ROUNDNESS AND SHAPE OF MARINE GRAVELS FROM URK (NETHERLANDS), A COMPARISON OF SEVERAL METHODS OF INVESTIGATION

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ROUNDNESS AND SHAPE OF MARINE GRAVELS FROM URK (NETHERLANDS), A COMPARISON OF SEVERAL METHODS OF INVESTIGATION[1]

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ABSTRACT

The petrology of gravels from a spit in the lee of the former island of Urk is discussed. The composition shows the gravels to have been derived from glacial till. The relations of roundness to distance of transport and of shape to vertical position on the spit are analyzed. Two principal methods of evaluating roundness and shape, those of Wadell-Krumbein and of Cailleux are compared theoretically and in relation to their results.

INTRODUCTION

The reclamation of the northeastern part of the bottom of the former Zuyderzee has made accessible a large area of predominantly fine grained marine sediments. Only in a few places coarse sands and gravels occur, derived from outcrops of Pleistocene boulder clay. One of these outcrops constitutes the wave-resistant core of the island of Urk. At the northeastern extremity of this island a spit, the so-called "Tail of Urk," has been formed, consisting of sandy gravel, which in this region acquired some economic value as a construction material. The imminent danger of disappearance by exploitation has made it desirable to investigate at least in some respects this deposit, so exceptional in the Netherlands. A detailed morphological study was impossible for lack of time and it was decided to concentrate on an investigation of shape and roundness of the pebbles, with some additional work on composition and grain size. The deposits have disappeared since. The main reason for using this opportunity has been the wish to compare two different methods for the study of roundness and sphericity, the one principally in use in the United States, the other in Europe.

The cooperation of the direction of the North Eastern polder, which made the field work possible and the valuable assistance of Dr. D. J. Doeglas and Dr. R. D. Crommelin are gratefully acknowledged. Very substantial assistance has been given by Dr. H. Scheen in the mathematical evaluation of the relations between Krumbein and Cailleux measures. Of the various parts of this paper the first author assumes main responsibility for the petrological studies, the second for the geology and the third for the determination of the composition of the gravels.

GEOLOGICAL BACKGROUND

The following geological description has been based on studies by De Waard (1946, 1949), Muller and Van Raadshoven (1947), and as yet unpublished work by one of the authors (Wiggers). A geological and sample map is given in figure 1.

The whole area is underlain by Pleistocene glacial deposits, essentially boulder clay of Riss-glacial age (Illinoian) which crops out in the south-west part of Urk and over an extensive area north of the former island.

Incorporated in the Riss-glacial boulder clay lenses of a different till occur

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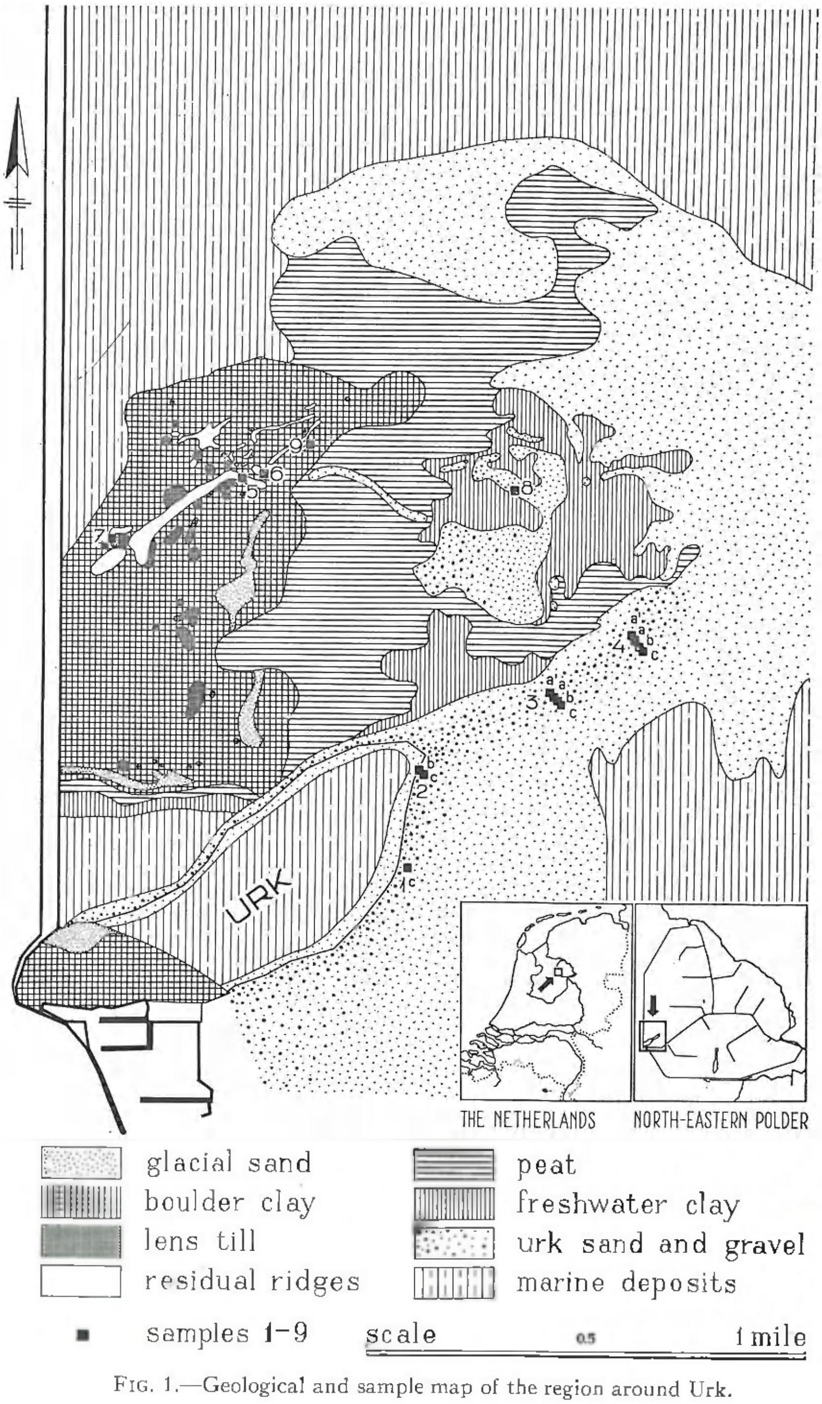

FIG. 1.—Geological and sample map of the region around Urk.

According to De Waard (1949) these lenses have been derived from deposits of an older glaciation, presumably in northwest Germany, and have been carried westward by the ice as kinds of gigantic erratic blocks.

Originally the Pleistocene sediments were partly covered by Holocene peat. About the beginning of this era a layer of fresh water-clay was deposited on this peat. Archeaological observations proved that this clay region, protected by dikes against the rising sea-level, was inhabited in the Middle Ages.

About the beginning of the 13th century the contact between the North Sea and the Zuyderzee became more extensive. A large part of the clay and peat area has been destroyed by erosion. The sea abraded considerably the boulder clay outcrops, which became covered with extensive residual pebble and cobble deposits, rounded and concentrated by the waves.

The finer material was washed out and deposited around the outcrops on the partly eroded peat and clay. The coarse, gravelly sand is called Urk sand. The map shows that the Urk sand has been deposited mainly east of the boulder-clay outcrops.

Farther away marine clayey sediments occur, partly resting upon the Urk sand.

The island of Urk consists of an outcrop of boulder clay and a low clay area. Under the marine clay of the island occurs the freshwater clay, which crops out north of the island. In a shoreward direction the clay changes into sand. The Tail of Urk consists of sandy gravel and represents, as it were, the continuation of these sand ridges. Archaeological data prove that the area around Urk was still inhabited at the end of the 12th century. The first reliable topographical maps, which date from ± 1700 A.D. show the the island and the Tail already with their present shape and position. So the Tail of Urk must have been formed between the 12th and 18th century.

The orientation of the Tail (N. 60° E.) does not agree entirely with the prevailing south-southwest winds. It has been shown by Van Veen (1940), however, by means of a study of ancient observations, that during the 18th century, the main direction was slightly more westerly. Hence long-shore drift and accumulation of materials derived from the boulder clay core in the lee of the then prevailing winds may account partly for the formation of the Tail. This does not preclude the possibility of sediment supply from the northern till outcrops by storm floods, or from the entire southern and eastern sand area.

Under the conditions just prior to the reclamation, the south side of the Tail was more exposed to the prevailing wind and wave action than the northern side. Hence the western part (fig. 2, section 3) shows pronounced lateral asymmetry in its profile with the steep slope exposed southeastward. The end of the Tail, however, bends northward and probably reached far enough to come under the influence of the swell that bent around the island and had obtained a more westerly direction. The vertical asymmetry in this part has therefore been reversed (fig. 2, section 4).

At its northeast extremity the wall flattens and broadens and imperceptibly merges into its base. On the island side its morphological development is abnormal as a result of artificial shore protection by groins and stone embankments.

The body of the spit is built up by alternating sandy and pebbly layers, but the surface is constituted by a residual layer of pebbles only. The wide flat platform consists of a very sandy gravel. Apparently wave action at this depth has not been capable of washing out all sand.

A series of samples has been collected along the south shore of the island and on the Tail, and where possible from the platform, the slope and the top. For comparison samples of the boulder clay of the northern outcrops, of the residual ridges on the latter, and of the Urk sand were investigated also.

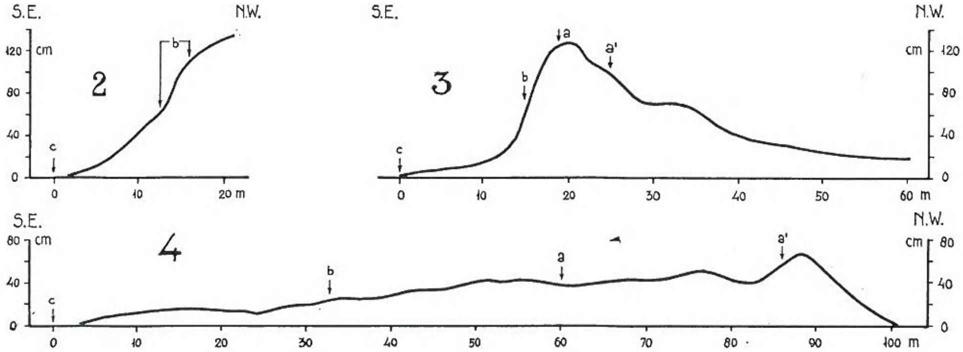

FIG. 2.—Cross sections of the island shore and Tail at the various sample locations. Position of the lowermost sample is zero.

GRAIN SIZE AND COMPOSITION

A study of grain size can be truly significant only when each sample represents a layer deposited under essentially uniform conditions. On the Tail this condition is difficult to fulfill in consequence of considerable artificial disturbance, the very limited thickness of the superficial residual layer and the underlying beds, and the presence of finer-grained interstitial material deposited during the short tranquil phase, when dikes already protected the area. In the short time available it appeared impossible to avoid these sources of errors and only the limited information required for the roundness and shape studies could be obtained by sieving the gravel grade (>4 mm). The artificiality of the lower limit introduces a certain amount of negative skewness in some distributions and produces better sorting. For those distributions only the median retains a certain value. In table I the phi[2] median, phi sorting and phi skewness are given. The latter two have been derived from the 16th and 84th percentile (Inman, 1952). From these data it can be concluded that the samples from the spit wall are generally finer than the corresponding sediments from the platform. The latter show a linear increase of size in phi with increasing distance from the boulder clay core of the island (fig. 3). This fact seems to disagree with other evidence, which points to this core as a major source of the Tail sediments (see below). Progressively greater exposure to wave action with increasing distance from the protection offered by the island may explain this phenomenon.

The other samples, which occupy very different positions in relation to the relief and show a strong influence of the deficiencies of the method, do not permit any general conclusions.

The Pleistocene boulder clay forms the only possible source of the Tail gravels. As concerns petrographic composition this source is not homogeneous. De Waard (1949) has shown that incorporated in the dark normal till numerous large lenses or blocks of a very different till occur. According to De Waard these lenses have been derived from the deposits of an older glaciation, presumably in northwest Germany, and have been carried westward by the ice as kinds of gigantic erratic blocks. The petrographic composition of their gravels is very different from that of the normal boulder clay and since they contain many more pebbles per unit of till ($\pm$3–5 times as many) the composition of the outwash

[2] Diameters in phi are the negative logarithms to the base of 2 of the diameters in mm. as proposed by Krumbein.

TABLE I.—*Parameters of grain size distributions of Tail gravels*

Sample number	1c	2b	2c	3a′	3a	3b	3c	4a′	4a	4b	4c
Md ϕ	3.45	2.85	3.75	3.55	3.50	3.50	4.20	2.65	3.30	3.00	4.30
Sorting $=\sigma\phi$	1.30	0.50	1.30	1.00	0.65	1.20	1.20	0.55	0.80	0.60	1.70
Skewness $=\alpha\phi$	−0.06	−0.06	−0.42	−0.12	−0.24	−0.50	−0.35	−0.51	0.0	0.18	−0.11

gravels is largely controlled by the presence of lenses of till in the source area. Table II contains the petrographic analyses of some of the samples (analyses by Maarleveld).

From this table and analyses of De Waard (1949) the principal difference between lens till and normal till appears to be the absence of flint in the former. Moreover, the limestone percentage, though variable, is much lower in the normal till.

The percentages of the principal components flint, crystalline rocks and limestone have been recomputed to 100 and plotted in fig. 4 (20–30 mm grade). All mixtures between normal till and lens till would plot in the cross-hatched area. The Urk sand sample represents such a mixture in which normal till predominates. It is apparent that the composition of the samples from the residual ridges does not result from mixing only. Such a composition has to be explained by selective removal (by abrasion) of the limestone, resulting in high percentages of crystalline rocks. Since they contain but little flint and flint under the existing conditions is very resistant, the original material must have contained a large amount of lens till material.

The position of the Tail samples can be explained in two ways. The first possibility is progressive mixing of residual ridge type material and a fresh gravel in which lens till predominates. The amount of residual ridge material required would not exceed 40 per cent. Another explanation is selective removal by abrasion of limestone from a limestone-rich source material without admixture of residual gravel. The line B represents such a theoretical development by removal of limestone from a lens till gravel with ±20 per cent or normal till. Petrographic considerations alone are insufficient to solve this problem, especially since the data are scarce.

Similar relations could be shown for the 5–8 mm grade. The relative increase of limestone in this grade, which accompanies the decrease in the 20–30 mm grade, points to selective abrasion as a major cause for the variations in composition of the Tail gravels. The combined data from both fractions are therefore in favor of a derivation from lens till and modification by abrasion, that is a derivation from the boulder clay core of the the island itself and not from the Urk sand, if the single sample of this latter would be representative of the whole. As

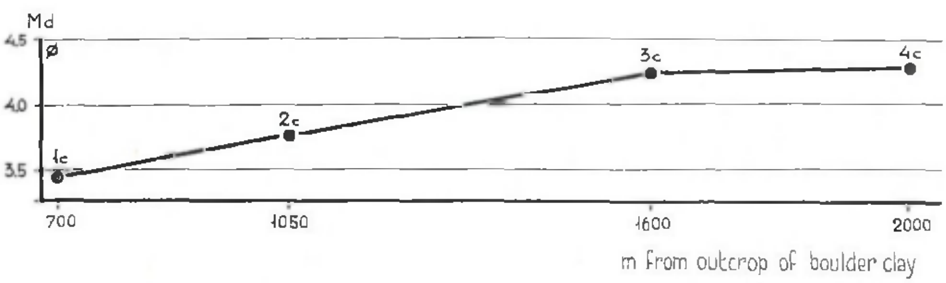

FIG. 3.—Relation of median size in phi to distance from the boulder clay core of the island for platform samples (c-series).

TABLE II.—*Petrographic composition of samples from the Tail and from source formations*[1]

Number		Flint		Crystalline		Limestone		Quartz		Others	
	Size Grade in mm	20–30	5–8	20–30	5–8	20–30	5–8	20–30	5–8	20–30	5–8
1c	Tail	12	5	32	41	29	28	—	5	27	21
2c	Tail	14	8	27	36	30	29	2	4	27	23
3c	Tail	20	8	32	47	24	23	—	2	24	20
4c	Tail	19	6	32	41	18	32	2	4	29	17
5	Residual Ridge	7	5	50	44	16	26	3	6	24	19
6	Residual Ridge	16	4	42	44	1	23	4	8	37	21
7	Lens till	1	—	26	26	63	70	—	—	9	4
8	Urk sand	32	21	26	37	5	2	2	6	35	34
9	Norma till	38	14	23	44	1	1	2	9	36	32

[1] Figures given in percent by number of pebbles in a given size grade.

it is, this argument has to be used with considerable care.

METHODS OF STUDY OF SHAPE AND ROUNDNESS

Wadell (1932) was the first to show that there is a fundamental difference between shape and roundness and that these properties are geometrically independent. An object may be quite spherical in shape but completely angular, for example a dodecahedron; or perfectly rounded but far from spherical, for example a cylinder capped by two half spheres. The shape of particles influences their behavior during transport and deposition, since spherical particles settle more quickly from a suspension and roll faster in bottom transport than flat particles. Hence sorting may be controlled partly by shape. Roundness is influenced by rigor of wear and distance of transport, but does not have any effect on sorting or transport. The definitions of roundness and sphericity are entirely independent and it is generally assumed that only very great changes in one may influence the other (Pettijohn, 1949, p. 54). This independency of definitions is an important prerequisite for the study of both properties.

Based on the assumption that particle shapes can be arranged in a series with the sphere as the most developed stage, Wadell has expressed shape as the ratio between the surface of the particle and the surface of a sphere with the same volume. Krumbein (1941a) has shown that this ratio, the sphericity (S) of the grain which ranges from 0 to 1 for perfect sphericity, can be simplified with satisfactory accuracy to one in which only the longest (a), the intermediate (b) and the shortest (c) diameters of the particle appear, that is $S=\sqrt[3]{bc/a^2}$. His definition of these diameters has been followed in the present study. The computation of the ratios b/a and c/b permits the graphical determination of the sphericity. Figure 5 shows the plotting in a sphericity graph of all pebbles of sample 1 c.

So far it has been tacitly assumed that shape and sphericity are identical notions. Figure 5 shows, however, that, for instance, disc-shaped and rod-like particles may have the same sphericity, notwithstanding the fact that they have very different shapes, and presumably will behave in different ways during transport and deposition (Krumbein, 1941a). Hence the use of sphericity values in sediment studies does not always permit the complete evaluation of shape influence. This difficulty can be overcome by using sphericity diagram plots instead of actual sphericity values, whereas large numbers of samples may be summarized by classing the pebbles into 4 classes, each indicating a part of the field of the sphericity diagram. These classes have been used first by Zingg (1935) and the Zingg percentages constitute a useful

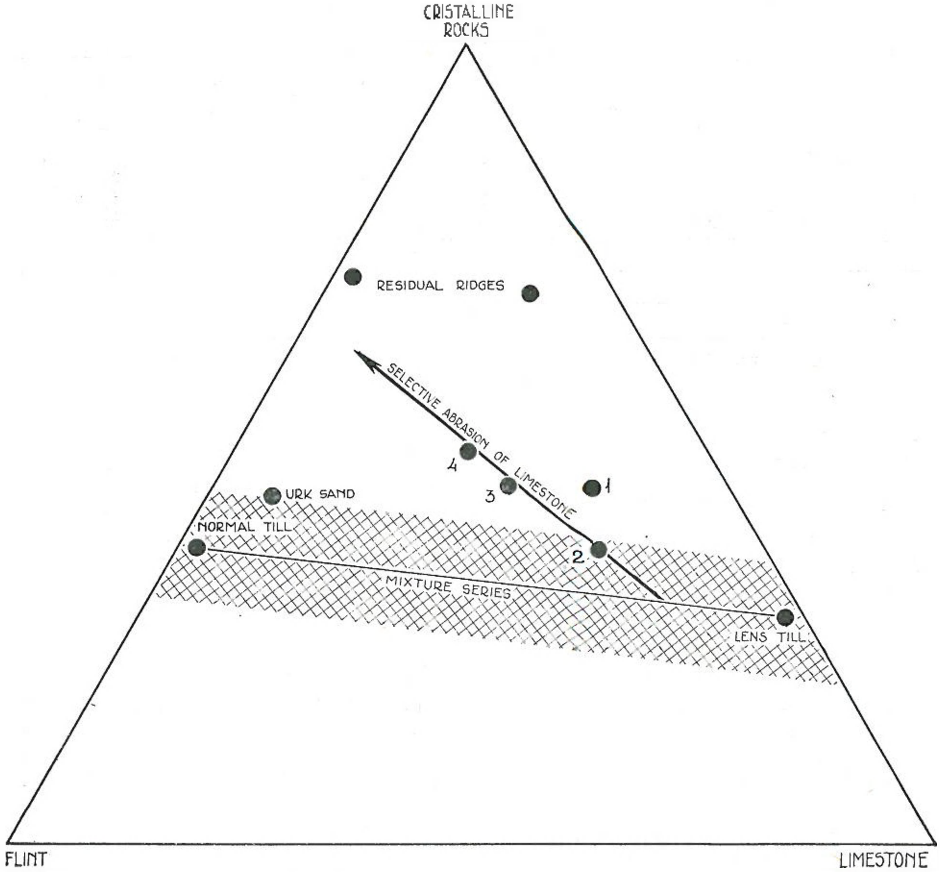

FIG. 4.—Triangular diagram of the petrographic composition of tail and potential source samples, 20–30 mm grade.

supplement to the sphericity values.

Roundness (*Rw*) was expressed by Wadell as the ratio between the radius *r* of the sharpest corner of the particle and the radius *R* of the largest inscribed circle, both in the maximum projection of the particle. The measurement of roundness in this way is lengthy and Krumbein (1941a) has constructed a chart for visual determination of roundness (*Rk*) by comparison with pebbly images, the roundness of which has been measured by Wadell's method. The agreement between determinations in both ways is close, when large numbers of pebbles are used (25 or more). The values range from 0–1, the latter representing perfect roundness, whatever the shape may be.

Many more methods for the determination of shape and roundness have been proposed. The majority have not found wide usage, except those of Cailleux (1945, 1948), which have provided the data for a considerable series of investigations by French and German students (for example Berthois, 1950, 1951; Cailleux, 1945, 1947, 1948; Hövermann and Poser, 1951; Pouquet, 1950; Tricart, 1951; Tricart and Schaeffer, 1950, and

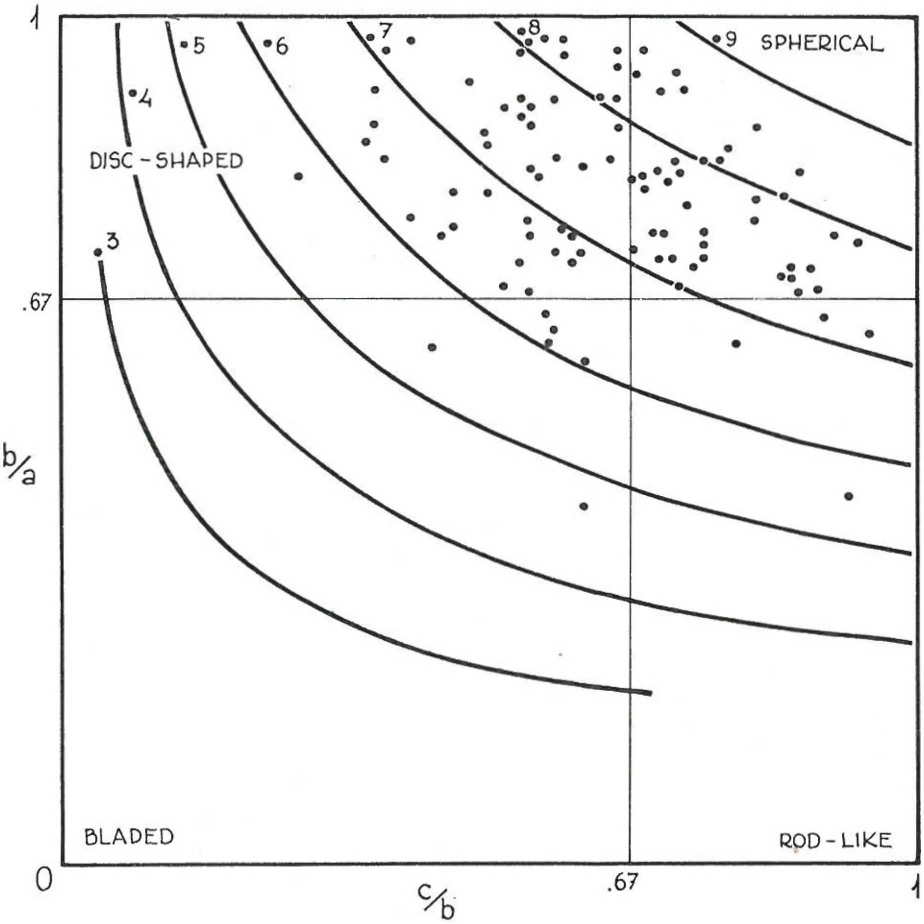

FIG. 5.—Sphericity diagram of all pebbles of sample 1 c.

others). It is therefore desirable to examine the theoretical relationships between both sets of measures. The results obtained by both will be compared in the next section.

Cailleux's shape factor is the flatness index $F = a+b/2c$, as originally proposed and used by Wentworth (1922). The definition of the intercepts a, b and c is the same as for Krumbein's sphericity S.

In figure 6 the relations between S and F has been given for all Urk samples. All available F measurements of individual pebbles have been classified acccording to their S-class (class-interval of 0.1). The arithmetic mean and standard deviation of the F distribution in each S-class have been plotted against the mid-point of the S-class. This method is not entirely correct but considered to give a fair approximation.

The theoretical relation between $F = (a+b/2c$ and $S = (bc/^2)^{\frac{1}{3}}$ depends on the distributions of a/b, b/c and c/a. Uniform or patchy distributions of each of these ratios and their mutual relationship result in a different relationship between S and F. The mathematical treat-

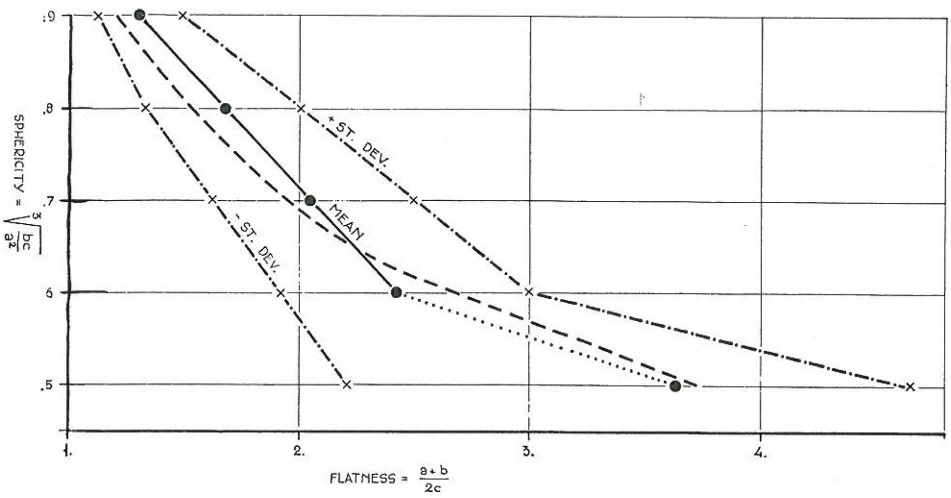

FIG. 6.—Relation between sphericity (S) and arithmetic mean and standard deviation of flatness (F) per class of S for all Urk samples. Broken line: theoretical relationship of F and S assuming uniform distribution of b/a and c/b (see text).

ment of these various possibilities, which has kindly been undertaken by Dr. H. Scheen, will not be discussed here. However, if we assume uniform distribution of b/a and c/b, visualized by points distributed evenly over a diagram like that of figure 5, we find a relationship between S and F as represented by the broken line in figure 6, which quite closely agrees with the experimental relations. If the points occur mainly in the upper left hand or lower right hand corner of figure 5 the line of theoretical relation shifts to the position of one of the standard deviation curves. From this we may draw the conclusion that the combined usage of S and F would supply information of the same type as do the Zingg-percentages. The flatness ratio itself does not distinguish between roller-shaped and disc-shaped pebbles, since it compares c to the average of a and b. Thus it does not offer a means of avoiding the deficiencies of S.

Roundness (Rc) has been defined by Cailleux (1947) as the ratio of the diameter of the sharpest corner ($2r$) in the plane of maximum projection and the greatest length a. It bears a certain resemblance to the Wadell-Krumbein definition of roundness, which as a first approximation may be written as $Rk = 2r/b$. In both cases the maximum value of $2r = b$ and it is obvious that only when the largest projection of the particle is a circle can Rc reach its maximum value of 1. A cylinder capped by two spheres is perfectly rounded, $2r = b$ and $Rk = 1$, but Rc may have one of an infinite series of values, depending on the ratio b/a. As a mathematical conception Rc, partly controlled by shape, is definitely inferior to Rk.

If we assume the largest projection to be an ellipse then $2r = b^2/a$, $Rk = 2r/b = b/a$ and $Rc = 2r/a = b^2/a^2$. The relation between Rc and Rk is thus the function $2r/a = (2r/b)^2$ or $Rc = (Rk)^2$. When the largest projection is not an ellipse Rk will always be higher for the same value of Rc, than the value given by the equation. The Rc values of all pebbles of Urk have been classified according to their Rk classes. The arithmetic mean and standard deviation of the Rc distribution in each Rk class have been plotted in figure 7 against the mid-

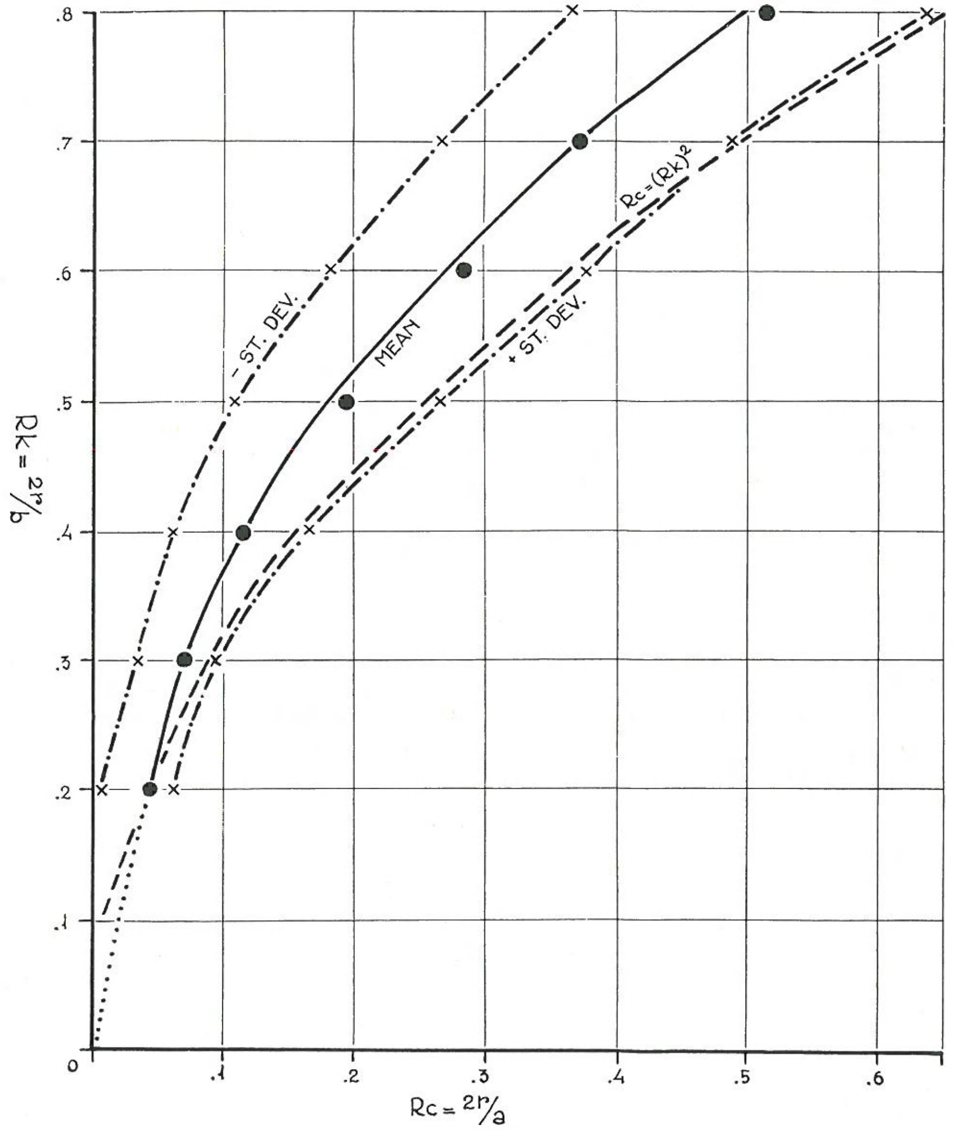

FIG. 7.—Relation between Krumbein roundness (*Rk*) and arithmetic mean and standard deviation of Cailleux roundness (*Rc*) in each class of *Rk* for all Urk samples. Broken line: theoretical relationship, when the largest projection is an ellipse.

point of the latter. The curve for the positive deviation closely agrees with the theoretical relation for an elliptical projection. The majority of the pebbles, however, apparently have projections that are not ellipses and their *Rk* values are higher than expected from theoretical considerations.

TABLE III.—*Correlation between size and shape and size and roundness in the 20–40 mm grade of Urk samples*

Sample number	n	Shape—Size		Roundness—Size	
		r	P	r	P
1c	100	0.17	>0.10	0.18	0.10
3a	100	0.13	>0.10	0.18	0.10
3c	100	0.16	>0.10	0.09	>0.10
7	100	0.11	>0.10	0.11	>0.10

The determination of $2r$ for Rc is carried out by selecting visually the sharpest corner and determining its diameter on a disc with concentric circles to the nearest 0.5 mm. With decreasing size and rounding the accuracy of this technique also decreases rapidly (Berthois, 1952).

The numerous studies mentioned before demonstrate that in spite of their deficiencies Rc and F are valuable tools especially in environmental studies. It is beyond doubt, however, that a large scale application of Rk, S and Zingg percentage would yield the same results. The determination of S is slightly more time-consuming than that of F, but this is counter-balanced by the more rapid and accurate determination of Rk as compared to that of Rc. Personal experience and published data (Krumbein, 1941a) show, that the accuracy of all measurements, even when carried out by different persons, is very satisfactory.

A definite relation exists between roundness or sphericity and size. Since separate determinations in all size grades would be too time-consuming, only the 20–40 mm grade has been studied. Within the limits of this grade there is no significant relation betweeen size and shape or roundness. Correlation coefficients (r) for size/roundness and size/sphericity within the chosen grade have been calculated for a set of representative samples, using b as a size measure. The correlation is virtually non-existent in all cases, since r is low and P, indicating the probability that the relation is due to chance only, is high.

Since the rock type is of considerable influence on the effects of abrasion and on shape, petrographic homogeneity of the material is necessary. In this study limestone has been selected for its abundance, easy recognisability, comparative susceptibility to wear and rather uniform hardness. Samples 1c, 3a, 3c, and 7 have been measured for one hundred randomly picked pebbles (table III).

SHAPE AND ROUNDNESS OF THE URK GRAVELS

The roundness and shape frequency distributions of each sample can be summarized in conventional statistics, that is in terms of a normal probability distribution and deviations thereof. Usually the median and quartile parameters are used, but for the present study it was thought that statistics describing not only the central part of the distribution but also its extreme ends would be most relevant. Hence the first three moments about the mean have been calculated and the arithmetic mean, standard deviation, and skewness of the frequency distributions of Rk, Rc, S and F have been tabulated in table IV together with the Zingg percentages.

The data for Rk and Rc have been represented in figure 8. Assuming as a working hypothesis that distance of transport is one controlling factor for roundness, the means of the c-series of Tail samples have been plotted against the distance from the island, a potential gravel source. The samples of lens till (no. 7), residual ridges (no. 5) and Urk sand, presumably in the given order, also

TABLE IV.—*Arithmetic mean, standard deviation and skewness of the frequency distributions of roundness (Rc—Rk) and shape (S—F) and Zingg values of all Urk samples*

Sample number	1c	2b	2c	3a	3b	3c	4a	4c	5	7	8
Rk = Krumbein roundness											
Arithm. Mean $\bar{X}$	.494	.500	.499	.549	.537	.533	.553	.575	.422	.305	.478
Std. Error of $\bar{X}$	.008	.010	.007	.009	.008	.007	.009	.008	.010	.013	.010
Std. Dev. σ	.085	.096	.071	.086	.080	.075	.089	.082	.102	.133	.105
Skewness α	+.040	+.045	+.040	+.055	+.049	+.056	+.047	+.032	+.057	+.076	+.093
Rc = Cailleux roundness											
Arithm. Mean $\bar{X}$	.234	.282	.259	.267	.298	.309	.289	.333	.156	.085	.194
Std. Error of $\bar{X}$	.010	.014	.009	.010	.012	.012	.013	.011	.010	.006	.013
Std. Dev. σ	.104	.139	.095	.106	.117	.123	.127	.114	.102	.059	.102
Skewness α	+.074	+.109	+.044	+.042	+.076	+.095	+.118	+.018	+.110	+.112	+.099
S = Sphericity											
Arithm. Mean $\bar{X}$	.698	.678	.695	.699	.729	.747	.720	.702	.711	.690	.685
Std. Error of $\bar{X}$	.007	.010	.007	.007	.008	.008	.009	.008	.007	.008	.008
Std. Dev. σ	.070	.104	.074	.075	.083	.079	.088	.076	.073	.084	.076
Skewness α	+.228	+.048	+.111	+.148	+.408	+.744	+.627	+.403	+.053	+.059	+.381
F = Flatness ratio											
Arithm. Mean $\bar{X}$	1.75	2.45	1.81	2.02	1.86	1.75	2.00	1.86	1.75	1.96	1.93
Std. Error of $\bar{X}$	0.05	0.10	0.05	0.06	0.07	0.04	0.07	0.05	0.04	0.05	0.05
Std. Dev. σ	0.49	0.96	0.54	0.57	0.68	0.42	0.66	0.47	0.39	0.50	0.47
Skewness α	+0.52	+1.03	+0.56	+0.61	+0.83	+0.43	+0.74	+0.48	+0.49	+0.39	+0.40
Zingg shape percentages											
Bladed	6	14	6	12	9	3	10	5	4	5	10
Rod-like	14	13	12	12	15	13	15	10	16	26	15
Disc shaped	38	64	48	54	42	44	44	45	42	50	50
Spherical	42	9	34	22	34	40	31	40	38	19	25

represent a series of progressive wear, but the distances of transport corresponding to each stage are unknown and even low and irrelevant in the case of wave-rounding in the residual ridges. In the left hand part of figure 8 these samples are therefore spaced equally and the steep rise of the curve connecting their mean roundnesses does not represent an especially rapid increase. Only the *c*-series has been represented, since only these samples were taken in comparable places. Only such samples can be compared directly, since it is conceivable that a lower or higher position on the gravel wall may appreciably affect roundness. On this point the available information is somewhat contradictory. We shall first confine the discussion to the *Rk* data.

The increase of roundness with increasing distance from the island points again to the boulder clay of Urk as the principal source and confirms the reasoning based on the composition of the gravel. If we assume the gravel of the boulder clay of Urk to have the same mean roundness as the pebbles of sample no. 7, we may tentatively reconstruct the complete roundness-distance graph (fig. 9) The shape of this curve is quite remarkable. After a steep rise the curve levels off markedly after about 1500 m. In general shape this part of the curve is quite similar to abrasion mill graphs published by Krumbein (1941b) but for the distance, which is only about half the distance of travel in the abrasion mill. We may see here the influence of the waves on this somewhat exposed shore, washing the pebbles back and forth and causing the actual distance of travel to be much greater than the distance measured in a straight line from the point of departure.

After this subhorizontal part the curve

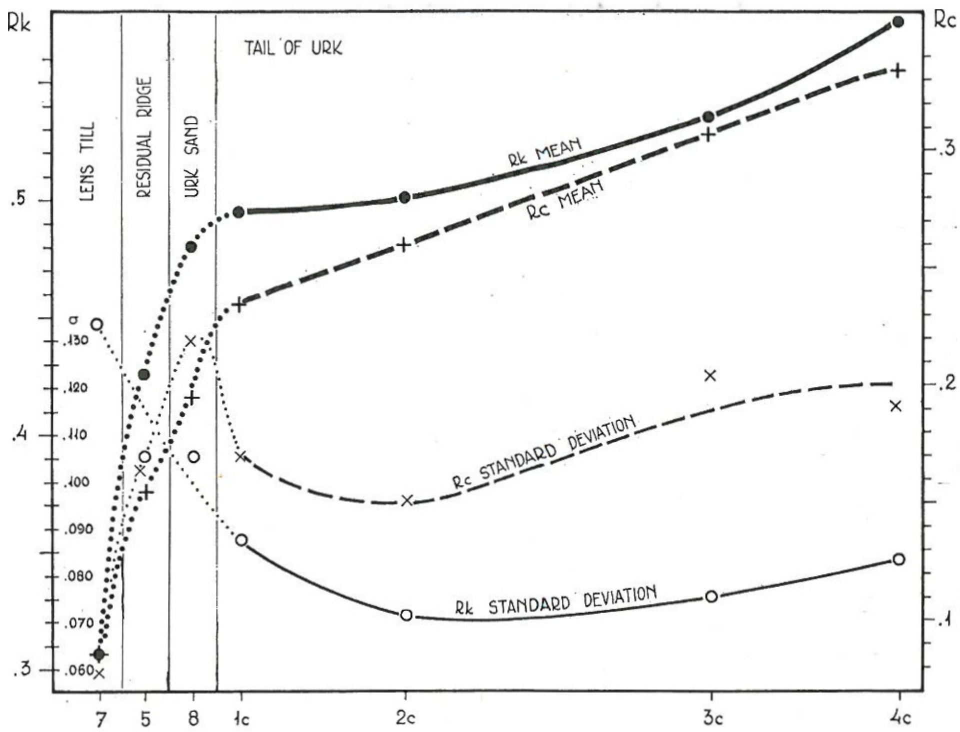

FIG. 8.—Variations of mean roundness (*Rk* and *Rc*) along the Tail of Urk (horizontal axis indicates field spacing of samples) and among possible source gravels (spacing unrelated to transport distances).

surprisingly starts to rise again about halfway down the Tail. This behavior recalls the unexpected increase of grain size with increasing distance from the island as described before. Probably the explanation is the same and has to be sought in an increase of wave energy where the protection offered by the island gradually disappears. Thus the pebbles enter a second cycle of rounding after their first adaptation to the moderate vigor of transport along the island shore.

The trend of the rounding curve at the same time seems to exclude the possibility of a fresh supply of gravel, for instance from the Urk sand from the north, since such a supply of relatively low roundness would considerably affect the smooth rise of the curve. The possibility remains, however, that the Tail has originated as a result of concentration by waves of a local patch of Urk sand sufficiently long ago to reach a stage of roundness equilibrium. The roundness curve in that case would only reflect the adaptation at each point to local wave activity and not the relation between rounding and transport. The petrographic composition is not a very reliable argument against this hypothesis, since Urk type sand deposits so near the island may well have had a composition more similar to that of lens till than sample no. 8. On the other hand a progressive increase of wave energy, sufficient to explain the first steep increase of roundness, seems hardly probable along the island beach. Moreover longshore transport cannot be

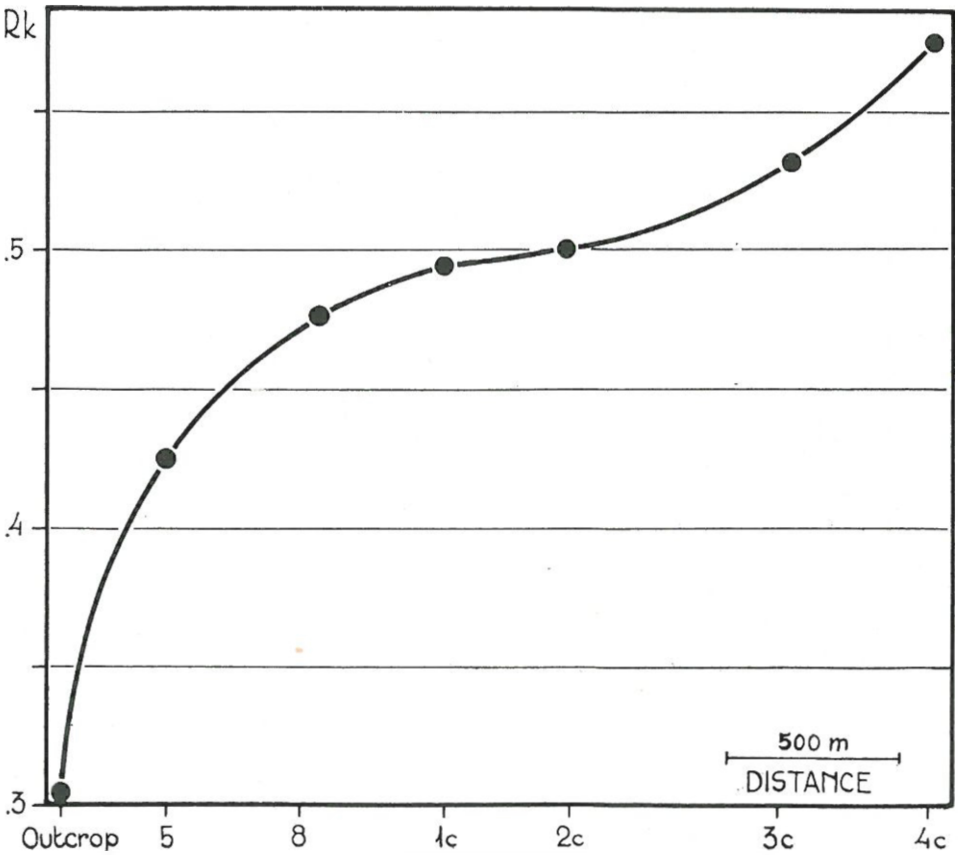

FIG. 9.—Reconstructed relation between mean roundness and distance of transport on Urk.

ruled out with wind directions from the south-southwest. A composite origin seems therefore probable. An argument in favor of such a composite origin is the relative scarceness of gravel between the island core and point 2. We may therefore tentatively explain the Tail as a wave concentrate of an Urk sand type deposit, which itself originally has been derived from till. Some supply of gravel directly from the island must have been going on. Recent supply of Urk sand from the north or northwest seems improbable.

The standard deviation of the roundness frequency distributions shows a marked tendency to decrease with increasing mean roundness until the first equilibrium stage is reached. Apparently all pebbles tend to reach the same roundness which is the mean roundness of the equilibrium stage. The onset of a new cycle of rounding interrupts this development and is accompanied by a slight increase of the standard deviation possibly as a result of chipping and even initial breakage. In the light of the theory on the origin of the Tail as given above this means that no perfect adaptation to local wave energy and no complete stability have as yet been reached.

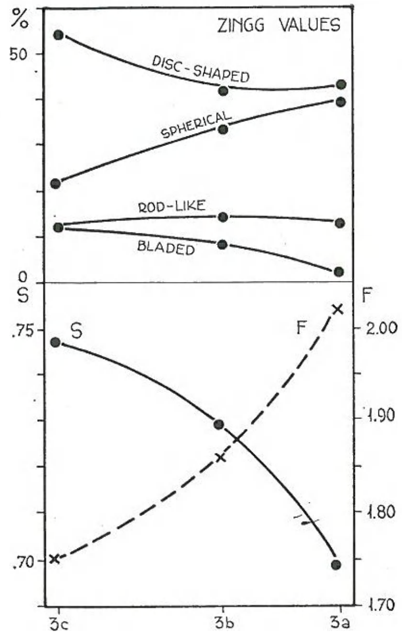

FIG. 10.—Changes in shape in a section across the Tail at location 3.

Thus longshore transport may still be important. The asymmetry as expressed in the skewness of the distributions is small and positive. The latter indicates that everywhere an appreciable number of pebbles are considerably less rounded than the majority, but that nowhere have any been rounded much better. This again points to the existence of a roundness maximum for each local set of conditions. Frost action and glacial transport easily account for the very high skewness in the source material (no. 7). In this case of no. 8, an explanation is not easily given but may be sought in the fact that this is the only deposit in which sand predominates.

The *Rc* data show the same general increase, but with less detail (figure 8). It would be possible to trace and explain all deviations from the *Rk*-curve by means of a detailed analysis of the *a/b* relations. The second rounding cycle for instance is entirely obscured by the much higher rate of increase of high *Rc* as compared to high *Rk* values (compare fig. 7). Since each of the lower *Rc* classes comprises a much wider range of roundness values than do the lower *Rk* classes, a relation which gradually reverses with increasing roundness, the *Rc* standard deviation begins low, increases to a maximum and decreases again.

Inspection of the shape data of table IV shows that no significant variations in *S*, *F* or Zingg values are discernable along the Tail. The variation is small and hardly exceeds the standard error of estimate of the mean. If there is a tendency of special shapes to be transported more rapidly, the effect is entirely obscured by the inaccuracies of sampling and analysis.

A profile across the wall, on the other hand, shows a marked regularity. The changes in section 3 are presented in figure 10. The other sections are incomplete and the positions of the samples, as appears from figure 2, are not comparable. The marked decrease of sphericity and increase of flatness towards the top of the wall is explained by the concentration of spherical particles on the platform and bladed and disc-shaped pebbles high on the slope (Zingg values). The rod-like pebbles show no special preference. Since spherical particles are more susceptible to traction and flat particles are more susceptible to suspension transport (Wadell, 1934, Krumbein, 1942), it seems that suspension transport is the main agent in wave sorting. Possibly this active lateral sorting process is partly responsible for the lack of longshore shape sorting.

The *S* and *F* frequency distributions show no significant variations in standard deviation and their skewnesses vary largely and erratically.

Cailleux (1945, 1947, 1948) and Tricart and Schaeffer (1950) give typical values for *F* and *Rc* in various environments. Their values for glacial and marine pebbles have been tabulated below (table V) for comparison with the Urk samples. The general agreement is quite satisfactory. Unfortunately insufficient

TABLE V.—*Typical roundness and shape values of morainic and beach pebbles compared to Urk data*

	Morainic Gravel		Beach Gravel	
	RC	*F*	*Rc*	*F*
Cailleux 1948	—	—	0.32 –0.51	2.3 –3.4
Cailleux 1947	—	1.7	—	2.0 –3.0
Cailleux 1945	—	—	0.250–0.610	—
Tricart & Schaeffer	0.100–0.150	—	0.300–0.350	—
Urk	+0.100	1.75	0.200–0.330	1.75–2.50

Rk and *S* data are available to permit a similar comparison.

SUMMARY AND CONCLUSIONS

The results of this study may be summarized as follows:

A. Concerning methods of investigation.

1. Krumbein (*Rk*) and Cailleux roundness (*Rc*) are closely related. Determination of *Rc* is more precise at least for higher classes than determination of *Rk*, but also more time-consuming.
2. *Rk* data seem to provide more detailed and more pertinent information than *Rc* data.
3. Sphericity (*S*) and flatness (*F*) are shape factors of the same type and both provide incomplete information only. Determination of *S* is more lengthy but provides Zingg shape values at the same time. The latter constitute a necessary additional source of information.
4. *Rk*, *S* and Zingg data together constitute a set of measures which are as practicable as and more relevant than *Rc* and *F*.

B. Concerning the Urk gravels.

5. Petrographic and roundness data point to lens till in the island as a source of the Tail gravel. Probably, however, a patch of Urk type sand material has partly supplied the material. Longshore transport probably played a minor but significant part.
6. Roundness and grain size increase with increasing distance from the island, probably in consequence of progressive disappearance of the protection offered by the island.
7. The roundness at each point of the Tail is largely in equilibrium with local wave energy.
8. Shape sorting is a factor in the distribution across but not along the Tail.

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