this feature is also to be noted in diagram 4. Thereafter, the amount of *Sphagnum* decreases sharply in both diagrams.

The binding down by vegetation of the dunes and their »death» did not occur all of a sudden in the Tohmajärvi area, as Fig. 52 indicates. At times, paludification advanced along the edge of some dune, but later on sand was again blown on top of the peat. These alternating and, with respect to genetic conditions, contrary happenings were due, as the author conceives it, to the alternation of humid and dry periods.

The struggle between the peat and the eolian sand is also illustrated by another samples series taken from dune field 56 (Figs. 55 and 56). It was taken about one meter from the contact between the peat and the dune in the direction of the bog (Fig. 55). Underneath a peat layer, measuring about half a meter in thickness, there

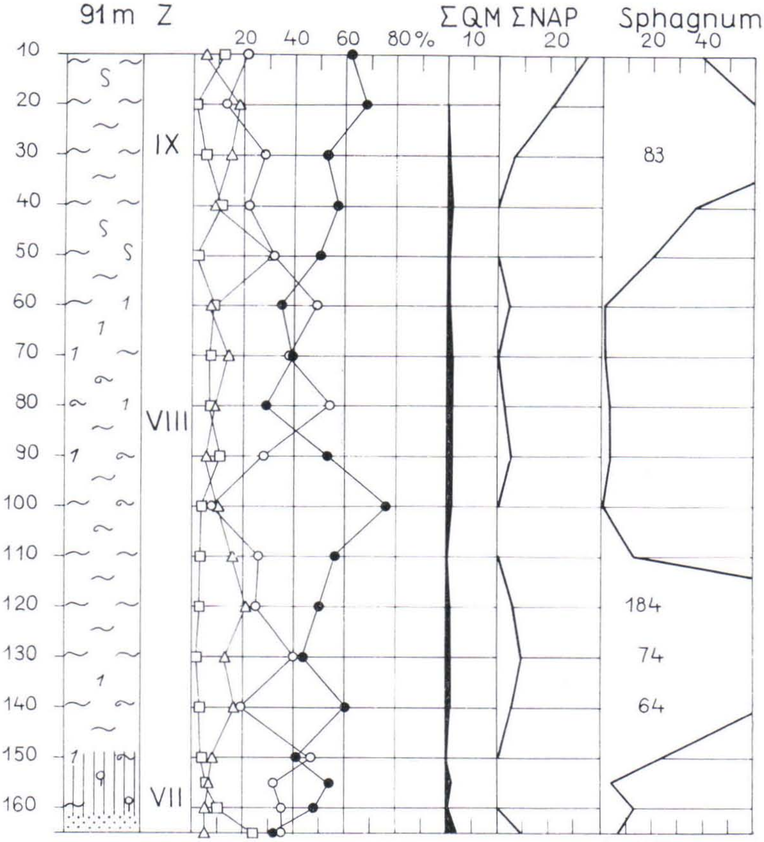

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FIG. 54. Pollen diagram 6, from middle of dune field 56.

FIG. 55. Strip of sand covers peat in dune field 56.

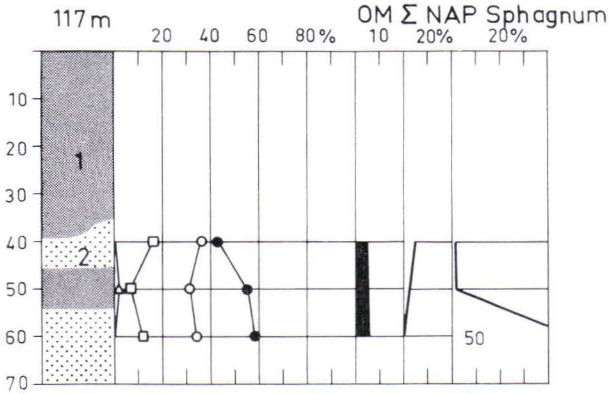

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FIG. 56. Pollen composition of peat buried under sand shown in preceding figure: 1 = peat, and 2 = sand.

is a strip of dune sand nearly 50 cm long, which is also underlain by peat. The pollen composition of the sample series and, in particular, the presence of rare deciduous species of trees provide evidence that the peat underlying the sand dates from a warm Atlantic period. Seppälä (1971) likewise observed signs of deflation and redeposition in dune fields, his investigations having been carried out in Finnish Lapland. The processes of deflation diminished there as a result of the rise in humidity during the Atlantic stage.

Evidence of a sub-Boreal dry climatic stage is provided by the sand grains contained in the sample series taken from a depth of 110 cm at the margin of dune field 56 (Fig. 51). Also the small quantity of *Sphagnum* spores bears witness to a dry period. The last-mentioned series was taken from a site outside the limits of a large parabolic dune. The presence of sand grains in peat is the most conclusive proof of the fact that the dune surface had at the time become rid of vegetation and the wind had, at least to some extent, transported the dune material again. In the lowest-lying interdune area, no sand grains could be detected in the peat. This indicates that the vegetation had not worn off any very extensive area. The probability is that only the crests of the largest dunes had become bare. On the other hand, the hollows and dune margins had continued to be covered with vegetation, for there the groundwater table had been closer to the surface and the ground had retained moisture better. The slight amount of sand grains in the peat further indicates that there could not have been very much sand blown by the wind, for the dune is situated only a few meters away from the site of the peat profile.

The post-glacial development of the dunes

According to Sauramo (1928, 1937), the glacier margin receded rapidly toward the northwest from Salpausselkä II (see also Niemelä 1971). At the same time, there was a rapid seaward displacement of the shore, the Yoldia regression, which exposed ever broader tracts of land. The deltas occurring as a continuation of Salpausselkä II (comp., p. 9) from the line of Heinävaara to the northwest probably represent the level of the Baltic Ice Lake before its discharge (Sauramo 1928, p. 15). A well-developed delta of this kind occurs, for example, on the east side of Aittolampi (Fig. 6). Its height is 125—128 m above sea level (Repo 1969, Fig. 21, p. 33). To the west and northwest from this point, delta plateaus as high as these are no longer met with. The height of the distal plateaus of Jaamankangas between Liperi and Joensuu varies between 105 and 110 m above sea level (Repo 1960, p. 8; Fig. 3). In the western portions of Jaamankangas, the elevation of the afore-mentioned plateaus is about 105 m.

The dunes of the vicinity of Aittolampi (Fig. 6) might have formed as late as the Yoldia regression following the discharge of the Baltic Ice Lake. This conclusion is supported by, in addition to the form and location of the dunes, the northeastern direction of transport of the material. The rest of the dunes in the Joensuu area and the dunes of Mönni formed during the late stage of Yoldia regression.

The westernmost dunes of the study region, which occur in the vicinity of Liperi, are among the youngest as well. They could conceivably have evolved only after the Yoldia regression had exposed the land to the 90—95 m level. Also in the Liperi area, there are dunes of different ages. Dunes 12 and 13 are situated distinctly higher than the rest — between 115 and 120 m above sea level. Thus they could have formed at the very first stage of the Yoldia regression. The rest of the dunes of the Liperi area date back to the final stages of the Yoldia regression.

For the determination of the age of the Liperi dunes, a sample series was taken from the lee side of dune 5, at a distance of about four meters from the flank of the dune (Appendix I). The pollen diagram of the sample series, 7, is presented in Fig. 57. Paludification started on the site at just about the zonal boundary IV/V, perhaps slightly on the side of zone V. This event corresponds chronologically to the C^{14} dating arrived at in the Tohmajärvi area, i.e., 6 850 ± 200 B.C. (Fig. 51). The formation of the Liperi dunes might thus be considered terminated at around 6 800 B.C. The final stages of the Yoldia regression might be estimated as having taken place around 7 000—6 800 B.C. (cf., Sauramo 1958; Hyyppä 1963, 1966; Hyvärinen 1966 a, Fig. 10, 1966 b; Donner 1969). The time of genesis of the dunes of the Liperi area must thus be squeezed into a narrow span. Rather than centuries, it must have taken only a few decades for the dunes to form. This is only natural because shore dunes are in question, dunes that took shape fairly rapidly along a receding shore. Farther from the shore, there grew vegetation, which spread quickly to bind the dunes. Owing to their brief time of development, these dunes could not appreciably migrate but became bound nearly to the very spot where they had originally piled up (comp., profiles in Figs. 44 and 45). The briefness of the time of formation of the shore dunes is also indicated by the fact that the ridges run fairly straight along their longitudinal axes (comp., dunes 5 and 11, Appendix I). Further

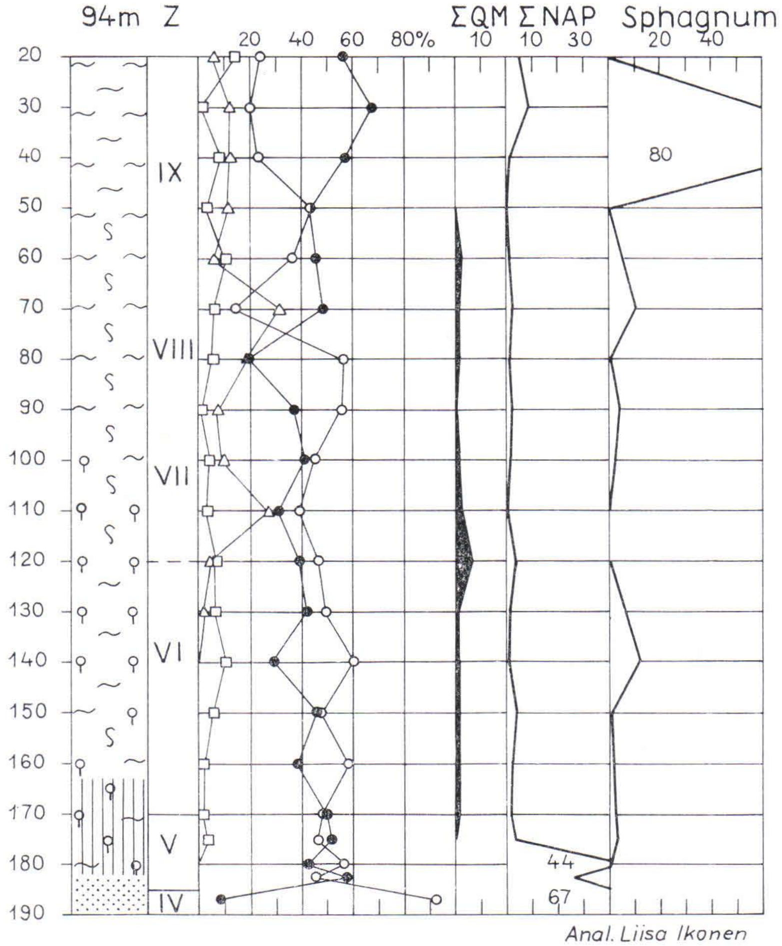

FIG. 57. Pollen diagram 7, from east side of dune 5.

evidence of the short time and the rapidity with which the sand was bound to the ground is provided by the circumstance that the ridges are composed in many instances of almost separate mounds or rows of mounds (e.g., dunes 5, 16 and 18, Appendix I and Fig. 3). Such a row of sand mounds must thus be regarded as evidence of an early phase in the development of a dune.

Although it was probably nearly two thousand years long, the sub-Boreal dry climatic stage was not able to bring about any very great or, at least, lasting changes in the dune fields. The paludification of the surrounding ground, which had started before the dry stage, continued once more afterward. The bare crests of the dunes became covered again with vegetation after the dry stage. However, the plant cover was quite sparse on top of the dunes and also sensitive to climatic changes. Even brief spells sufficed to renew eolian action, provided, however, that some agents, such as animals, had damaged the continuous vegetation on the summits of the dunes, enabling the wind to get at the sand. This is what could have happened especially after large forest fires, as evidenced by the carbon layer in Fig. 52 (see also, Glückert 1971; Seppälä 1971). As an example of relatively recent movement of of eolian sand, there is the loose layer met with on dune 5 which overlies remnants of vegetation (Fig. 58). Another comparable but possibly even more recent occurrence dates from perhaps the end of the 19th century. Proof of it is offered by the studies of Frosterus and Wilkman (1915) (Fig. 59). The bare dunes described by Wilkman (op. cit.) are now wholly covered by vegetation (comp., Fig. 19).

The formation of dunes terminated at the time their margins and surroundings became covered with vegetation and paludification also got underway. Subsequent events prove that the evolution of the dunes has by no means yet ceased. Their development is a dynamic process, in which interruptions occur during humid climatic periods. The balance between wind erosion and vegetation is not very stabile. During dry climatic periods, dunes that had appeared quite dead are likely to become, at least to some extent, active again. The literature offers numerous examples of wind erosion that had begun to produce effects again (cf., e.g., Jelgersma et al. 1970). Cases are even cited of dunes that had started once more to migrate.

At present, in North Karelia, there prevails a peaceful stage in the evolution of the dunes. All of them are completely covered with vegetation. Although on the shores of the lakes as they exist today, there is sand that lies nearly bare or is in the

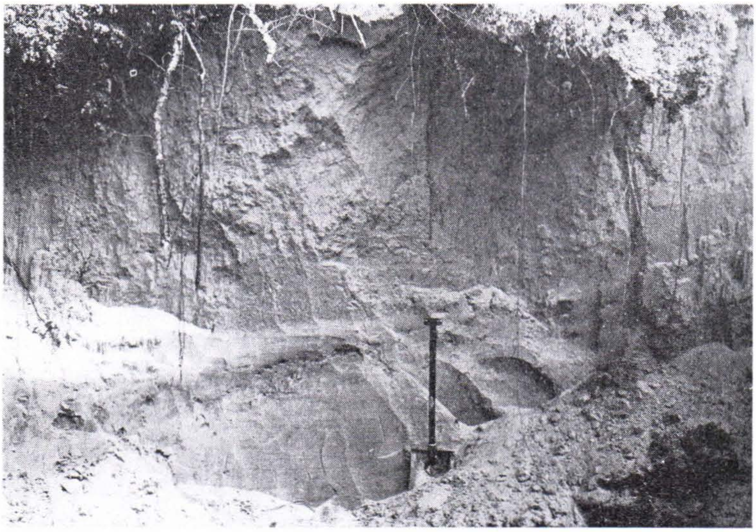

FIG. 58. Buried under sand, dark horizon contains organic matter (dune 5). Dune sand overlying it is distinctly looser in texture than the material below it.

FIG. 59. Largest transverse dune in dune field 42, situated on southwest side of Honkalampi, as it appears in photograph taken at beginning of 20th century by W. Wilkman (Frosterus and Wilkman 1915, Fig. 33). Surface of dune was then fairly extensively exposed, although it had previously been completely grown over by woods, as the stump appearing in the center of the picture indicates. At present, the dune is again entirely covered with vegetation (see Fig. 19).

FIG. 60. Owing to land uplift, sands are exposed along the northwest end of Pyhäselkä. The sand is soon covered by sparse vegetation. Under present-day climatic conditions, no eolian activity takes place. Photo: R. Repo.

process of becoming exposed as a result of land uplift and the tilting of lake basins — sand that might admirably serve as primary material for the formation of dunes —, dunes nevertheless do not form there (Fig. 60). The present-day conditions in the study region thus do not favor the development of dunes. The climate is so humid that the vegetation is capable of keeping potential wind erosion totally in check. Although the evolution of the dunes does appear to have ceased by now, it cannot be regarded as necessarily only a thing of the past. The dunes of North Karelia are labile. In the event that climatic conditions turn drier, wind erosion might start anew.

CONCLUSIONS

In the zone characterized by the existence of the great ice-marginal formations Salpausselkä II and Jaamankangas, the occurrence of dunes, now bound by vegetation, was investigated in 58 dune fields situated within the region of North Karelia, Finland. Various measurement and research methods were applied in identifying the following types of dunes: longitudinal and transverse sand ridges, parabolic and barkhanoid dunes, and sand mounds of irregular shapes. On the basis of the occurrence of dunes, the following major areas were marked off: the Liperi, Joensuu, Mönni and Tohmajärvi areas.

Of the dune material, more than 90 per cent is of the grain size ranging from 0.6 to 0.06 mm and, on the whole, over 70 per cent is finer than 0.2 mm. Although the granular composition of the dunes occurring in the study region is highly similar, differences in this respect can nevertheless be observed between the different areas. The material composing the dunes of Mönni is the coarsest of all, but almost equally coarse is the material of the Liperi dunes (Fig. 24). In these two areas, roughly 30 per cent of the material is coarser than 0.2 mm. The material of the dunes of Tohmajärvi is the finest of all. In this area, the dunes seldom contain coarse sand.

The material composing the dunes of North Karelia is fairly well sorted. The average degree of sorting of all the dune samples studied, there being over 100, all told, is $S_0 = 1.36$. The material of the Mönni dunes is best sorted. This is probably because the dunes in this area are mainly parabolic dunes. In the dunes situated closest to the ice-marginal formations or to sequences of glaciofluvial accumulations, the material is more poorly sorted than in dunes situated farther away. The skewness values of the dune material generally fall below 1. Exceptions are only certain dune fields in the Liperi and Mönni areas. The coarse fractions in the dune material are better sorted than the fine ones.

The petrographic composition and the roundedness of the grains of the dune material deviate conspicuously from the glaciofluvial material, from which they derive. Before the material was subjected to transportation by the wind, it had undergone the sorting and erosive processes of the littoral stage. The dune material has more light minerals and less rock fragments than the glaciofluvial material. These differences appear most distinctly in the dunes of Liperi and Joensuu. The extent of the erosion involved in the eolian process was slight, owing to its rather short duration, compared to the earlier erosive processes. For this reason, the light mineral constituents of the dunes, which have best been able to resist erosion, are only slightly more rounded than the corresponding grains of the glaciofluvial material. On the other hand, the differences are quite clear-cut with respect to the dark minerals and the rock fragments. The dark minerals and rock fragments of the dune material are distinctly more rounded than the corresponding components of the glaciofluvial material. With diminishing grain size, the share of the light minerals increases at the expense of the other components; but the proportion of light minerals in the dune material is always somewhat higher than in the glaciofluvial material. In the dune material, there are fewer bright quartz grains than in the glaciofluvial material. On the basis of the various properties of the material, it has been possible to demonstrate that in many parts of the study region eolian sand of the cover-sand type occurs in deposits ranging between 30 and 100 cm in thickness.

In cross section, the strata of transverse dunes generally dip in line with one or the other flank. Most commonly, the stratification is steep, dipping in line with the lee side; but cross-bedding also occurs. In longitudinal dunes, cross-bedding is met with, and the strata are frequently observed to dip parallel to each flank. In parabolic dunes, cross-bedding is common, bearing witness to the variability of the wind directions.

In the evolution of dune forms, an early phase is represented by rather low and serpentine transverse dunes as well as by, in some instances, longitudinal dunes. Parabolic dunes or longitudinal dunes that have evolved from them are, by contrast, among the most highly developed dune forms existing in the study region.

Inland dunes are generally situated in the proximity of glaciofluvial deposits, from which their material also derives (cf., Högbom 1923, p. 140; Hörner 1929, pp. 112—113; Lundqvist 1943, p. 136; Granlund 1943, p. 87; Myannil, Orviku and Ryahni 1958, p. 10; Wright 1961, p. 948). The dunes have piled up on sand fields situated at the edges of these primary formations as well as on the glaciofluvial material or, in certain instances, till deposits. Between the dunes and the primary ground at their base, no signs of vegetation or humus have been detected. Particularly in the areas of Liperi and Joensuu, the ground on which the dunes have been deposited appears to be some kind of littoral deposit. When the dunes of these areas developed, winds blew mainly from directions between northwest and southwest. During the formation of the Tohmajärvi dunes, the winds had blown from between the northwest and the northeast.

It is generally understood that after the deglaciation, conditions favoring eolian processes have prevailed at different periods and in different regions (see, e.g., Dylik 1961, Gudelis 1961, pp. 479 and 482—483, Stankowski 1964, Mücke and Linke 1967, among others). On the evidence of their location, the dunes of Tohmajärvi are among the oldest in the study region. This conclusion is further supported by the findings of the present investigation. The dunes of dune field 41 at Vatala originated under periglacial conditions while the glacier margin was still at the line of Salpausselkä II. The rest of the Tohmajärvi dunes could have formed soon after the discharge of the Baltic Ice Lake. Peat started to form at the edges of the dunes as early as the pre-Boreal stage, the oldest C^{14} dating going back to 7 250 ± 100 B.C. In the light of such findings, the conclusion was drawn that in the main the dunes of the Tohmajärvi area developed during the period from 8 100 to 7 600 B.C. The dunes of the Mönni, Joensuu and Liperi areas are younger. They formed during the time of the Yoldia regression and the process of their formation ceased about 6 800 B.C.

Although the actual formation and possible migration of the dunes came to a fairly rapid end, vegetation was unable to bind the dunes themselves immediately. The later evolution of the dunes has been marked by constant struggle between eolian activity and the advance of vegetation. From time to time, the vegetation has had to give way, allowing the wind to attack the material. The strongest active phase in the movement of the dune material took place after the stabilization during the sub-Boreal stage and the latest one at the turn of the 19th and 20th centuries. At present, a state of equilibrium prevails again, for the dunes are completely covered with vegetation and no new dunes are forming on lake shores.

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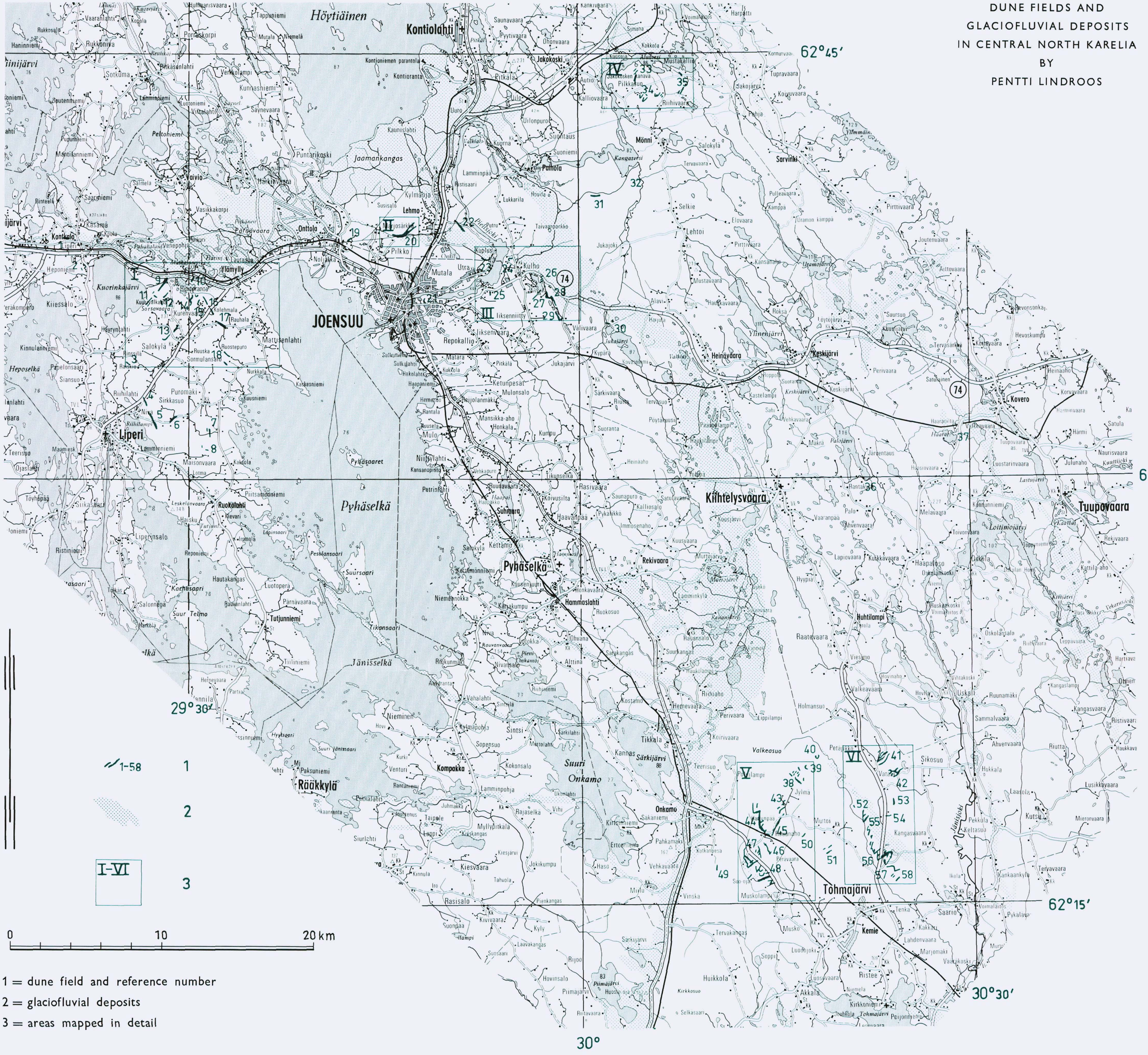
DUNE FIELDS AND GLACIOFLUVIAL DEPOSITS IN CENTRAL NORTH KARELIA

BY

PENTTI LINDROOS



1 = dune field and reference number

2 = glaciofluvial deposits

3 = areas mapped in detail