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Formentwicklung der Trondhjemitgerölle auf den Stranden der südwestichen Küste Finnlands

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Résumé de l'article

Cet article porte sur l'étude de la morphométrie des galets et des blocs de trondhjémite provenant de tills et d'eskers ainsi que de plages de matériel morainique et d'eskers de la région d'Airisto. Les indices d'arrondi, de sphéricité et d'aplatissement-allongement de 2000 galets et blocs dont la taille variait de 16 à 256 mm ont été mesurés. Aux sites choisis, l'énergie développée par les vagues étant plutôt faible, le soulèvement du terrain a rendu ces endroits hors d'atteinte des forces littorales en un temps relativement court (environ 800 ans pour la partie supérieure de la plage). Des trois indices, l'indice d'arrondi est celui qui varie le plus (0,30 - 0,72). L'indice d'aplatissement-allongement présente également des variations importantes (-0,66 à + 1,43). L'indicateur le moins important, mais tout de même utile, est celui de la sphéricité qui présente la plus petite variation (0,69 - 0,78). La progression de l'arrondi et la diminution de l'aplatissement allongement sont le résultat de l'abrasion provoquée par le glissement et le roulement des galets et des blocs dans les zones de brisants et de déferlement. Dans les plages de matériel morainique constituées d'un mélange de cailloux et de blocs, les galets (16-64 mm) sont plus discoïdes, tandis que les blocs (64 - 128 mm) le sont davantage sur les plages d'esker.

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SHAPE DEVELOPMENT OF TRONDHJEMITE PEBBLES AND COBBLES ON SHORES IN THE SOUTHWESTERN FINNISH ARCHIPELAGO

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ABSTRACT The morphometry of trondhjemite pebbles and cobbles from till and esker material and from moraine-shore and esker-shore material was studied in the Airisto area, SW Finnish Archipelago. The maximum projection roundness, sphericity, and oblate-prolateness were measured on 2000 pebbles and cobbles in the 16-256 mm size range. Wave energy was low at the study sites, which owing to land uplift rise beyond the reach of littoral forces in a relatively short time (the upper beach over a period of about 800 years). Of the three indices, roundness shows the greatest variation, from 0.30 to 0.72. The oblate-prolate index also showed significant variations (−0.66 – + 1.43). The poorest indicator, but not entirely useless as a discriminatory tool, is the sphericity index, which showed least change (0.69 – 0.78). The increase in roundness and decrease in oblate-prolate index are predominantly the results of abrasion caused by the sliding and rolling of pebbles and cobbles to and fro over sand and gravel in the breaker and swash zones. On mixed gravel-cobble shores from till pebbles (16-64 mm) were most disc-like while cobbles (64-128 mm) were most disc-like on esker shores.

RÉSUMÉ *L'évolution morphométrique des galets et des blocs de trondhjémite sur les plages de l'archipel au sud-ouest de la Finlande.* Cet article porte sur l'étude de la morphométrie des galets et des blocs de trondhjémite provenant de tills et d'eskers ainsi que de plages de matériel morainique et d'eskers de la région d'Airisto. Les indices d'arrondi, de sphéricité et d'aplatissement-allongement de 2000 galets et blocs dont la taille variait de 16 à 256 mm ont été mesurés. Aux sites choisis, l'énergie développée par les vagues étant plutôt faible, le soulèvement du terrain a rendu ces endroits hors d'atteinte des forces littorales en un temps relativement court (environ 800 ans pour la partie supérieure de la plage). Des trois indices, l'indice d'arrondi est celui qui varie le plus (0,30 – 0,72). L'indice d'aplatissement-allongement présente également des variations importantes (−0,66 à +1,43). L'indicateur le moins important, mais tout de même utile, est celui de la sphéricité qui présente la plus petite variation (0,69 – 0,78). La progression de l'arrondi et la diminution de l'aplatissement allongement sont le résultat de l'abrasion provoquée par le glissement et le roulement des galets et des blocs dans les zones de brisants et de déferlement. Dans les plages de matériel morainique constituées d'un mélange de cailloux et de blocs, les galets (16-64 mm) sont plus discoïdes, tandis que les blocs (64 – 128 mm) le sont davantage sur les plages d'esker.

ZUSAMMENFASSUNG *Formentwicklung der Trondhjemitgerölle auf den Stranden der südwestichen Küste Finnlands.* Die Morphometrie der Trondhjemitgerölle im Geschiebe- und Osermaterial wie auch im Moränenstrand- und Oserstrandmaterial wurde im Gebiet Airisto in den Schären süd-west Finnlands untersucht. Die Maximumprojektion die Rundungs-, Kugeligkeits- und Oblate-Prolate-Index-ziffer betreffend wurde an 2000 Steinen gemessen, deren Grösse zwischen 16 und 256 mm lag. Die Wellenenergie war gering an den Undersuchungsstellen, die auf Grund der Landhebung in ziemlich kurzer Zeit für Strandkräfte unerreichbar wurden (der obere Teil des Strands in *ca.* 800 Jahren). Unter den drei Indexziffern zeigte die Rundung am meisten (0.30 – 0.72). Der Oblate-Prolate-Index zeigte auch eine bemerkenswerte Abwechslung (−0.66 – + 1.43). Der schlechteste Index, aber nicht völlig nutzlos als diskriminierendes Mittel ist der Kugeligkeits-Index, der am wenigsten Abwechslung zeigte (0.69 – 0.78). Die Zunahme der Rundung und die Abnahme der Oblate-Prolate-Indexziffer hängen in erster Linie von der Abrasion ab, die durch das hin und her Gleiten und Rollen des Gerölls auf Sand und Kies in Brandungs- und Spülungszonen entsteht. Auf den gemischten Kies-Geröllmoränenstränden waren die Gesteinstücke von den zwei kleinsten Dimensionen (16 – 64 mm) am meisten Diskus ähnlich, während auf den Oserstränden die von den mittleren Dimensionen die grösste Ähnlichkeit mit einem Diskus zeigten.

INTRODUCTION

Studies dealing with the shape development of shore pebbles and cobbles have been made mainly on ocean shores (*e.g.* CLARK *et al.*, 1912; WENTWORTH, 1919, 1922b; MARSHALL, 1928, 1930; CAILLEUX, 1945, 1961; TRICART, 1951; TRICART and CAILLEUX, 1953; CAILLEUX and TRICART, 1959; BLATT, 1959; MOSS, 1963; BLUCK, 1967; DOBKINS and FOLK, 1970) and only a few on lake shores (*e.g.* GROGAN, 1945). A few studies have been made in laboratories (*e.g.* RAYLEIGH, 1942, 1943, 1944; KUENEN, 1956, 1964; FLEMMING, 1964). In Finland HELLAAKOSKI (1930) and KAITANEN and STRÖM (1978) are the only persons who have studied the shape changes of pebbles and cobbles. Their studies have been made on uplifted shores of the ancient Baltic.

Most scholars have taken the view that waves sort pebbles and cobbles by shape and that discs accumulate high on the beach and spheres at the foot of the beach (*e.g.* KRUMBEIN and GRIFFITH, 1938; TRICART and SCHAEFFER, 1950; TRICART, 1951; VAN ANDEL *et al.*, 1954; FLEMMING, 1964; KUENEN, 1964; BLUCK, 1967). CAILLEUX (1945, 1961), however, demonstrated that the greater flatness of beach pebbles was due to marine wear. Also according to DOBKINS and FOLK (1970) abrasion is the chief reason for the abundance of discs on the beaches, though shape sorting is also important on some low-wave-energy shores; sandy beaches also tend to trap discs selectively. KAITANEN and STRÖM (1978) also found that abrasion creates discoidal shore pebbles. The aim of the present study is to explore the abrasion of shore pebbles and cobbles on moraine- and esker-generated stony shores in the southwestern Finnish Archipelago and the shape development of pebbles and cobbles, using crystalline equidimensionally-wearing trondhjemite clasts as research material. Trondhjemite is a potash feldspar-free granodiorite, usually very low in ferromagnesian minerals. Moraine shores are formed on till material transported and deposited by continental ice and esker shores on the slopes of eskers.

STUDY AREA AND METHODS

Pebbles and cobbles were measured on 19 beaches in Airisto Sound in the SW Finnish Archipelago (Fig. 1). Four size classes: 16-32 mm, 32-64 mm, 64-128 mm, and 128-256 mm (from $-4\ \phi$ to $-8\ \phi$) were examined, and only trondhjemite clasts were chosen because they wear homogeneously and are devoid of noticeable bedding or crystal orientation. Trondhjemite is also a common rock type in the study area and also in the area from which the continental ice sheet came (HIETANEN, 1947, p. 1033-1051; HÄRME, 1960, p. 27-33). Of the beaches studied 15 were formed in till and 4 in eskers. In addition trondhjemite pebbles and cobbles from 3 esker gravelpits and 3 building sites in till areas were measured in order to compare their shape with that of the beach pebbles and cobbles.

At each site 20 pebbles or cobbles from each size class were measured, making a total of 80 stones per site[1]. The three perpendicular dimensions L, I and S (long, intermediate, and short) of each stone were measured. In addition the diameter of curvature of the sharpest corner (D_k) and the diameter of the largest inscribed circle (D_i) in the maximum projection plane of the stone were also recorded (DOBKINS and FOLK, 1970, p. 1174-1175). The measuring point was selected at random at each study site. Through this point a tape-measure was passed at right angles to the shoreline, and the nearest 4 trondhjemite clasts of each size class were taken at five points; at depths of 50 cm (outer inshore) and 20 cm (inner inshore) below the mean water level, from the mean water level shoreline (lower foreshore), from the middle beach (upper foreshore), and from the upper beach (backshore) (PYÖKÄRI, 1979, p. 16). Shape-sorting bias caused by waves was avoided by making morphometric measurements on pebbles and cobbles from the breaker zone to the upper beach (*cf.* DOBKINS and FOLK, 1970, p. 1172-1173; KAITANEN and STRÖM, 1978, p. 25). In the case of eskers and till the measuring point in an excavation site was selected at random and 20 trondhjemite clasts of each size class nearest the measuring point were selected.

The indices of DOBKINS and FOLK (1970) were chosen for this work, because the values of these indices correlate best with the settling velocities of particles of different forms. Their roundness (R_{WI}) is more objective than other indices (WENTWORTH, 1919; WADELL, 1932; CAILLEUX, 1947; KUENEN, 1956) and combines the indices of Wentworth and Wadell. Their sphericity index (Ψ_P) compares the maximum projection area of a particle with that of a sphere of the same volume. Therefore Ψ_P gives a much better indication of the true hydraulic behaviour of rod-like vs. disc-like pebbles or cobbles than other sphericity of flatness indices (WENTWORTH, 1922a; WADELL, 1932, 1934; CAILLEUX, 1945; COREY, 1949). The correlation between Ψ_P and the settling velocity is +0.97 (SNEED and

1. Samples of 20 pebbles or cobbles from each size class from each study site is adequate for statistical use because in this study account is only taken of how the shape of *trondhjemite clasts* (*i.e.*, a crystalline isotropically-wearing rock type) changes on shores. Furthermore, the means and differences were calculated from the total amount in each size class and the differences were tested by Student's test (*t* test) when comparing the means.

FOLK, 1958, p. 120). Because sphericity measures the settling velocity of a particle relative to a sphere, when a thick disc and a thin rod may have the same sphericity value, another index is needed to indicate the oblateness vs. prolateness of a particle (SNEED and FOLK, 1958, fig. 6). The oblate-prolate index ($\overline{OP}$) of DOBKINS and FOLK (1970) indicates the differences in the settling velocity of these particles. Perfect blades have $\overline{OP} = 0.00$, all discs where the I axis is closer to the L axis have negative $\overline{OP}$ values, and all rods where the I axis is closer to the S axis have positive $\overline{OP}$. The $\overline{OP}$ index is also better than the indices of ZINGG (1935) and WILLIAMS (1965). Zingg has too few form classes to be useful (see KAITANEN and STRÖM, 1978, p. 41-45) and in Williams' index a very thick disc has the same value as a thin rod.

In the study area there are considerable quantities of equidimensionally-wearing trondhjemite clasts, which

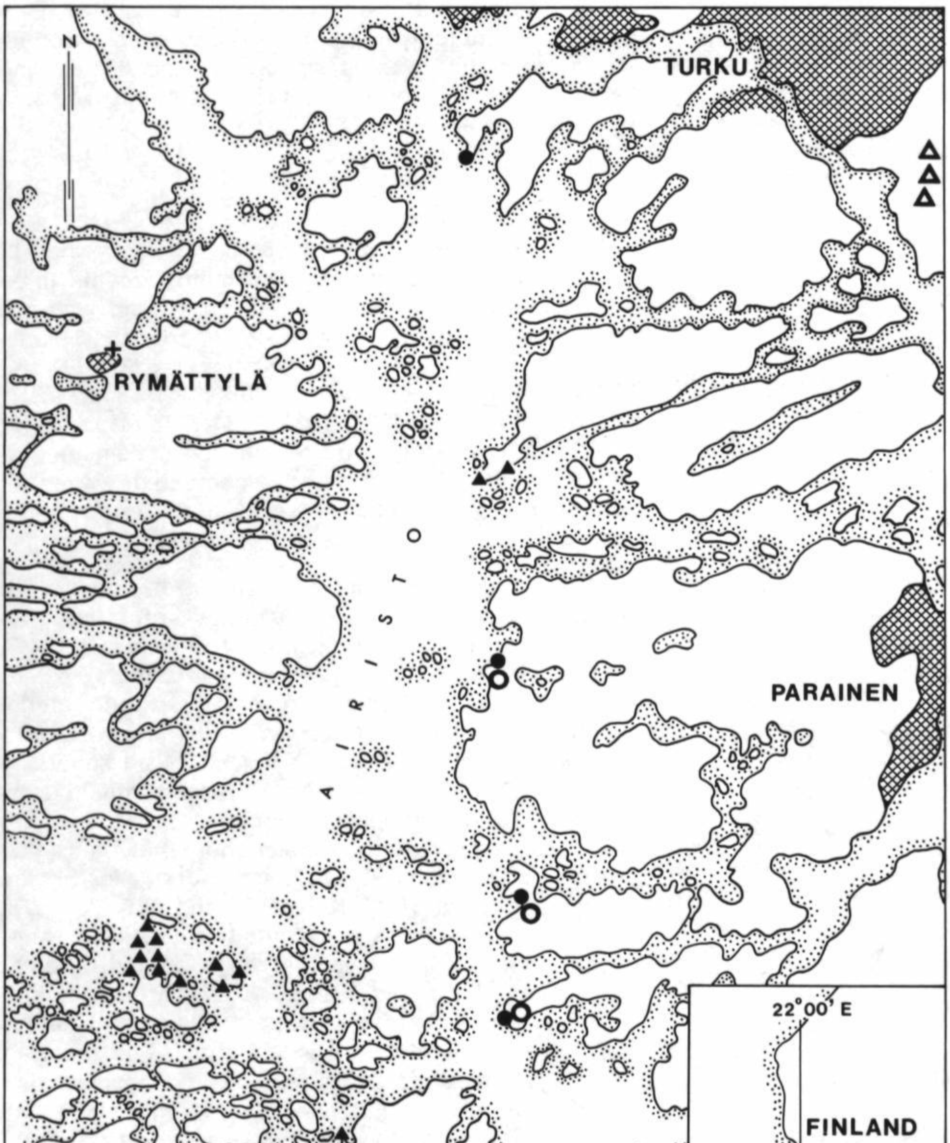

FIGURE 1. Location map of the study area in SW Finnish Archipelago and research sites. Open triangles = till; filled triangles = moraine shores; open circles = esker; filled circles = esker shores.

Carte schématique de la région étudiée dans l'archipel au sud-ouest de la Finlande et localisation des sites. Triangles = till; triangles noirs = plages de matériel morainique; cercles = eskers; cercles noirs = plages d'esker.

facilitates the observation of shape changes under the influence of shore forces. The study area belongs to the uplift area of the Baltic Shield, and land uplift in the area is at present 5 mm per year (KÄÄRIÄINEN, 1964, p. 18-19). Due to land uplift the shores have been subjected to the effects of shore forces for about 800 years; of this the effective period for the wearing of pebbles and cobbles is at most 200 years, after which abrasion is slight. Finally the shores rise above the reach of shore forces. Airisto Sound, on the shores of which the research sites are located, is about 20 km long and 3-8 km wide. In addition, there are numbers of islands in the southern part of the sound, so that the wind fetch lengths in the area are relatively short. The shores are thus typical low-wave-energy shores (*cf.* DOBKINS and FOLK, 1970, p. 1173). Cyclonic activity in northern Europe and the balance between marine and continental air masses at the margin of the continent cause wind situations of different origin and durations in the area. Southerly and southwesterly winds prevail, however, and during heavy storms the wave heights are about 100-110 cm. The tidal range is only a few centimetres. The shores are frozen for 3-4 months each year. Ice abrasion in the area is, however, very insignificant because the period when the ice breaks up into ice-floes is short and wind fetches are short. The thermal movement of ice cover in winters is also insignificant (PYÖKÄRI, 1978a). Ice has mainly a sheltering effect on shore material in the area. The shores studied range from stony moraine shores, where there is very little fine material between the stones, to mixed gravel-cobble shores from till and esker, where the proportion of fine loose material between the stones is considerable (PYÖKÄRI, 1978b, p. 84-85; 1979, p. 13-16).

RESULTS

ROUNDNESS

In this study roundness has been defined as Modified Wentworth Roundness, $R_{Wt'} = D_k/D_i$, where D_k is the diameter of curvature of the sharpest corner and D_i the diameter of the largest inscribed circle in the maximum projection plane (DOBKINS and FOLK, 1970; *cf.* WENTWORTH, 1919; WADELL, 1932; CAILLEUX, 1947; KUENEN, 1956).

Mean roundness is smallest (0.34 ± 0.01) in till and greatest (0.66 ± 0.01) in esker-shore material (*cf.* DIONNE, 1973, p. 139; SEPPÄLÄ, 1976, p. 88-89; KAITANEN and STRÖM, 1978, p. 40). Roundness increases highly significantly ($t = 14.6^{***}$) from till to moraine-shore material and fairly significantly ($t = 2.1^{*}$) from esker to esker-shore material (Table I, Fig. 2). Mean roundness is 0.49 ± 0.01 for moraine-shore pebbles and cobbles, but the pebble classes (16-32 mm and 32-64 mm) are more rounded than the cobble classes (64-128 mm and 128-256 mm). While the most rounded cobbles on esker shores fall in the size class 64-128 mm, the pebbles of the smallest size class are least rounded (Fig. 2). The differences in roundness between source area pebbles and cobbles (till and esker material) and shore pebbles and cobbles are very similar in all size classes. The differences between till and shore pebbles and cobbles from till are 0.12-0.18, which are highly significant ($t = 6.4^{***} — 8.3^{***}$). Between esker and esker-shore material the differences in roundness are 0.03-0.05, but they are not statistically significant (in size class 32-64 mm symptomatic, $t = 1.7^{\circ}$). The difference in both shore types, however, is smallest in the largest and second smallest in the smallest size class; it is largest in the size class 32-64 mm.

SPHERICITY

Maximum Projection Sphericity, $\Psi_p = \sqrt[3]{S^2/LI}$, where L, I, and S (long, intermediate, and short) are the three dimensions perpendicular to each other and where L and I were measured on the maximum projection plane, was used to calculate the sphericity index (SNEED and FOLK, 1958; DOBKINS and FOLK, 1970; *cf.* WENTWORTH, 1922a; WADELL, 1932, 1934; CAILLEUX, 1945; COREY, 1949). Using this formula the maximum projection area of a stone is compared with the corresponding projection area of a sphere with the same volume.

Mean sphericity is at its minimum (0.71 ± 0.01) in till, and at its maximum (0.75 ± 0.01) in esker material. The result is similar to the result of KAITANEN's and STRÖM's study (1978, p. 37). Sphericity increases highly significantly ($t = 3.4^{***}$) from till to moraine-shore material and decreases fairly significantly ($t = 2.4^{*}$) from esker to esker-shore material (Table II, Fig. 3). Mean sphericity is 0.73 ± 0.00 for moraine-shore trondhjemite clasts, but sphericity decreases from the smallest to the largest size class. The sphericity of esker-shore material is also greatest in the smallest size class and smallest in the largest class (Fig. 3) (*cf.* KAITANEN and STRÖM, 1978, p. 37). The differences in sphericity from till to shore pebbles and cobbles from till range, in the different size classes, from −0.00 to +0.05, the greatest differences being in the size classes 32-64 mm (highly significant, $t = 3.4^{***}$) and 64-128 mm (significant, $t = 2.8^{**}$). From esker to shore pebbles and cobbles from esker the range varies between −0.01 and +0.04; the differences increase towards the largest size class and the greatest difference is fairly significant ($t = 2.5^{*}$). In the smallest size class the difference is negative (−0.01), *i.e.* the pebbles on the esker shores are more spherical than pebbles in the esker material, but the difference is not statistically significant.

TABLE I

Mean roundness, standard deviations and standard errors of the mean

	Size class in mm				
	16-32	32-64	64-128	128-256	All sizes
Till (3 sites)					
Mean	0.39	0.36	0.32	0.30	0.34
σ	0.13	0.14	0.13	0.12	0.13
m	0.02	0.02	0.02	0.02	0.01
Number	60	60	60	60	240
Moraine shores (15 sites)					
Mean	0.53	0.53	0.48	0.41	0.49
σ	0.17	0.15	0.17	0.17	0.17
m	0.01	0.01	0.01	0.01	0.01
Number	300	300	300	300	1200
Esker (3 sites)					
Mean	0.58	0.64	0.68	0.63	0.63
σ	0.16	0.14	0.16	0.13	0.15
m	0.02	0.02	0.02	0.02	0.01
Number	60	60	60	60	240
Esker shores (4 sites)					
Mean	0.61	0.68	0.72	0.65	0.66
σ	0.19	0.17	0.15	0.17	0.18
m	0.02	0.02	0.02	0.02	0.01
Number	80	80	80	80	320

o = difference symptomatical (5% $< p \leq$ 10%)
* = difference fairly significant (1% $< p \leq$ 5%)
** = difference significant (0.1% $< p \leq$ 1%)
*** = difference highly significant ($p <$ 0.1%)

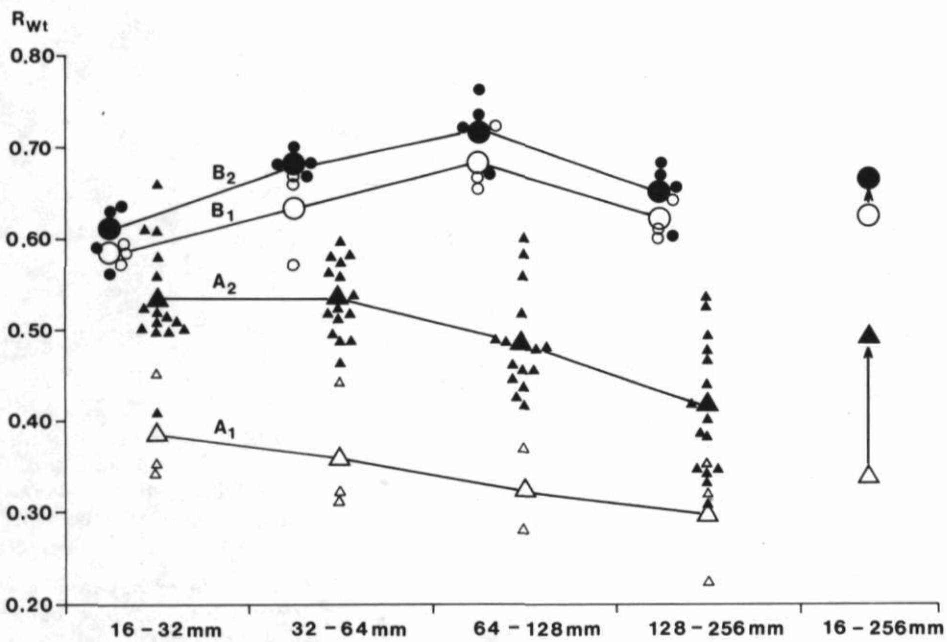

FIGURE 2. Roundness for the four environments, from smaller pebbles (left) to larger cobbles (right). Till, open triangles (A_1); moraine shores, filled triangles (A_2); esker, open circles (B_1); esker shores, filled circles (B_2). Each small symbol represents a mean of twenty pebbles or cobbles from one particular locality; each large symbol is the mean roundness of all pebbles or cobbles of that size in each environment.

L'indice d'arrondi pour quatre milieux donnés, des plus petits galets (à gauche) aux plus gros blocs (à droite). Triangle blanc: till (A_1); triangle noir: plage de matériel morainique (A_2); cercle blanc: esker (B_1); cercle noir: plage d'esker (B_2). Un symbole plus petit représente une moyenne de 20 galets ou blocs pour un site donné; un plus gros symbole représente l'arrondi moyen de tous les galets et blocs d'un milieu donné.

TABLE II

Mean sphericity, standard deviations and standard errors of the mean

	Size class in mm				
	16-32	32-64	64-128	128-256	All sizes
Till (3 sites)					
Mean	0.74	0.69	0.69	0.72	0.71
σ	0.11	0.11	0.10	0.09	0.10
m	0.01	0.01	0.01	0.01	0.01
Number	60	60	60	60	240
Moraine shores (15 sites)					
Mean	0.75	0.74	0.73	0.71	0.73
σ	0.09	0.10	0.10	0.11	0.04
m	0.01	0.01	0.01	0.01	0.00
Number	300	300	300	300	1200
Esker (3 sites)					
Mean	0.77	0.76	0.73	0.74	0.75
σ	0.07	0.09	0.08	0.10	0.08
m	0.01	0.01	0.01	0.01	0.01
Number	60	60	60	60	240
Esker shores (4 sites)					
Mean	0.78	0.74	0.71	0.70	0.73
σ	0.10	0.09	0.09	0.10	0.10
m	0.01	0.01	0.01	0.01	0.01
Number	80	80	80	80	320

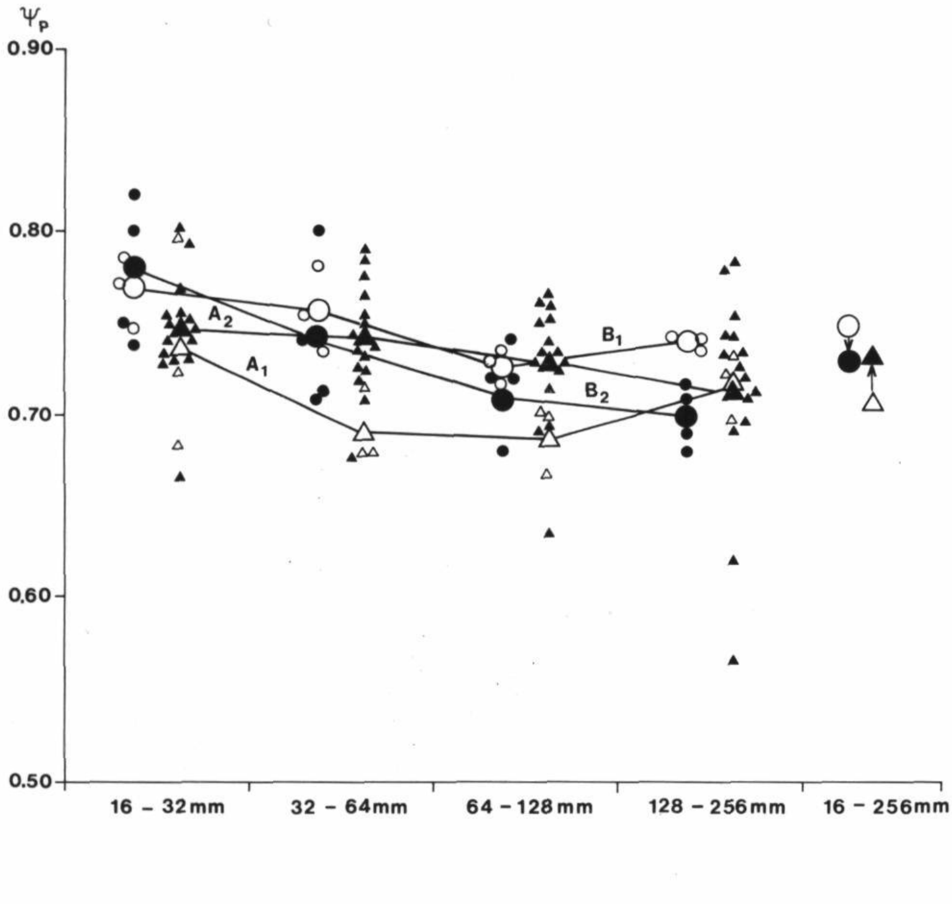

FIGURE 3. Sphericity for the four environments, from smaller pebbles (left) to larger cobbles (right). Symbols as in Figure 2.

La sphéricité pour quatre milieux donnés, des plus petits galets (à gauche) aux plus gros blocs (à droite). Mêmes symboles que ceux de la figure 2.

OBLATE-PROLATENESS

DOBKINS' and FOLK's Oblate-Prolate Index,

$$\overline{OP} = \frac{10\left(\frac{L-I}{L-S} - 0.50\right)}{S/L},$$

was used to determine oblate-prolateness (DOBKINS and FOLK, 1970; *cf.* ZINGG, 1935; WILLIAMS, 1965). The shape of stones with very low sphericity values can be defined with the aid of this formula. A blade-like stone has an $\overline{OP}$ index value of 0.00. The more negative the $\overline{OP}$ value is, the more oblate the stone is in shape, and the more positive the $\overline{OP}$ value is, the more prolate it is. The weakness of the index is its inability to discriminate between widely varying blade-like stones (KAITANEN and STRÖM, 1978, p. 39). The index values in the study area vary between − 16.5 and + 15.4, extreme values being uncommon.

The mean oblate-prolate index is at its minimum (−0.23 ± 0.25) in esker-shore material and its maximum (+1.11 ± 0.28) in till material. The index decreases fairly significantly (t = 2.3*) from till to moraine-shore pebbles and cobbles and from esker to esker-shore pebbles and cobbles (t = 2.3*; Table III, Fig. 4). The result is similar to the results obtained by DOBKINS and FOLK (1970) and KAITANEN and STRÖM (1978). The mean oblate-prolate index for moraine-shore material is 0.46 ± 0.03. The index is negative in the size class 16-32 mm and increases towards the larger size classes. For esker-shore material the index is most negative in the size class 32-64 mm, increasing both towards the smaller and larger size classes. It is greatest in the smallest size class (Table III, Fig. 4). The differences in oblate-prolateness from till to shore pebbles and cobbles from till range, in the different size classes, from −0.00 to + 1.44, the greatest difference being in the smallest size class, where the difference between mean values is also significant (t = 2.8**). In the size class 32-64 mm the difference is nearly symptomatic, but in the larger size classes the differences are not symptomatic. From esker to esker-shore material the range is from 0.36 to 1.76, the differences being greatest and fairly significant in the size classes 32-64 mm (t = 2.3*) and 64-128 mm (t = 2.1*). In the smallest and largest classes the differences are not statistically significant. Pebbles are consequently most oblate on moraine shores in the size class 16-32 mm and on esker shores in the class 32-64 mm and cobbles in the class 64-128 mm.

DISCUSSION

The roundness of trondhjemite clasts on the shores of the study area seems mainly to depend on the roundness of source material (Fig. 2, Table I). Thus trondhjemitic esker pebbles and cobbles are highly significantly (t = 21.6***) more rounded than trondhjemitic till pebbles and cobbles. The difference in roundness is highly significant in all size classes, the difference being greatest in the class 64-128 mm. This difference in roundness can also be seen in beach material from till and esker; the pebbles and cobbles on esker shores are highly significantly more rounded (t = 15.2***) compared with pebbles and cobbles on moraine shores. The difference is greatest in the class 64-128 mm and smallest in the class 16-32 mm.

Because of the short wind fetches the shores in the study area are low-energy shores (Fig. 1); thus any significant differences are unlikely to result from the fetch (*cf.* NORRMAN, 1964, p. 66). On the other hand, when comparing typical moraine-generated cobble shores, where there is little gravel and sand, with moraine-generated mixed gravel-cobble shores, where the proportion of gravel and sand is relatively large, there are highly significant differences in the size classes 16-32 mm (t = 5.4***) and 32-64 mm (t = 4.7***). On gravelly and sandy stony shores pebbles in these size classes are more rounded (Fig. 5). Wave action on mixed gravel-cobble shores obviously moves pebbles more easily and makes them more rounded. Material on typical cobble shores in these size classes settles in the interstices between larger stones and is thus not easily moved (*cf.* DOBKINS and FOLK, 1970, p. 1176-1178).

The difference in sphericity between till and shore material from till and between esker and shore material from esker are small (Fig. 3). However, in the material as a whole esker pebbles and cobbles are highly significantly more spherical (t = 4.7***) than till pebbles and cobbles (*cf.* KAITANEN and STRÖM, 1978, p. 37). In the different size classes of esker material the class 32-64 mm is highly significantly (t = 3.8***), the class 64-128 mm fairly significantly (t = 2.3*), and the class 16-32 mm symptomatically (t = 1.9*) more spherical than in till material. The largest size class does not differ significantly as to sphericity. Pebbles and cobbles on moraine and esker shores in the whole of the material do not differ even symptomatically (t = 0.2); only in the size class 16-32 mm is the difference significant (t = 2.8**), esker-shore pebbles being more spherical. On esker shores consisting of relatively coarse material the pebbles in the smallest size class probably settle into interstices between the large stones as they also do on cobble and stony shores from till. Thus sphericity index is nearly the same for both shore types (Table II, Fig. 3). On the other hand, on shores of till origin, rich in sand and gravel, pebbles (16-32 mm and 32-64 mm) are highly significantly (t = 5.6***, t = 6.2***) less spherical than pebbles on

TABLE III

Mean oblate-prolate index, standard deviations and standard errors of the mean

	Size class in mm				
	16-32	32-64	64-128	128-256	All sizes
Till (3 sites)					
Mean	1.27	1.43	0.68	0.86	1.11
σ	4.15	4.57	4.52	4.26	4.32
m	0.54	0.59	0.58	0.55	0.28
Number	60	60	60	60	240
Moraine shores (15 sites)					
Mean	−0.18	0.51	0.69	0.85	0.46
σ	4.49	4.51	4.34	4.79	1.05
m	0.26	0.26	0.25	0.28	0.03
Number	300	300	300	300	1200
Esker (3 sites)					
Mean	0.45	1.10	0.82	0.95	0.61
σ	3.84	4.39	4.21	4.76	4.29
m	0.50	0.57	0.54	0.62	0.28
Number	60	60	60	60	240
Esker shores (4 sites)					
Mean	0.08	−0.66	−0.34	−0.01	−0.23
σ	4.57	4.48	4.14	4.45	4.40
m	0.51	0.50	0.46	0.50	0.25
Number	80	80	80	80	320

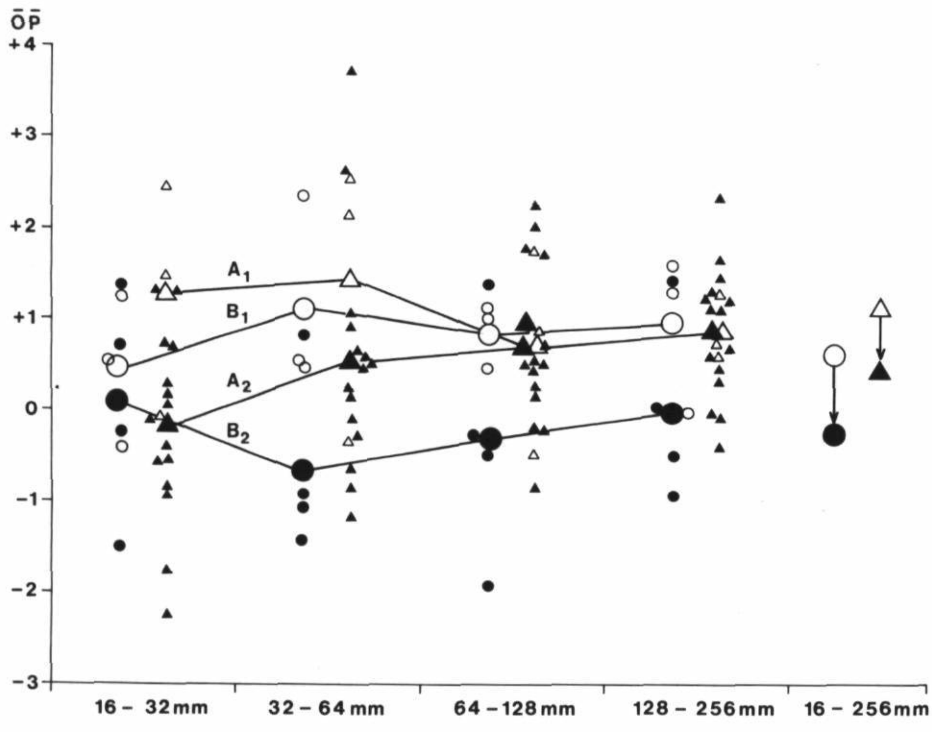

FIGURE 4. Oblate-prolate index for the four environments, from smaller pebbles (left) to larger cobbles (right). Symbols as in Figure 2.

L'indice d'aplatissement-allongement pour quatre milieux donnés, des plus petits galets (à gauche) aux plus gros blocs (à droite). Même symboles que ceux de la figure 2.

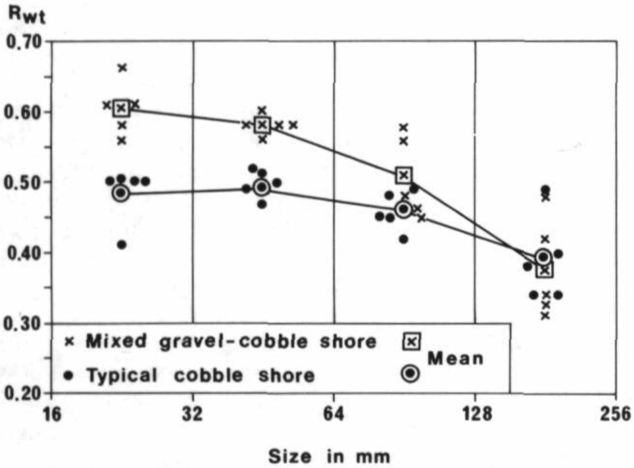

FIGURE 5. Pebbles (16-64) mm) are much rounder on mixed gravel-cobble shores than they are on typical cobble shores; cobbles (64-256 mm) are essentially similar in R_{wt} index in both shore types. Each small symbol represents a mean of twenty pebbles or cobbles from one particular locality; each large symbol is the mean of 100 pebbles or cobbles of that size.

Les galets (16-64 mm) sont beaucoup plus arrondis sur les plages caillouteuses à blocs que sur les plages entièrement constituées de blocs; les blocs (64-256 mm) ont un indice R_{wt} semblable pour les deux types de plages. Un point ou une croix représente une moyenne de 20 galets pour un site donné, tandis que le symbole entouré représente les valeurs moyennes de 100 mesures.

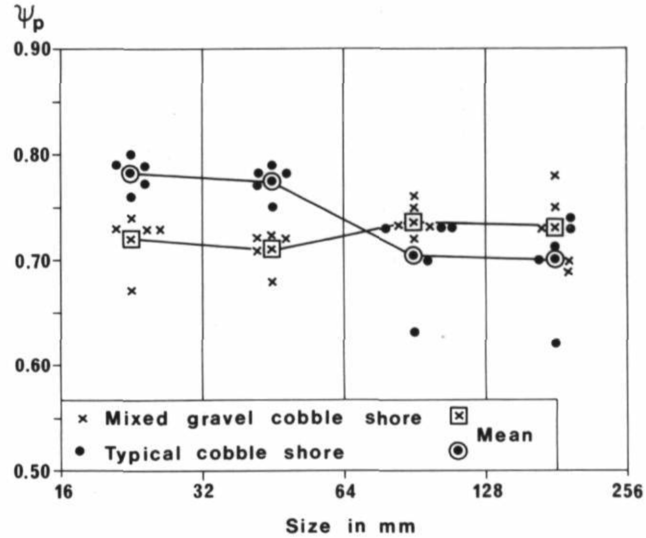

FIGURE 6. Pebbles (16-64 mm) have lower sphericity on mixed gravel-cobble shores than on typical cobble shores; for cobbles (64-256 mm) little sphericity difference exists. Symbols as in Figure 5.

Les galets (16-64mm) ont une sphéricité beaucoup moins prononcée sur les plages caillouteuses à blocs que sur les plages entièrement constituées de blocs; la sphéricité des blocs (64-256 mm) varie peu d'un type de plage à l'autre. Les symboles sont les mêmes que ceux de la figure 5.

stony shores as a result of greater abrasion (Fig. 6) (*cf.* DOBKINS and FOLK, 1970, p. 1181).

The oblate-prolate index decreases from till to moraine-shore material and from esker to esker-shore material (Fig. 4). As to the oblate-prolate index of till and esker material, there are no significant or even symptomatic differences, but in the total material esker-shore pebbles and cobbles are significantly ($t = 2.8^{**}$) and pebbles in the size class 32-64 mm and cobbles in the class 64-128 mm fairly significantly ($t = 2.1^{*}$, $t = 2.0^{*}$) more oblate than moraine-shore pebbles and cobbles. Pebbles in the size class 16-32 mm have been made most oblate on moraine shores and in the size class 32-64 mm on esker shores (Fig. 4). This is particularly the case on mixed gravel-cobble shores from till (Fig. 7). Pebbles in both the pebble classes on these shores are found to be highly significantly ($t = 3.9^{***}$, $t = 4.3^{***}$) more oblate than on typical cobble shores. The result is similar to that of DOBKINS and FOLK (1970, p. 1180).

It can be seen from Figures 2-4 that, as till material comes under the influence of shore forces, the roundness of pebbles and cobbles increases substantially but sphericity only slightly. The sole exception is the size class 128-256 mm, where cobbles become more rounded while sphericity remains the same. Oblateness increases only in the two smallest size classes. As esker material comes under the influence of shore forces, the rounding of pebbles and cobbles is much less, because they are already well-rounded owing to glaciofluvial processes; however, roundness increases and sphericity decreases in all cases with the exception of the size class 16-32 mm, where pebbles only become more rounded and slightly more oblate. In the other size classes of esker material oblateness increases markedly and sphericity decreases, *i.e.* pebbles and cobbles become more disc-like (*cf.* DOBKINS and FOLK, 1970, p. 1193; KAITANEN and STRÖM, 1978, p. 39).

The abundance of gravel and sand in shore material causes more effective abrasion, as a result of which the pebbles take on a more disc-like shape on moraine shores and also cobbles on esker shores (Figs. 3-4) (*cf.* DOBKINS and FOLK, 1970, p. 1188). However, this occurs best on mixed gravel-cobble shores from till in the pebble classes (16-32 mm and 32-64 mm) (Figs. 5-8) because the wind fetch is short and, owing to land uplift, the material is subjected to effective abrasion only for about 200 years. In these size classes pebbles are somewhat more oblate and less spherical

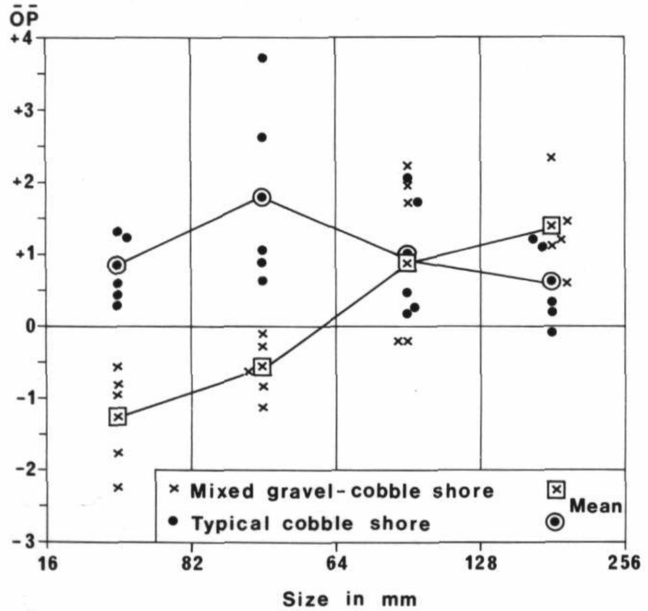

FIGURE 7. Pebbles (16-64 mm) are oblate on mixed gravel-cobble shores while they are prolate on typical cobble shores; cobbles (64-256 mm) are essentially similar (prolate) in $\overline{OP}$ index in both shore types. Symbols as in Figure 5.

Les galets (16-64 mm) sont aplatis dans le cas des plages caillouteuses à blocs tandis qu'ils sont allongés dans le cas des plages entièrement constituées de blocs; l'indice d'aplatissement-allongement ($\overline{AA}$) est à peu près le même pour les blocs dans les deux cas. Les symboles sont les mêmes que ceux de la figure 5.

than pebbles on typical cobble shores (Figs. 6-7; Fig. 8, fields A and B as well as C and D differ from each other). In the larger size classes there are no perceptible differences. On mixed gravel-cobble shores from till pebbles in the smallest size classes are also rather more rounded than pebbles on typical cobble shores (Fig. 5).

Generally it can be said that R_{Wt} and $\overline{OP}$ serve best as discriminators between moraine-shore and esker-shore pebbles and cobbles as sphericity is nearly the same in both shore types. R_{Wt} discriminates till material from moraine-shore material best, those in the latter environment being rather more rounded. On the other hand, Ψ_p and $\overline{OP}$ are less effective discriminatory tools in these environments. The oblate-prolate index discriminates esker pebbles and cobbles from esker-shore pebbles and cobbles best, the latter being more oblate (Figs. 2-4) (*cf.* KAITANEN and STRÖM, 1978, p. 62).

SNEED's and FOLK's (1958) triangle was used to calculate the shape of pebbles and cobbles. In the triangle there are ten three-dimensional form classes, which are given in Figure 9. For each form class the mean value for Ψ_p and $\overline{OP}$ index is also given. The frequency distributions of these ten form classes for till material and moraine-shore material are given in Figure 10 and for esker material and esker-shore material in Figure 11. The dominant form of till material is bladed; indeed in the size class 16-32 mm it is compact-bladed and yet the frequency for compact-elongated is greater than that for the form bladed. The most common form on moraine shores is compact-bladed, but in the largest size class it is compact-elongated. When comparing the frequency distributions of the form classes for till pebbles and cobbles and moraine-shore pebbles and cobbles (Fig. 10), in general it is found that the frequencies of the classes platy, bladed, and elongated decrease and of the classes compact-platy, compact-bladed, and compact-elongated increase from till to moraine-shore material. Probably the platy form changes on moraine shores into the compact-platy form, the bladed form into the compact-bladed and compact-platy forms, and the elongated form into the compact-bladed and compact-elongated forms. This occurs as roundness (Fig. 2) and sphericity (Fig. 3) increase. As oblateness increases (Fig. 4), the shape of pebbles and cobbles develops in general simultaneously in the direction elongated — compact-platy (*cf.* DOBKINS and FOLK, 1970, p. 1196). The predominance of this compact-platy form is best illustrated in the smallest size class (16-32 mm), where pebbles are most mobile (Fig. 10).

The most common form class in esker material is compact-elongated, but the compact-bladed form class has almost the same frequency and it is the dominant form class in the size classes 16-32 mm and 64-128 mm (Fig. 11). On esker shores the most common form class is compact-bladed. When comparing the frequencies of the form classes for esker pebbles and cobbles and esker-shore pebbles and cobbles, it is found in general that the frequencies of the elongated and compact-elongated form classes decrease and the frequencies of the platy, bladed, and compact classes increase most and the compact-platy and compact-bladed classes somewhat on esker shores (Fig. 11). In particular in the size class 32-64 mm the proportions of platy and compact-platy forms increase. In the size class 64-128 mm there are also many platy and bladed forms compared with esker cobbles. The compact-bladed, bladed and compact-platy forms increase in the largest size class (128-256 mm). In the smallest size class the increase in the compact form is striking. Esker pebbles and cobbles thus change under the influence of shore forces from the compact-elongated and elongated forms towards the compact-bladed and bladed forms and further from these to the compact-platy and platy forms. Some material also changes towards the com-

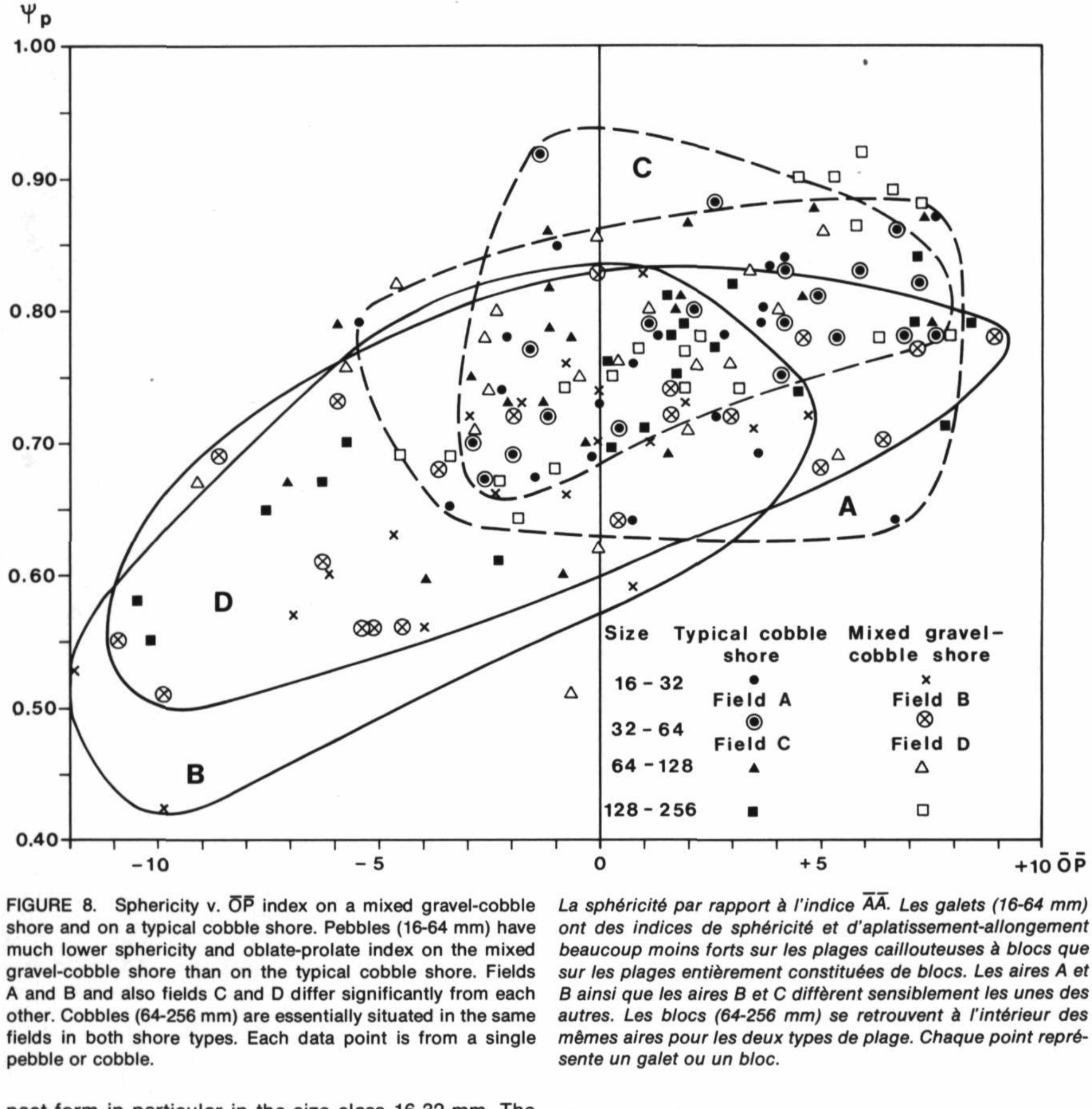

FIGURE 8. Sphericity v. $\overline{OP}$ index on a mixed gravel-cobble shore and on a typical cobble shore. Pebbles (16-64 mm) have much lower sphericity and oblate-prolate index on the mixed gravel-cobble shore than on the typical cobble shore. Fields A and B and also fields C and D differ significantly from each other. Cobbles (64-256 mm) are essentially situated in the same fields in both shore types. Each data point is from a single pebble or cobble.

La sphéricité par rapport à l'indice $\overline{AA}$. Les galets (16-64 mm) ont des indices de sphéricité et d'aplatissement-allongement beaucoup moins forts sur les plages caillouteuses à blocs que sur les plages entièrement constituées de blocs. Les aires A et B ainsi que les aires B et C diffèrent sensiblement les unes des autres. Les blocs (64-256 mm) se retrouvent à l'intérieur des mêmes aires pour les deux types de plage. Chaque point représente un galet ou un bloc.

pact form in particular in the size class 16-32 mm. The changes of shape occur as roundness increases (Fig. 2); sphericity decreases little except in the smallest size class (Fig. 3) and oblateness increases in particular in the size class 32-64 mm (Fig. 4).

In shore pebbles and cobbles from till shape changes occur most in the two smallest size classes, and the development towards the discoidal form occurs in these size classes only on mixed gravel-cobble shores. In general the shape develops from the elongated form class towards the compact-platy form class as roundness simultaneously increases strongly. On shore pebbles and cobbles from esker shape changes occur in all the size classes, but most in the middle ones and least in the smallest size class. This is obviously due to the fact that esker material is more mobile than till material and that the proportion of gravel and sand is greater in esker material, which results in stronger abrasion. In addition, the eskers in the study area are situated in places where the effective fetches are long-

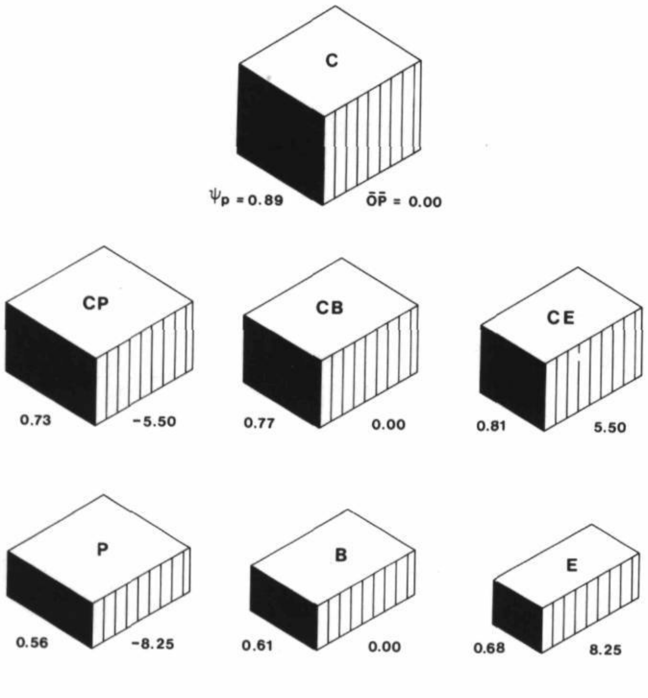

FIGURE 9. Ten form classes of pebbles and cobbles in the study area. C = compact. CP = compact-platy. CB = compact-bladed. CE = compact-elongate. P = platy. B = bladed. E = elongate. VP = very platy. VB = very bladed. VE = very elongate. For each form class the sphericity value and $\overline{OP}$ index are also given.

Les dix classes de galets et de blocs établies en fonction de la forme. C: isodiamétrique; CP: massive-aplati; CB massive-oblongue; CE: massive-allongée; P: aplati; B: oblongue; E: allongée; VP: en plaquettes; VB: en plaquettes oblongues; VE; en plaquettes allongées. Pour chacune des classes de formes, on donne également les indices $\overline{AA}$ et de sphéricité.

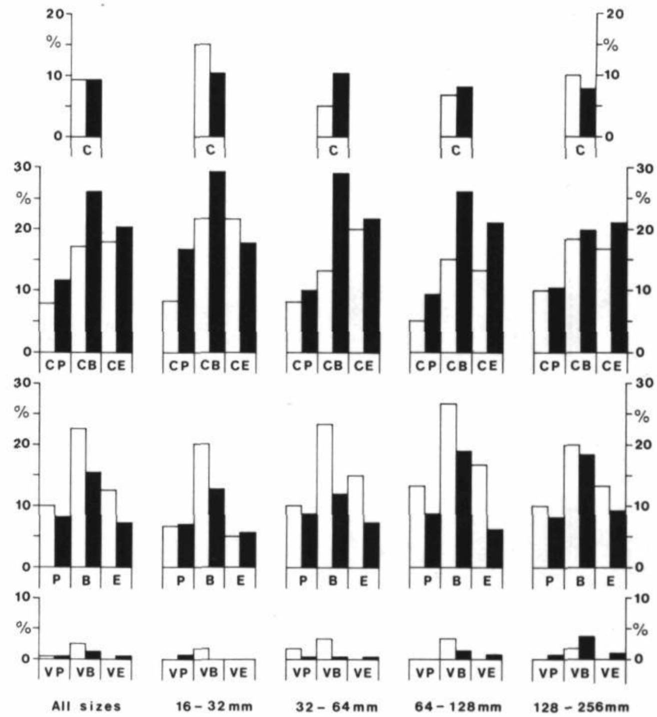

FIGURE 10. Frequency distribution of the form classes for pebbles and cobbles on till and moraine shores. Letter symbols as in Figure 9. White columns = till. Black columns = moraine shores.

Répartition de la fréquence des classes de formes de galets et de blocs sur le till ou une plage de matériel morainique. Les symboles sont les mêmes que ceux de la figure 9. Colonne blanche: till; colonne noire: plage de matériel morainique.

est and wave heights during strong storms are about one metre. The shape development on esker shores is from the elongated form towards the compact-platy and platy forms.

As river pebbles and cobbles are transported to ocean shores their shape develops from the compact-elongated form towards the very platy form, *i.e.* pebbles and cobbles become more discoidal (DOBKINS and FOLK, 1970, p. 1190-1191). In the study area the direction of shape development is, from till and esker material to shore material, mainly from the elongated form to the compact-platy form, *i.e.* the long axis of pebble and cobble shortens in relation to the intermediate axis while the flattening or relative shortening of the short axis is slight. Because the samples were taken at right-angles to the shore over the entire shore profile from a depth of 50 cm (breaker zone) to the upper beach, the shape changes must be due more to abrasion than shape sorting.

In Figure 12 the mean axial ratios of the different size classes for the four environments are presented in three-dimensional form and the pebble or cobble corresponding to them has been drawn as a rectangular block in the figure. Mean roundness is correspondingly shown in the lower half of the figure. The differences in axial ratios and consequently the mean shape changes in different size classes as till and esker pebbles and cobbles are worn by shore forces are small. On the other hand, the corresponding shape changes in roundness are great. The small increases in sphericity and oblateness on moraine-shore material and the decrease

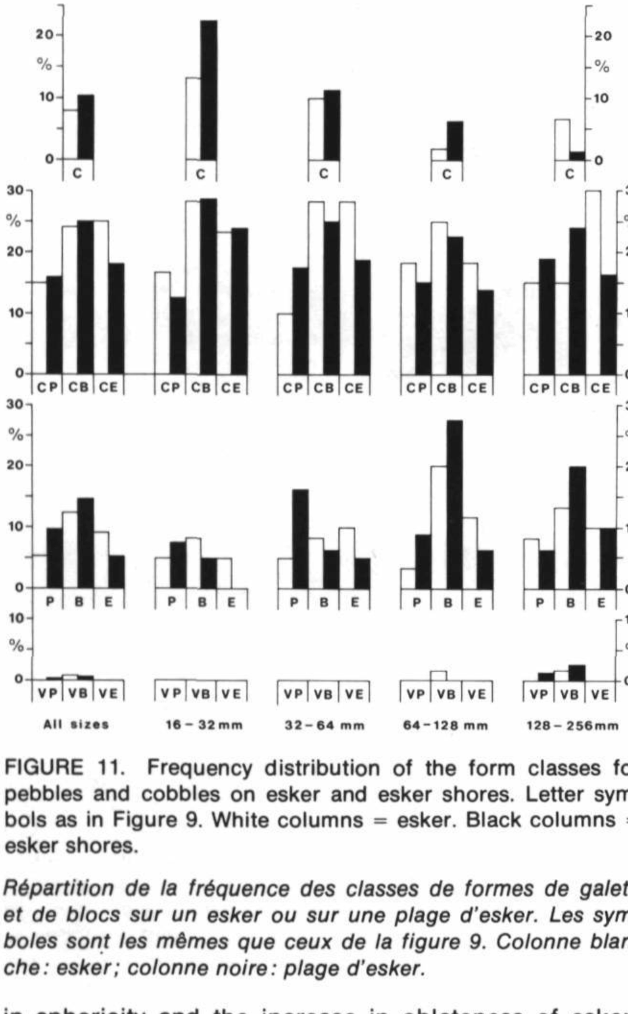

FIGURE 11. Frequency distribution of the form classes for pebbles and cobbles on esker and esker shores. Letter symbols as in Figure 9. White columns = esker. Black columns = esker shores.

Répartition de la fréquence des classes de formes de galets et de blocs sur un esker ou sur une plage d'esker. Les symboles sont les mêmes que ceux de la figure 9. Colonne blanche: esker; colonne noire: plage d'esker.

in sphericity and the increase in oblateness of esker-shore material are not in general found in the mean rectangular blocks in Figure 12. For the most part shore forces cause only an increase in roundness in the study area.

CONCLUSIONS

The maximum projection roundness, sphericity, and oblate-prolateness were measured on 2000 trondhjemite pebbles and cobbles in the 16-256 mm size range four size classes (16-32 mm, 32-64 mm, 64-128 mm, and 128-256 mm) in the Airisto area, SW Finnish Archipelago. Roundness averaged 0.34 for till material, 0.63 for esker material, 0.49 for moraine shores, and 0.66 for esker shores. Sphericity averaged 0.71 for till material, 0.75 for esker material, and 0.73 for moraine and esker shores. The oblate-prolate index averaged +1.11 (prolate, rod-like) for till material, +0.61 for esker material, +0.46 for moraine shores, and −0.23 (oblate, slightly disc-like) for esker shores.

Till pebbles and cobbles have the smallest degree of roundness and sphericity and they are also most prolate. Owing to previous processes esker pebbles and cobbles are more rounded and spherical and less prolate. As a result of wearing by shore forces, both clast types become more rounded, but the difference in roundness is much larger between till pebbles and cobbles and shore pebbles and cobbles from till than between esker pebbles and cobbles and shore pebbles and cobbles from esker. The sphericity of till material increases and that of esker material decreases in a shore environment; as a result both material types exhibit much the same sphericity. The prolateness of till material decreases owing to the shore forces and they become nearly neutral. Correspondingly, the slight prolateness of esker pebbles and cobbles also changes into slight oblateness in a shore environment.

The roundness of till pebbles and cobbles increases in shore environments in all size classes; however, it is smallest in the largest class (128-256 mm). On the other hand, sphericity increases only in the size classes 32-64 mm and 64-128 mm; in the others it remains nearly unchanged. Oblateness increases only in the size classes 16-32 mm and 32-64 mm, most in the smallest one; in the other size classes the $\overline{OP}$ index is unchanged. When esker pebbles and cobbles are transported on to a shore, roundness increases most in the size classes 32-64 mm and 64-128 mm. On the other hand, sphericity decreases most in the largest size class; in the smallest class, however, it increases a little. Oblateness increases most in the size class 32-64 mm and least in the smallest size class.

Shore processes have increased the roundness of shore material in the study area, but they have changed the axial ratios of pebbles and cobbles very little. The sphericity of shore material compared with that of till and esker material is smaller only on moraine-generated shores of the mixed gravel-cobble type in the pebble classes and on esker-generated shores in all size classes except the smallest. Also oblateness is larger on moraine-generated shores only in the pebble classes. In pebbles and cobbles from esker oblateness is greater on shores in all size classes, most, however, in the class 32-64 mm. Since the samples were taken at right-angles to the shore over the entire shore profile, abrasion must be the chief cause for the slight shape changes of material on the shore. The effect of sand and gravel upon the shape changes of pebbles and cobbles appears best on mixed gravel-cobble shores of till origin. On these shores the pebble size classes of till material have become most disc-like.

Roundness (R_{wt}) serves best and the oblate-prolate index ($\overline{OP}$) second best as a discriminator between materials from different sources in the study area. The

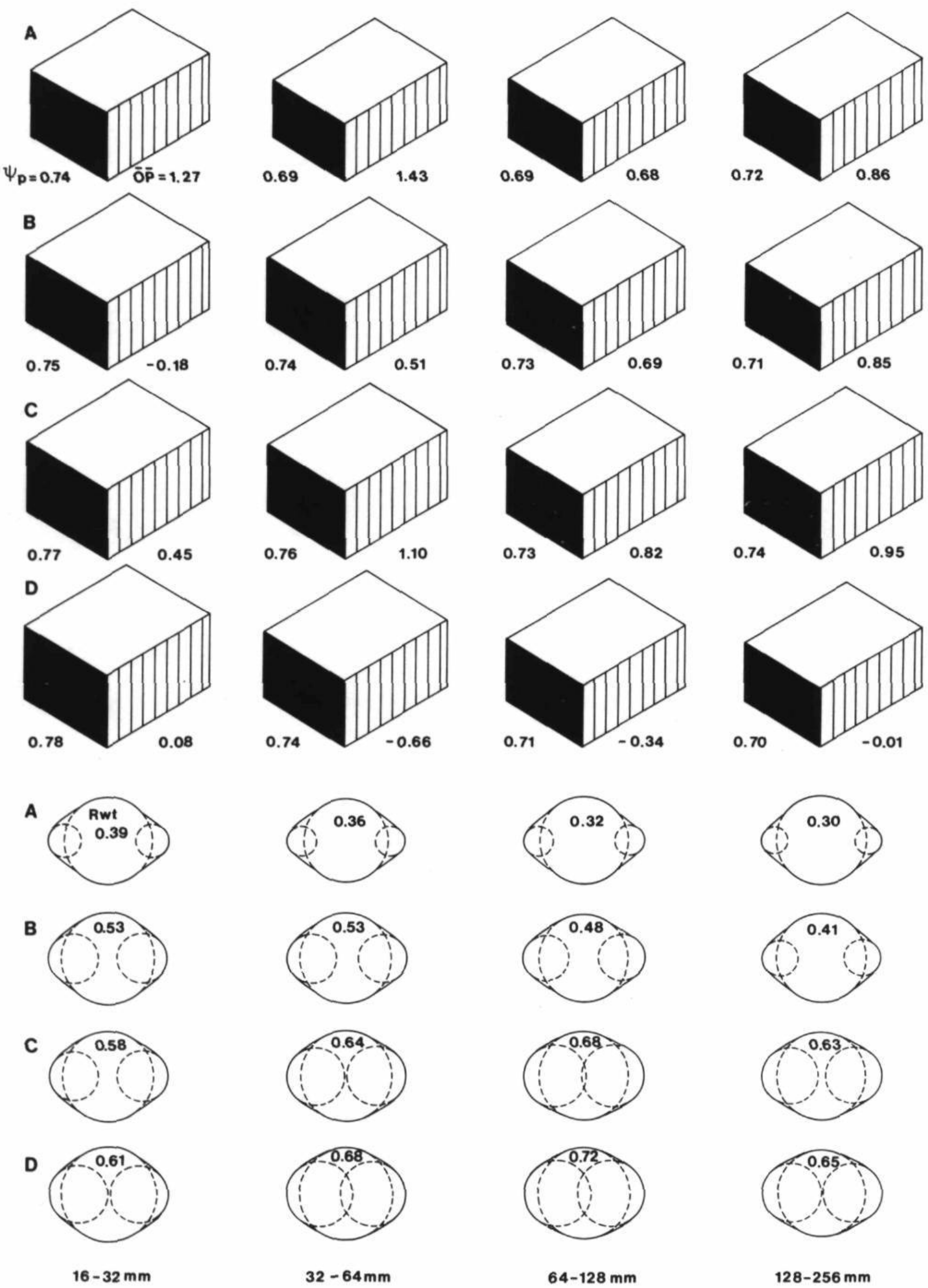

FIGURE 12. Calculated mean shapes for the four environments. Mean form is obtained by calculating the mean sphericity value and $\overline{OP}$ index for each size class, then constructing the rectangular block where the required dimensions (L, I, and S) are in the correct proportion. For each mean form block, the sphericity value and $\overline{OP}$ index are also given. Mean roundness for each environment is shown by the diagrams in the lower half of the figure, where corner radii are drawn in the correct proportion. For each mean roundness figure the value for roundness is also given. A = till. B = moraine shores. C = esker. D = esker shores.

Calcul de la forme moyenne pour quatre milieux donnés. On obtient une forme moyenne en calculant la valeur de la sphéricité moyenne et l'indice $\overline{AA}$ pour chaque classe de taille. Par la suite on dessine un bloc rectangulaire où les dimensions requises (L, I et C) sont indiquées proportionnellement. Pour chacun des blocs représentant une forme moyenne, on donne également le degré de sphéricité et l'indice $\overline{AA}$. Les diagrammes en bas de page donnent les mesures de l'arrondi moyen pour chaque milieu donné. On indique également la mesure d'arrondi dans chaque cas. A: till; B: plage de matériel morainique; C: esker; D: plage d'esker.

poorest index in this respect in sphericity (Ψ_P) owing to relatively small abrasion. The main shape change is the increase in roundness with, at the same time, a slight increase in sphericity. However, on esker shores, richer in gravel and sand than moraine shores, abrasion results in a decrease in sphericity with increasing roundness and oblateness. On moraine shores this trend appears pronounced only on the mixed gravel-cobble type of shore in the small size classes. However, owing to the short effective fetch and land uplift the shape development of shore pebbles and cobbles in the study area remains slight and thus their wearing in this shore environment is also relatively small.

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