

## ON THE GRAIN SIZE AND ROUNDNESS OF WIND-BLOWN SANDS IN FINLAND AS COMPARED WITH SOME CENTRAL EUROPEAN SAMPLES

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### ABSTRACT

Ten aeolian sand samples from Finland and four samples from Central Europe were analysed by means of sifting and the mechanical graniformameter of Krygowski. The grain size and the sorting of the wind-blown sands both in Finland and in the other investigated countries are quite similar, but the quartz grains in Finland are usually angular and unworn, while the others are more rounded. The origin of the mother material, and the influence of the earlier geomorphological processes on the roundness can be seen clearly in a comparison of the characteristics of the sands.

### Introduction

For a long time the investigators of sediments have been interested in the granulometric composition and roundness of the quartz grains because of the palaeogeographical information given by them. Methods of roundness investigation have been developed by the following scientists, for example Cailleux, Guggenmoos, Krygowski, Pettijohn, Russell, v. Szádeczky-Kardoss, Taylor, Wadell, Wentworth (*e.g.* Köster 1964 p. 138—192), and Kuenen who has investigated abrasion experimentally.

The present paper is a comparison between the grain size and roundness of some Finnish wind-blown sands and four samples from Central Europe. On the basis of the results, an attempt will be made to find out reasons for the abrasion and the origin of the material. An effort has been made to select the samples so as to

make them represent the material typical of each area as well as possible.

The grain size will be examined in the classic way by means of test-sieves. This is the first time that the shape of Finnish sand grains has been analysed by means of the bulldozer graniformameter apparatus (Krygowski 1964) which professor Bogumił Krygowski has been developing since 1937. This apparatus was purchased recently by the Department of Geography, University of Turku. It has proved to be very useful because of its fastness, and the ease of comparing the results. The mechanical graniformameter removes from the analysed results the factor of human subjectivity, which is a problem of those using visual methods. The apparatus treats the grains, not merely their projections, as three-dimensional objects; this treatment of only projections is a defect in several methods based on measurements.

The present writer will point out some dune sand examples from Finland which show a marked difference from those in Central Europe, particularly as far as roundness is concerned.

At the end of the paper, there will be a discussion on the importance of the quartz grains worn in earlier processes to the analysed samples, and their influence on the conclusions.

### Localities and backgrounds of the samples

Ten samples were collected from Finland (1—10) and four from some dune fields in Central Europe: Hungary (11), Denmark (12), and Poland (13 and 14) (Fig. 1). The list of the samples (giving number, place, geographical position, and height above the sea level in metres) is as follows:

TABLE 1.

1. Kiellajoki .....	69°18'N	26°47'E	215
2. Vatala .....	62°17'N	30°22'E	95
3. Luomushjärvi ..	69°27'N	26°23'E	410
4. Kuttanen .....	68°24'N	22°52'E	320
5. Hietatievat .....	68°28'N	24°42'E	380
6. Yyteri .....	61°33'N	21°32'E	15
7. Säkyliä .....	61°02'N	22°27'E	80
8. Koverhar .....	59°52'N	23°13'E	25
9. Oripää .....	60°52'N	22°45'E	95
10. Kalajoki .....	64°14'N	23°49'E	10
11. Ágasegyháza ...	46°52'N	19°25'E	130
12. Rømø .....	55°08'N	08°30'E	10
13. Nowy Tomyśl ..	52°22'N	16°09'E	95
14. Obrowo .....	52°58'N	18°53'E	110

Sample No 1 Kiellajoki was collected from Inari, Lapland, about 38 km west of Kaamanen. This is where one of the largest areas of parabolic dunes in Finland is situated. The material was primarily accumulated in a large ice-dammed lake (Tanner 1915 p. 276—277), and the surface has been deformed by wind action after the deglaciation. Present aeolian activity forms 1—10 metres deep deflation basins in the dunes.

No 2 Vatala is situated in Northern Karelia about 5 km north of Tohmajärvi Railway Station. Between the ice-marginal formations of the first and second Salpausselkä there is a landscape of radial eskers (Frosterus and Wilkman 1917 p. 82). 2—8 metres high irregular fossil sand dunes and cover sands can be found between them and on their slopes.

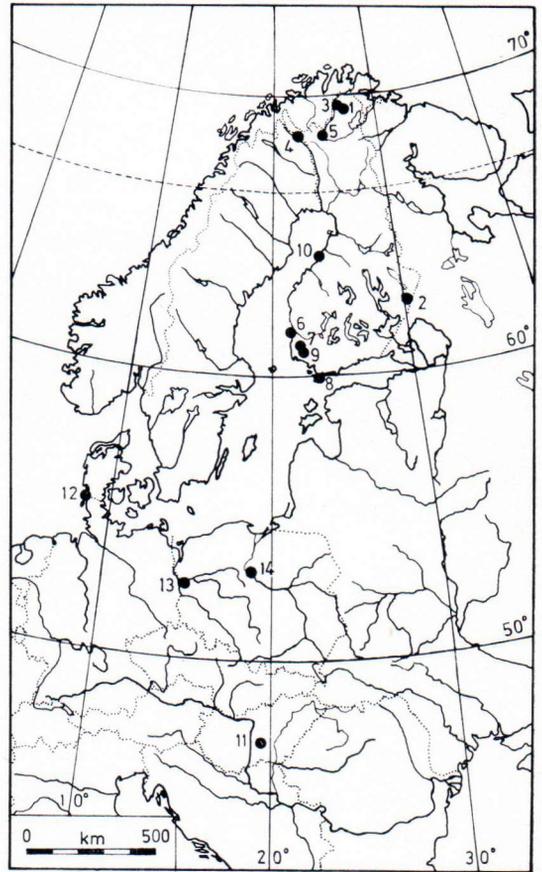


Fig. 1. Map of sampling localities.

No 3 Luomushjärvi is a lake 12 km east of Karigasniemi in Utsjoki, Lapland, in a tectonical valley running in NE-SW direction. An esker with many bifurcations (Tanner 1915 p. 272), which is 8—30 metres high and about 12 km long, goes through the lake. The fine glaciofluvial material in the neighbourhood of the esker, on the eastern slope of the valley, has formed a diffuse area of drift sand with irregular dunes 1—6 metres high. Present deflation forms are characteristic of the region.

No 4 Kuttanen, Enontekiö, Lapland, near the western border of Finland. Here, too, the position of the 2—8 metres high parabolic dunes is in connection with an ice-dammed lake (Kujansuu 1967 Appendix 1), and partly with an esker, about 15 metres high and about 20 km long, going in the direction S 25° W (Tanner 1915 p. 253). Some quite large, fresh deflation forms can also be found here among the dunes.

No 5 Hietatievat, Eastern Enontekiö, was taken, like the other samples (1, 3 and 4) from Northern Finland, from the region north of the last ice divide. Hietatievat is a big 30–35 metres high undulating esker ridge running in N-S direction. It is 4 km long and c. 1.5 km wide. It is just part of a bigger esker system (Tanner 1915 p. 262–265, Ohlson 1957 p. 129, Seppälä 1966 p. 276). The esker is covered with drift sand which is primarily glaciofluvial material. The dunes are of the barchan type, and they form long chains. Deflation is strong in spite of the Pine and Birch forests of the region. Sample No 5 has been described in an earlier paper by the author (Seppälä 1966 p. 282–283, sample No 3).

No 6 Yyteri lies 20 km northwest of the town of Pori on the coast of the Gulf of Bothnia. The fine sand has sedimented during the deglaciation in connection with the esker system of Koski—Yläne—Säkylä—Kokemäki—Harjavalta—Ulvila running in NW-SE direction (Atlas of Finland 1960 Map 4), which continues as a submarine esker WNW of Yyteri according to Kukkonen (Ignatius 1966 p. 17–18). Later on, the sea levelled the sand which was then accumulated by the wind into coastal dunes 10–20 metres high. Formations of active accumulation can be seen only near the coast. Though the Kokemäki delta is near (Säntti 1954) the river has not played any important role in the accumulation of the dune sand. According to Sauramo (1924 p. 36), the sand of Yyteri has plenty of quartz (85 %), which is shown by the grey colour of the drift sand. The Jotnian arkose sandstone met at the lower run of the River Kokemäenjoki would render the sand a reddish colour.

No 7 Säkylä lies on Southwestern Finland. East of the village of Säkylä there is the Säkylä esker running in NW-SE direction, which is a part, 20–50 metres high and about 20 kilometres long, of the same longer esker complex as the one from which the previous sample was taken. At the western foot of the esker there is a large area of 3–10 metres high coastal dunes and barchanlike fossil sand dunes. The material was first accumulated by glaciofluvial processes. The littoral forces constituted the second sorting and depositing phase the influence of which is proved by the cobbly ancient coast lines on the slopes of the esker. In Säkylä the highest coast line of the postglacial Ancyclus lake is about 105 metres above the present sea level, and the coast of the first *Litorina* transgression is 64 m.a.s.l. (Aurola 1938 Appendix II, Hyypä 1966 Fig. 2). Thus the dunes can have come into being at the height of 80 metres only at the end of the Boreal time at the earliest. The red colour of the sand is caused by the Jotnian arkose sandstone.

No 8 Koverhar is situated on the Hanko Peninsula in southernmost Finland. These 6–15 metres high

coastal dunes run south of the first Salpausselkä on its distal side. This ice-marginal formation is an important source of the aeolian material, though the esker itself has been totally levelled here by marine forces, and later covered by littoral and aeolian deposits (Virkkala 1963 p. 18). The sand dunes are young postglacial formations, which are nowadays covered with vegetation.

No 9 Oripää is connected with the same esker system running in NW-SE direction as Yyteri and Säkylä. The analysed sample was taken from the large sand plateau of Oripäänkangas west of the Oripää—Virttaa esker which was washed by the Ancyclus Lake (Aurola 1938 Appendix II). During the Boreal time at the earliest, the surface of the plateau was covered by undulating aeolian sand without any bigger dune formations. Here, too, the reddish colour of the sand is caused by the Jotnian arkose sandstone.

No 10 Kalajoki is the third example of typical coastal dunes in Finland. The sand deposits came up at the continuation of the esker system of Pihtipudas—Reisjärvi—Sievi—Rautio running in NW-SE direction at the end of the glacial period; this continuation was situated on the bottom of the Gulf of Bothnia (Leiviskä 1905 p. 9–10 and Appendix). No submarine morphological esker has been found here so far. The glaciofluvial material near the shore has been levelled by littoral forces (Okko 1949 p. 42). Owing to land uplift there are fossil coastal dunes as a wide zone consisting of 12 ridges here and there on the coast. The dunes are several kilometres long and 2–20 metres high. Their direction seems to determined only by the direction of the shore (Okko 1949 p. 63). Features of active accumulation can be seen only on the shore line.

No 11 Ágasegyháza is situated about 23 kilometres west of the town of Kecskemét in Central Hungary. The sample represents the large dune fields of the Danube-Tisza interfluvial area where windblown sands overlie the large Pleistocene alluvial fan accumulated on the Pannonian layers (Borsy 1965 b p. 85–87, Molnár 1966, Pécsi & Sárfalvi 1964 p. 90–91, Rónai 1965 p. 18–19). The region has never been under the continental ice cap, but the fossil periglacial phenomena are quite common. The dunes are semi-consolidated, and wind furrows, arrested by the plant cover, are characteristic (Borsy 1965 b p. 88) The active sand dunes are about 12 metres high.

No 12 the Isle of Rømø lies off the western coast of Jylland. The whole island is covered with beach aeolian sands. During the Last Glaciation (Würm) Rømø was free from the ice cap (Hansen 1965 p. 43) The sand may have accumulated as early as during the deglaciation of

the Riss Glaciation. Later on the area has been several times under the sea level because it shows many regressions and transgressions (Hansen 1965 p. 72—80). The dunes have come into being as late as during the Holocene time, and aeolian accumulation can partly be still noticed.

No 13 Nowy Tomyśl is a small town 50 km west of Poznań in Western Poland. The Nowy Tomyśl outwash plain (Krygowski 1961 Fig. 6) is situated between the two margins of the Scandinavian inland-ice, the Leszno (Brandenburg) and Poznań (Frankfurt) stages (Galon & Roszkówna 1961). Thus the origin of the aeolian sand is glaciofluvial. There are single parabolic dunes on the outwash plain (Stankowski 1963 Fig. 23) 5 km north of Nowy Tomyśl. It was on the top of one of these, a partly c. 20 metres high dune, that the analysed sample was taken.

No 14 Obrowo about 15 km east of Toruń in Northern Poland. The sampled dune was on the Pleistocene Plateau at the northeastern side of the vast dune fields of the Toruń Basin in the Vistula Valley. The sand material has been carried by the wind from the terraces of the Vistula-Noteć ice-marginal streamway (Mrózek 1958 Appendix and 1961 p. 125—126), and accumulated into 10—20 metres high semi-consolidated dune ridges. Samples 13 and 14 also occur in an earlier paper by the present writer (Seppälä 1967 p. 31 and 35).

All the samples under consideration were taken from the stratified fresh material under the weathered soil horizons in the topmost parts of the sand dunes.

**Granulometric composition and statistical evaluation**

The granulometric composition of the samples was analysed by means of test-sieves ASTM. The series which was used consists of 10 sieves. The diameters of their square holes are as follows: 1.410, 1.000, 0.707, 0.500, 0.354, 0.250, 0.177, 0.125, 0.074, and 0.037 mm. The weights of the analysed samples varied between 400 and 600 grams. The results are given by means of cumulative curves on a semilogarithmic paper and with a triangular graph (Fig. 2).

The median grain size (*Md*) of the samples ranges from 0.15 to 0.35 mm. Hietatievat (No 5)

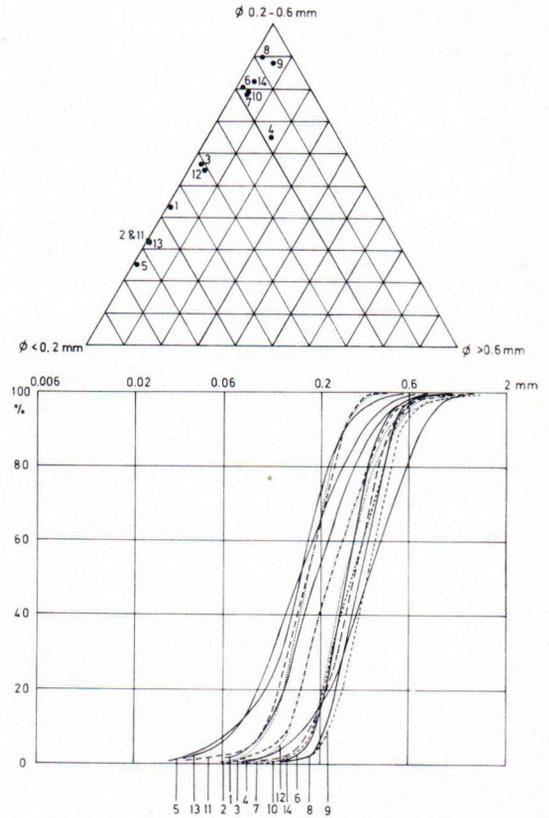


Fig. 2. Triangular graph and cumulative curves of the grain size compositions in the analysed blowsand samples.

and Nowy Tomyśl (No 13) represent the lower limit value, and the samples Kuttanen (No 4) and Oripää (No 9) give *Md* value of 0.35. The results given here are well in accordance with the grain sizes of wind-blown sands in general.

The maximum diameter of the grains is c. 1.5 mm; these grains mainly occur in samples No 8, 9, and 12. For the sake of comparison, it may be mentioned that Kuhlman (1960 p. 80) reports about occasional grains in Denmark whose diameter was even 10 mm, and Mrózek (1958 Fig. 6) shows stones 7—8 mm in diameter in the drift sand of the Toruń-Bydgoszcz area in Poland. The samples analysed here did not contain so big grains.

The minimum grain size to be met was 0.02 mm. The grains of this size did not, however, suffice to fill the minimum amount required by weighing accuracy (0.1 weight percentage). So fine material is common in loess layers, but not in dunes. Several samples contained very few grains whose diameter was less than 0.05 mm.

Upon an examination of the triangular graphs (Fig. 2) it will be seen that the commonest fraction in nine samples is between 0.2 and 0.6 mm, i.e. fine sand according to Atterberg's classification (1905 p. 232). The rest five samples show mainly a diameter of less than 0.2 mm. There is no difference in the granulometric composition between the Finnish and the foreign samples. Both the finest (No 5) and the coarsest (No 4) samples are from Enontekiö, Lapland. On the basis of the triangular graph, the samples can be grouped as follows: 1) *the coarse aeolian sands* containing more than 10 weight % grains whose diameter is bigger than 0.6 mm (No 4), 2) *the semi-coarse sands* containing less than 30 weight % grains less than 0.2 mm in diameter (Nos 6, 7, 8, 9, 10, and 14), and 3) *the fine aeolian sands* containing more than 30 weight % grains less than 0.2 mm in diameter (Nos 1, 2, 3, 5, 11, 12, and 13).

The sorting was examined statistically by computing the two parameters  $S_0$  (sorting) and  $S_k$  (skewness) on the basis of the cumulative curves (e.g. Köster p. 141)

$$S_0 = \sqrt{\frac{Q_3}{Q_1}} \quad (\text{formula of Trask})$$

$$S_k = \frac{Q_1 \cdot Q_3}{Md^2}$$

$Q_1$  and  $Q_3$  are quartiles  
 $Md$  is the median grain size

All the samples are very well sorted ( $S_0$  values vary from 1.24 to 1.55), which is usual with wind-blown sands. Sindowski (1961 p. 173) gives the figure 1.20—1.30 as the commonest value of the  $S_0$  parameter of the continental and coastal dunes, and the figure 1.30—1.50 as the commonest deviation value. Most of the samples of the present writer take their place within the above mentioned range. Maruszczak & Wojtanowicz (1967 Table 12) have noted an average sorting value of 1.52 in the dunes of Southeastern Poland and 1.42 in Hungary. There is no significant difference between the drift sands in different countries; however, it can be stated that the samples from the southern parts of Finland are best sorted (Nos 2, 6—9).

The skewness values vary a little on both sides of the figure 1 (1.09—0.95), which means that the cumulative curves are rather symmetric in relation to the value of  $Md$ . When the  $S_k$  value is more than 1, finer fractions are better sorted than coarse ones, and when it is less than 1, coarse fractions are better sorted; in other words, finer fractions are predominating (e.g. Köster 1960 p. 141, Molnár 1966 p. 138—139). A general feature seems to be that, when the value of  $Md$  is small, the  $S_k$  value is more than 1, i.e. fine fractions are then better sorted than coarse ones. A clear exception to the rule is, however, Kuttanen (No 4) whose  $Md = 0.35$  and  $S_k = 1.08$ . The  $S_k$  values of the coastal dunes (Nos 6, 8, 10, and 12) are regularly less than 1 (0.98—0.95). No clear system can be perceived in the other samples on the basis of this material.

**Roundness of the quartz grains**

The abrasion grade of the quartz grains was determined by means of the mechanical method

TABLE 2.

	$Q_3$	$Md$	$Q_1$	$S_0$	$S_k$
1. Kiellajoki . . .	0.27	0.18	0.13	1.44	1.08
2. Vatala . . . . .	0.22	0.17	0.14	1.25	1.07
3. Luomushjärvi	0.33	0.23	0.155	1.46	0.97
4. Kuttanen . . .	0.53	0.35	0.25	1.46	1.08
5. Hietatievat . .	0.20	0.15	0.12	1.29	1.07
6. Yyteri . . . . .	0.34	0.28	0.22	1.24	0.95
7. Säkylä . . . . .	0.35	0.26	0.21	1.29	1.09
8. Koverhar . . .	0.40	0.32	0.25	1.26	0.98
9. Oripää . . . . .	0.43	0.35	0.27	1.26	0.95
10. Kalajoki . . .	0.41	0.30	0.22	1.54	0.97
11. Ágasegyháza	0.23	0.17	0.13	1.33	1.03
12. Rømø . . . . .	0.33	0.23	0.155	1.46	0.97
13. Nowy Tomyśl	0.24	0.15	0.10	1.55	1.07
14. Obrowo . . . .	0.39	0.30	0.22	1.33	0.95

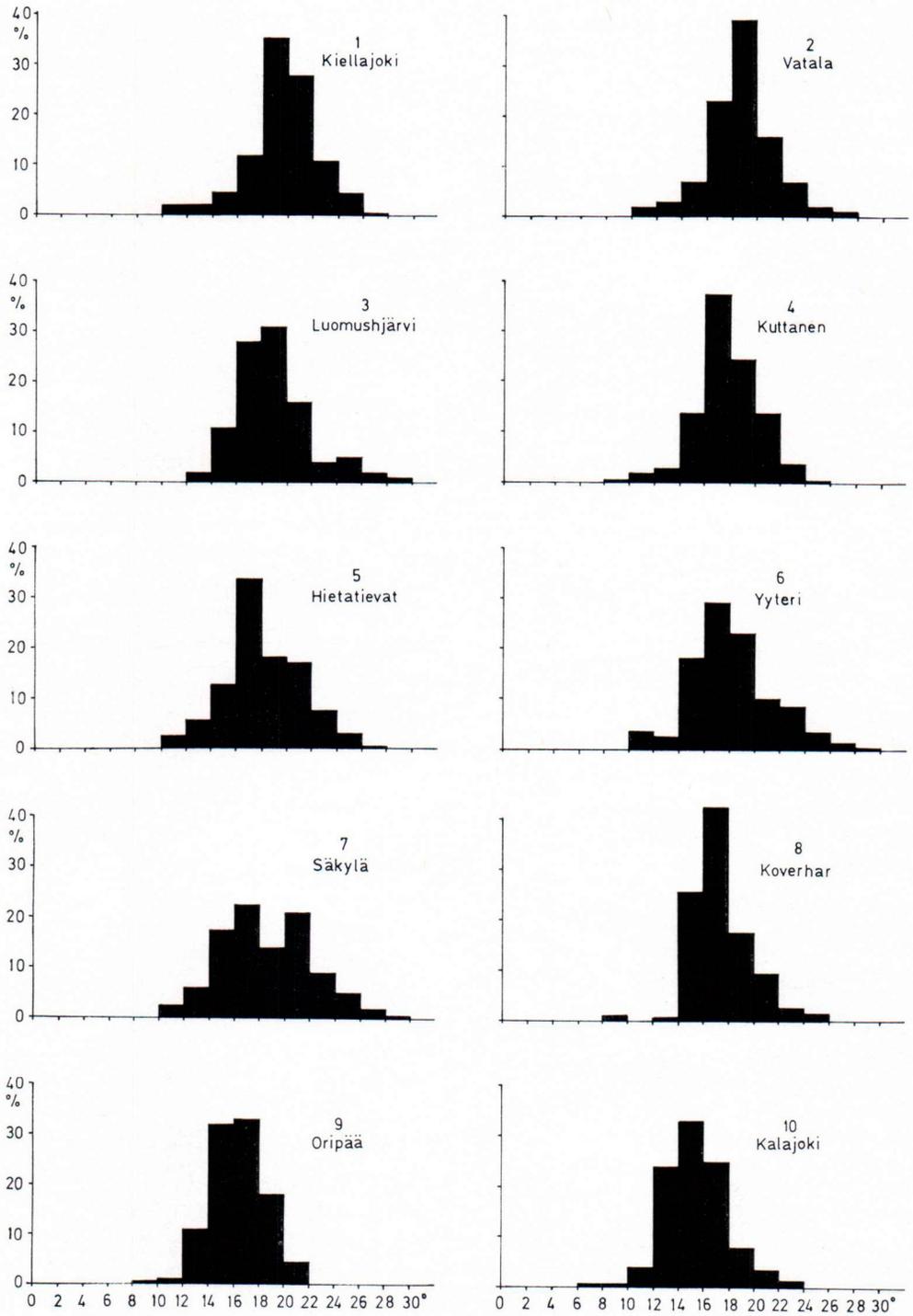


Fig. 3. Histograms of distribution of quartz grains in the graniformametrical angle classes. Finnish aeolian sands.

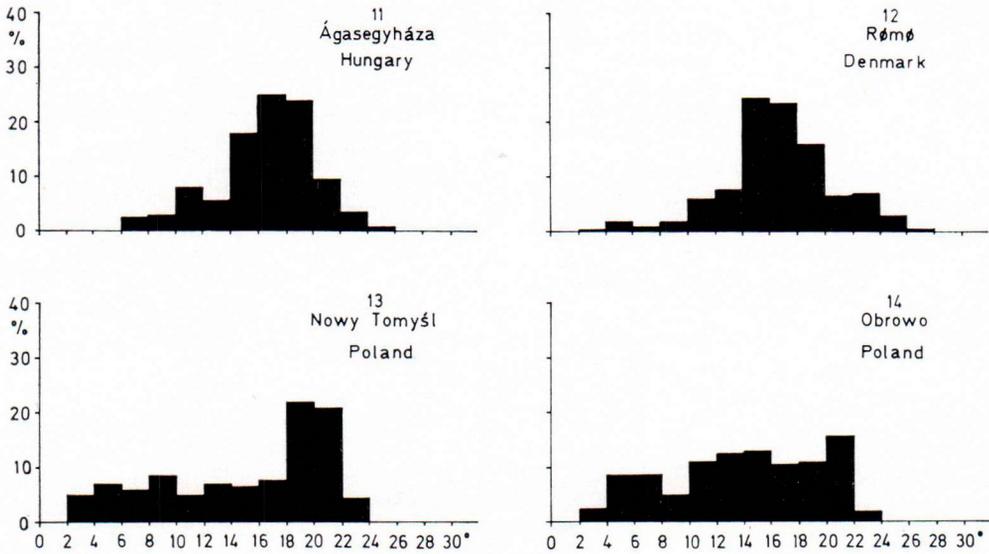


Fig. 4. Histograms of distribution of quartz grains in the graniformametrical angle classes. Central European aeolian sands.

developed by Krygowski. The functioning principle of the apparatus — the mechanical graniformameter — has been explained by several various papers (*e.g.* Krygowski 1964, 1965, Krygowski & Krygowski 1965).

The analysis begins by sifting the material and separating from it the fraction  $\phi$  1.000—0.707. 100—200 quartz grains are then separated from the selected fraction under a binocular microscope. These grains are washed in 10 % hydrochloric acid to remove the dust and the possible limonite and calcareous film. The grains are rinsed out in distilled water and dried up in a heat-box of 105° Centigrade. After this preliminary treatment, the grains are put on the inclined glass plain of the apparatus along the »bulldozer» when the inclined plane is in the horizontal position. The analysis commences by starting the motor when the inclination angle of the glass plain is 2°. The inclination angle is increased 2° each time. The increase is carried out always when the »bulldozer» begins to carry the remaining quartz grains upwards. The procedure

is repeated till no grains are left on the plain. The maximum number necessary to complete the separation of the samples was 15, and the maximum grade was then 30°. The grains which had rolled into the collector at each inclination point are counted separately. The sample is treated twice in the apparatus, and the means ( $n$ ) are computed for each inclination class respectively. Thus the quartz grains have been selected mechanically. The histograms (Figs. 3 and 4) have been drawn according to their abrasion grade. The smaller the rolling angle of inclination is, the more abraded is the grain.

Krygowski (1964 Table 7) divides the grains into three main classes according to the rolling angles as follows: 1) 0—8° =  $\gamma$  well rounded, 2) 8—16° =  $\beta$  relatively well rounded, and 3) 16—24° =  $\alpha$  unabraded. The present writer incorporated all the angular grains from 16° to 30° in the last mentioned class. The triangular graph (Fig. 5) and the synthetical diagram about the abrasion grade (Fig. 6) are based on the division into these three classes.

The abrasion index ( $W_0$ ) is computed according to the formula (Krygowski 1964 p. 40):

$$W_0 = 2400 - \frac{\sum (n \cdot k) \cdot 100}{N}$$

2400 = constant

$n$  = number of grains in angle class

$k$  = mean angle characterizing a given angle class e.g. in the class 4–6°  $k = 5$

$N$  = total number of grains in the sample examined

If  $W_0 = 0-800$  badly rounded, 800–1600 relatively well rounded, and 1600–2400 very well rounded material (Krygowski 1964 Table 7)

Another statistical parameter characterizing the sample is the index of heterogeneity (or unhomogeneity)  $Nm$  described as

$$Nm = Q_3 - Q_1$$

where  $Q_1$  and  $Q_3$  are the first and the third quartiles respectively.

The average standard deviation of  $W_0$  was  $\pm 22.7$  in many analyses by Krygowski & Krygowski (1965 p. 497). Pearson's correlation coefficients for the results obtained by means of two other methods (Cailleux, and Kuenen), and for the mechanical graniformametry are rather high (Krygowski & Krygowski 1965 p. 497–498). This shows convincingly the practicability of the method.

According to the analysis results of the present writer, the Finnish samples are weakly rounded in general. An exception is provided by No 9

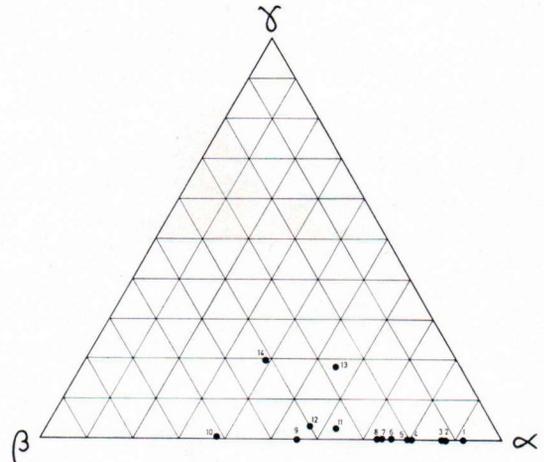


Fig. 5. Triangular graph of abrasion composition of quartz grains of aeolian sands.  $\gamma$  = well abraded, angle classes 0–8°,  $\beta$  = quite abraded, angle classes 8–16°, and  $\alpha$  = unabraded, angle classes 16–30°, see Table 3.

Oripää and No 10 Kalajoki which are partly rather abraded. These two are even better rounded than the more heterogeneous No 11 Ágasegyháza and No 12 Rømø which contain, however, some entirely ball-shaped quartz grains. The roundness index  $W_0$  is bigger in Nos 9 and 10 than in 11 and 12. The well rounded Polish drift sands (Nos 13 and 14) form, however, a category of their own. Another typical feature in them is that the material is evenly distributed between several angle classes (Fig. 4). This causes the heterogeneity index  $Nm$  of the Polish drift sands to be much bigger (more than 8.5) than that of the other samples, in which it is regularly

TABLE 3.

	$W_0$	$Q_1$	$Q_3$	$Nm$	$\gamma$	$\beta$	$\alpha$
1. Kiellajoki	438	18.25	21.35	3.10	—	8.5	91.5
2. Vatala	535	17.07	20.00	2.93	—	12.5	87.5
3. Luomushjärvi	500	16.88	20.52	3.64	—	13.0	87.0
4. Kuttanen	623	16.29	19.47	3.18	—	19.5	80.5
5. Hietatievat	584	16.25	20.41	4.16	—	20.5	79.5
6. Yyteri	578	16.06	19.97	3.91	—	24.0	76.0
7. Säkylä	541	15.86	21.21	5.36	—	26.0	74.0
8. Koverhar	661	15.82	18.71	2.89	—	27.0	73.0
9. Oripää	764	14.78	17.86	3.08	—	44.5	55.5
10. Kalajoki	856	13.64	17.06	3.42	0.5	61.5	38.0
11. Ágasegyháza	740	14.67	19.08	4.41	2.5	34.5	63.0
12. Rømø	740	14.52	19.00	4.48	3.3	40.0	56.7
13. Nowy Tomysl	898	9.65	20.05	10.40	18.0	27.0	55.0
14. Obrowo	1 008	10.09	18.64	8.55	19.5	41.5	39.0

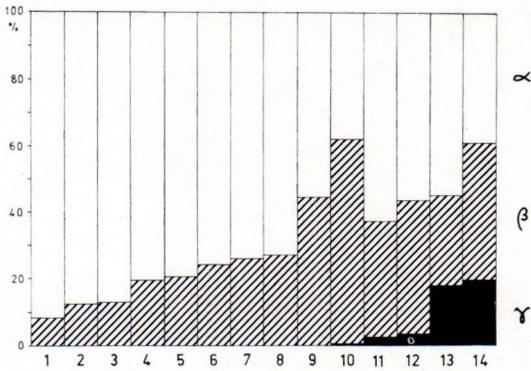


Fig. 6. Divided rectangles of roundness composition of quartz grains of aeolian sands. For  $\alpha$ ,  $\beta$  and  $\gamma$  see Fig. 5.

less than 6 (Fig. 9 and Table 3). The Finnish drift sands occupy 7–10 angle classes (Fig. 3), and most of them (except Nos 7 and 9) have one clear maximum angle which takes considerably more quartz grains than the other angles. In the histograms most Finnish samples represent approximately the normal distribution. The Central European samples are distributed between 10–13 angle classes (Fig. 4). This result shows a marked divergence from that of Maruszczak & Wojtanowicz (1967 Fig. 38) in which the material from the dunes in Southeastern Poland takes 8–9 angle classes and that from Hungary 5–6 classes. There is almost a total absence of especially very angular grains in their examples. Krygowski's (1964 Fig. 15) results (10–11 angle classes) from Central Poland correspond to those given above, though he investigated the fraction 1.0–1.25 mm.

A couple of previous studies (Borsy 1964, Maruszczak & Wojtanowicz 1967) have already compared the Hungarian drift sands with those from Poland. Their results have been quite similar to the one shown by this paper, too: the Polish dune sands have a much higher rate of mechanical wear than the Hungarian ones. The sam-

ple from Denmark (No 12) corresponds rather well to the Hungarian samples. The abrasion index  $W_0$  of most Finnish samples is remarkably smaller than that of the Central European ones.

Figure 9 has been made by placing the parameters  $W_0$  and  $Nm$  in a rectangular diagram. In doing so, the points from areas typical of each material respectively (Krygowski 1964, 1965, Krygowski & Krygowski 1965). The diagram indicates that all the other samples take a relatively small area (A–B II–III) except the Polish ones which constitute totally a group of their own at the upper part of the diagram (C–D III–IV). The present writer found no grains with as strong rounding as reported by Krygowski (1964 and 1965). In the triangular graph and the rectangular diagram, the Finnish samples, considering their roundness characteristics, correspond most closely to the weathered granit material from the Sudetes Mountains, according to Krygowski (1964 Fig. 36 and 37). The Lappish drift sands are especially characterized by highly angular quartz grains, which is typical of frost weathered material (Ohlson 1964 p. 132–133).

**The texture of the surface of the quartz grains**

According to the quality of the surface, the quartz grains can be separated into three groups by means of a binocular: 1) those with a brilliant surface, typical of frost weathered and fluvial materials; 2) those with semi-mat surfaces: there are also some etched surfaces clearly to be seen, but the grain still has a partly brilliant surface; 3) those with mat surface whose entire surface is dim. Grains with mat surfaces are very typical of aeolian material (Cailleux 1942, 1952).

Considering the quality of the surfaces, the percentage distributions of the quartz grains in the analysed samples were as follows:

TABLE 4.

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Brialliant .....	11	55	23	83	31	73	64	58	10	31	12	47	—	1
Semi-mat .....	55	30	40	13	40	12	19	32	32	22	42	35	7	29
Mat .....	34	15	37	4	29	15	17	10	58	47	46	18	93	70

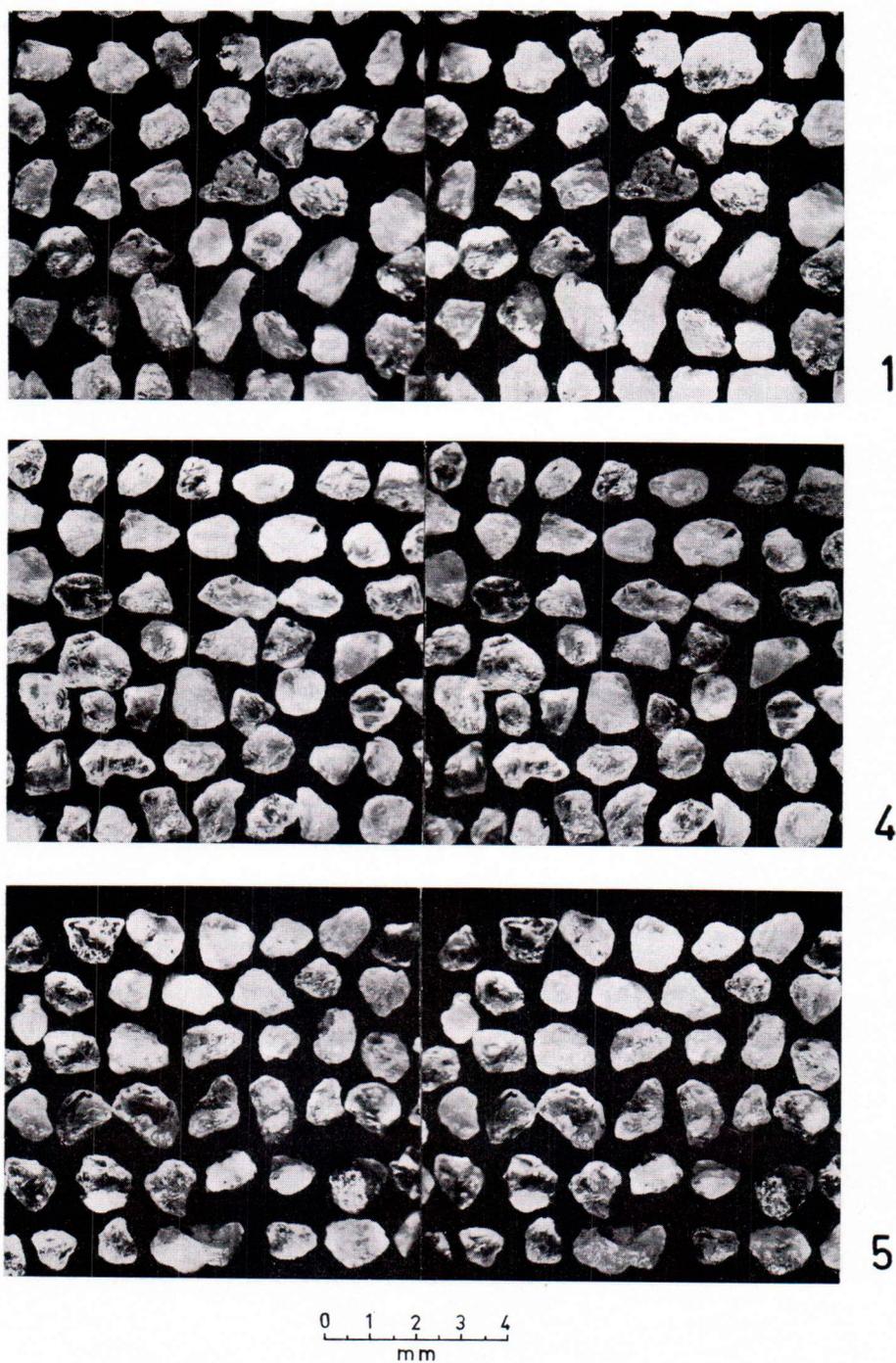


Fig. 7. Stereophotos of some quartz grains of Lappish wind-blown sands. Fraction 1.0—0.707 mm. 1 Kiellajoki, 4 Kuttanen and 5 Hietatievat. Photographed by the author.

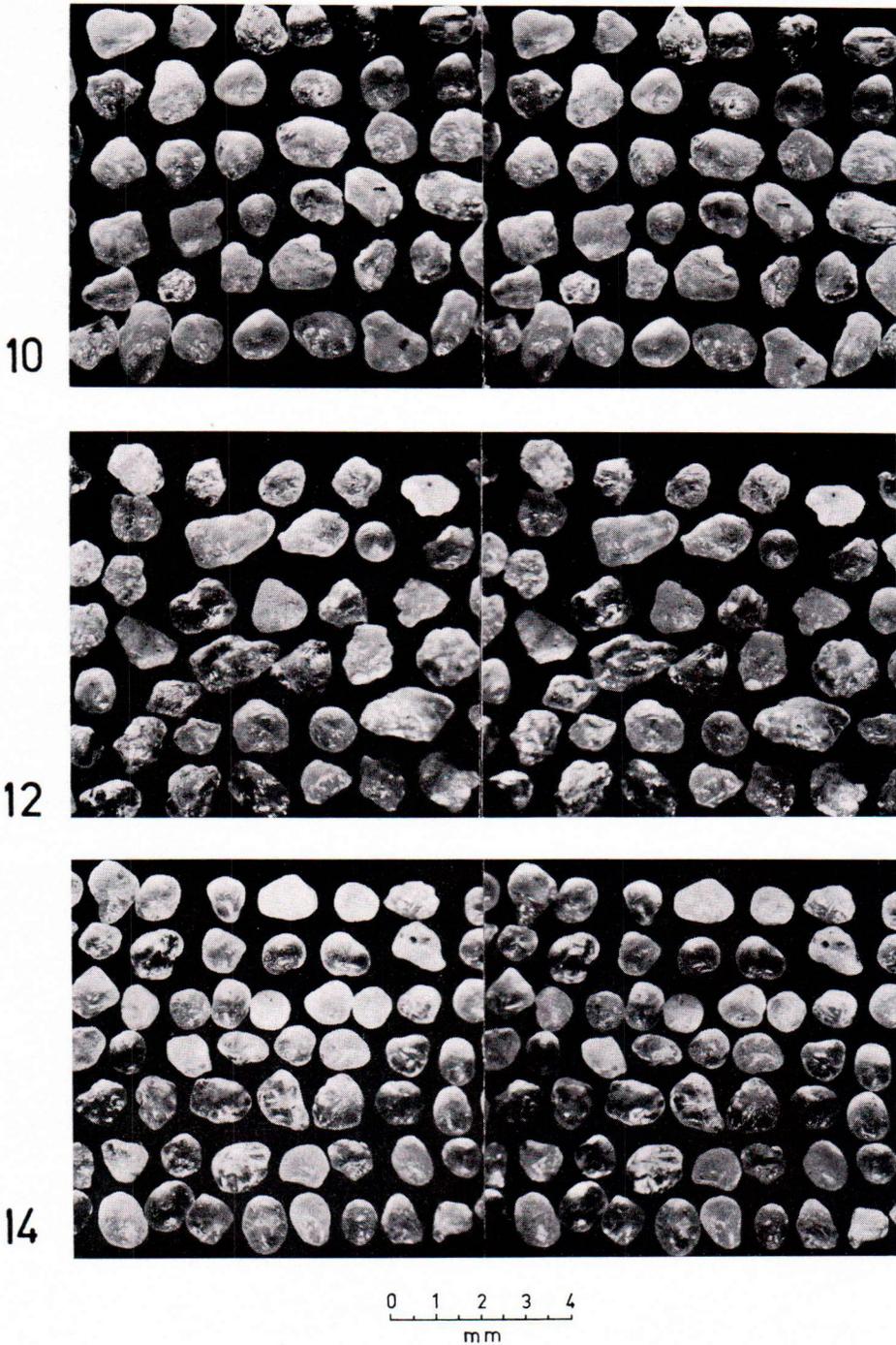


Fig. 8. Stereophotos of some quartz grains of wind-blown sands in the following samples: 10 Kalajoki, Finland, 12 Rømø, Denmark, and 14 Obrowo, Poland. Photographed by the author.

The relatively big number of grains with mat and semi-mat surfaces in the weakly rounded samples from Northern Finland is due to the cold weather and frosting, and the wind has nothing to do with this kind of occurrence of mat surfaces. The very essence of the wind action is the fact that it makes edges round while it dims the surface of the grain. This problem has been investigated thoroughly by Cailleux (1942) and Kuenen & Perdok (1962) among others.

The abundance of the grains with mat surfaces in samples No 9 and 10 is explained by the below examination of the origin of the material. The surface of the grains has not, in this case either, been dimmed by the Postglacial wind action which formed the dunes, but we must go back to much earlier processes.

In Hungary the material is dimmed rather strongly by the wind, whereas most quartz grains from Rømø are brilliant grains originating in relatively young glaciofluvial sediments.

The wind activity typical of the area of Poland is emphasized clearly at the examination of the surface of the quartz grains. It is even difficult to find a wholly brilliant quartz grain in a Polish drift sand (fraction 1.0—0.707).

## Discussion

The grain size and sorting of wind-blown sands depend primarily on the velocity of wind and on the sedimenting conditions. The higher the velocity of the wind is, the bigger grains begin to move off, and the further do the small grains fly. At the loess sedimentation, for instance, the velocity of the wind must have been low. The fact that the wind blowing at a certain velocity carries grains of a given size and weight has been utilized by various scientists (*e.g.* Sokolów 1894, Carroll 1939, Bagnold 1965, Pernarowski 1959) at the measurements of the interdependence between the velocity of wind and the grains size. On the basis of these measure-

ments, conclusions can be drawn on the climate conditions during the formation of the fossil dunes when the grain size of the material is known.

The rest friction and the motive friction of a rounded material are smaller than those of an angular material, and, consequently, rounded grains do not require so swift a wind to move, as is required by the angular grains of the same size. It follows that, at the accumulation of weakly abraded Finnish drift sands, the velocity of wind has been higher than at accumulation of the well rounded Polish sands. It has been suggested in Poland that the velocity of dune-forming winds has been 5—6.8 m/s (Pernarowski 1959 p. 60), and 6—9 m/s (Dylikowa 1958 p. 263—265, Table 1) as measured on the surface of the earth. At the accumulation of the Finnish dunes the velocity of wind will have been 6—7 Beauforts.

A phenomenon almost regularly to be noticed in Finland is that wind-accumulated formations have come into existence in every place that has provided, in favourable climate conditions, a material having the grain size suitable to the velocity of the wind. Thus it can be asserted that the present differences in the grain sizes of drift sands are due to the differences in the grain sizes of the mother material rather than caused by the sorting activity of the wind. To the knowledge of the present writer, there is not a single case in which the material of dunes would have separated directly from *e.g.* boulder clay or till without any fluvial or coastal processes.

Wind action is the strongest of the factors rounding fine fractions (Kuenen 1959, 1960, 1964, Kuenen & Perdok 1962). The difference between the wind and the water influence can be seen most clearly in the grains whose diameter is 0.7 mm (Cailleux 1952 p. 18), and the roundness of the grains is biggest in the coarsest grade decreasing rapidly in the finest sand (Carroll 1939 p. 22). The influence of deflation is bigger on big, rolling grains than on small ones moving suspended in the air. For these reasons it is not

sensible to examine any smaller fractions of the aeolian material than the one of 0.7 mm. The quartz grains are of the greatest importance in the investigation since quartz is the hardest of the ordinary minerals of sand. Besides, quartz splits upon crushing both into concave and convex surfaces, and it does not observe any cleavage planes like feldspar.

The Lappish drift sands are in the neighbourhood of the rock from which the material originally separated as a result of frost weathering and glacial abrasion. Glaciofluvial processes were the main factor in the sorting of Finnish sands. An important role, though a secondary one, was also played by fluvial and beach processes. All these three, however, left the grains rather unrounded. The final phase was that wind carried the Finnish sands, which, in most cases, only meant accumulating the glaciofluvial material into dunes closely connected with deltas, eskers, kames, and beaches. According to Cailleux (1942 p. 109), the sand must be under the influence of recurrent aeolian processes for a very long time before the greater part of the grains are formed into ballshaped ones. Kuenen (1960) thinks that the complete rounding of quartz grains requires that they are carried by wind for hundreds of kilometres.

The relatively big abrasion index of the Oripää (No 9) and Kalajoki (No 10) samples as compared with the other Finnish drift sands is explained by the fact that the sand of Oripää originates from the Jotnian arkose sandstone of Satakunta, and that of Kalajoki has got ingredients from the Postarcean sandstones on the bottom of the Gulf of Bothnia (Okko 1949 p. 37), in which, according to Veltheim (1958 p. 20), aeolian variations can be noticed. Thus, considering their Finnish backgrounds, the Oripää and Kalajoki samples contain plenty of grains with mat surface. On the other hand, it is surprising that the sample from Säskylä (No 7) is not more rounded, though the material partly originates from the sandstone of Satakunta.

Fluvial processes have mainly dominated the accumulation of sands in Hungary. This is shown by the vast alluvial fan between the Danube and the Tisza. On the other hand, 25 % of the area of Hungary is covered with drift sands (Borsy 1965b p. 85) which are, however, originally fluvial. The weakness of aeolian processes is indicated by the accumulation of thick loess layers. During the culminations of the glacial periods, too, Hungary was a periglacial steppe whose vegetation partly impeded wind action. For these reasons, the drift sands in Hungary are often not even so well rounded as the one in sample No 11 Ágasegyháza (*cf.* Borsy 1965 a). However, the wind-carried distance of a couple of kilometres proposed by Borsy (1965 a p. 16) in the interfluvial area of the Danube-Tisza is not sufficient to round and dim the grains even as much as this.

The dune formations on the coast of Jylland are apparently very young as such because the quartz grains are not more rounded. The material is originally glaciogenic. Though the area of Rømø was not covered by the continental ice during the final glaciation (Würm), the sands of the area did not move any long distances with the wind because they were covered by the sea many times. The best-rounded grains in the Rømø sample probably date back to older deposits.

The well rounded Polish drift sands have gone through several sorting processes carried out by water and wind. The area is situated at the marginal area of the Scandinavian ice cap where the margin of the ice was oscillated (Galon & Roszkówna 1961). There are in Poland plenty of Early Tertiary and Mesozoic sediments containing quartz grains which have rounded a long time ago. These were broken off by weathering, and now form part of the sand. Further, every glaciation brought to Poland its own portion of sand which had been previously under the influence of abrasion in Scandinavia. The many Rapakivi stones found in Poland bear an evidence of the transfer of sediments. Afterwards the materials were sorted many times by the

glaciofluvial and fluvial forces. Poland has been several times a periglacial zone (Jahn 1956), which notably has a strong wind activity owing to the scantyness of vegetation. The plainness of the area further contributed to the aeolian activity (Cailleux 1942 p. 109). A clear evidence of the manyfolded accumulation of the material is provided by the rounded, winddimmed quartz grains which occur in the Polish moraines (Cailleux 1942 p. 81—82). According to Cailleux (1942 Fig. 16), Poland has been an optimal area for wind action, which is also proved by many ventifacts.

The smallness of the heterogeneity index  $N_m$  in the samples (Fig. 9) indicates that all the grains of these drift sands represent approximately the same phase of abrasion, whereas the Polish samples are very unhomogenous. This is explained by the fact that the material represents several ages and, accordingly, consists of quartz grains which represent different stages of abrasion.

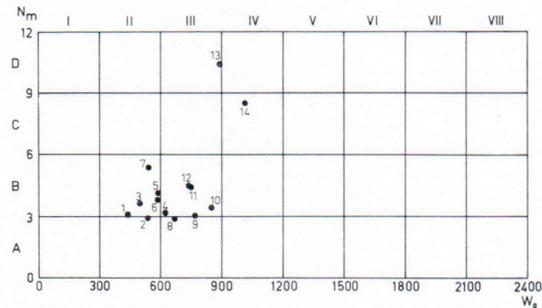


Fig. 9. Rectangular graph showing the abrasion grade  $W\%$  and graniformametrical heterogeneity  $N_m$  of the analysed samples. See also Table 3.

When investigating the roundness of the grains in sediments, it is very easy to find out the present stage of abrasion. The matter changes into a complicated one when trying to explain on the basis of the observations, by which factors, and when, this abrasion was caused. Often it is totally impossible to say whether the mineral material originally separated from the rock (and from which rock?) as a result of a chemical or a

physical weathering. This thing, as well as chemical corrosion, has its own influence on the grain shape. Especially in Central Europe, it is very difficult to say how many sorting processes, and which of them, a given material has gone through before its latest accumulation. According to the findings of the present writer, many of the totally ball-shaped quartz grains in the drift sands were shaped in the Preglacial time.

## Conclusions

The Finnish drift sands do not show any marked difference in the grain size from the Central European ones. The present writer divides dune sands into three groups on the basis of the grain size: 1) coarse sands containing more than 10 weight % grains bigger than 0.6 mm in diameter; 2) semicoarse sands containing less than 30 weight % grains smaller than 0.2 mm in diameter, and 3) fine sands with more than 30 weight % grains smaller than 0.2 mm. Besides the velocity of wind, the factor having the most important influence (in Finland) on the difference in the grain sizes is the grain size of the mother material.

The samples taken from Southern Finland were best sorted. There were, however, no big differences between the various samples.

Finnish drift sands are generally weakly rounded when compared with the Central European ones. This may be caused by the fact that the Finnish material has been primarily broken off from the rock by frost weathering and glacial abrasion. Considering the fresh surfaces of the stones in boulder clay and gravel, there has been little chemical weathering. Glaciofluvial action seems to have been the primary sorting factor. The third and the most important reason for angularity is the fact that the wind has carried the, from the geological point of view, young sand for just short distances. The well rounded quartz grains in the Finnish samples obviously originate from sand stone.

In the present writer's opinion the considerable rounding in the Polish sands is also partly due to the high age of the sediments, and thus already caused by the several fluvial and aeolian sorting processes in the Preglacial time. A knowledge of the age of a fossil dune does not imply the knowledge of the age of the material in the dune.

Plenty of detailed information and experimental investigation is still needed for solving the problem of sorting and rounding processes. Further, the geological structure of the area, and the weathering and sorting factors must be known thoroughly before we can arrive at any unambiguous palaeogeographical conclusions on the basis of the present roundness of the grains.

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