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SIZE, SHAPE AND DENSITY SORTING AROUND TWO BARRIER ISLANDS ALONG THE NORTH COAST OF HOLLAND

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ABSTRACT

The sand movement on and around two barrier islands flanking the tidal flat area north of The Netherlands is studied by means of size, shape and density sorting. Since there is mainly fine sand in the area, the competency of the transporting media is seldom reached and selection mainly occurs on shape and density.

In the deeper off-shore, a coarse grain-population shows inherited characteristics from a higher energy early transgressive phase, whereas a finer population is consistent with the present-day hydrodynamic situation.

Tidal channels in between the islands form outer tidal deltas. These deltas protect the islands against the waves produced by N-W gales and they form a "shadow" for the W-E longshore currents.

The coastline of the islands is still retreating. The removal of sand mainly occurs during storm surges. The eroded material is redeposited in sorted zones parallel to the coast. Only the susceptible material, that is deposited farthest from the beach, can be transported by the longshore currents. The coarsest, most spherical and densest grains remain closest to the beach and can re-enter the beach as prograding bars during more quiet conditions.

This process gives rise to a stepwise diminishing grain-size from island to island towards the east.

The eastern island is situated on top of older river and/or tidal channel deposits, which are easy to erode. This gives the tidal inlet, and hence the tidal delta, a great lateral mobility. The eastern island is therefore very mobile.

The western island is bordered by a deep tidal channel, which cuts into more resistent glacial deposits. This keeps the channel and hence its outer tidal delta in the same site. The western island therefore did not change longitude and constantly retired over its own deposits. This resulted into completely different sand properties for both islands, which mainly shows in the garnet percentages and the high rollability values for the western island.

INTRODUCTION

This article deals with sand transport on and around the islands Ameland and Schiermonnikoog (Fig. 1). Both islands form part of a chain of barrier islands, which reaches from the northern point of the dutch west coast till the danish coast. As a whole, these barrier islands had and still have the tendency to withdraw towards the mainland, from which they are separated by a huge tidal flat area. In between the islands are tidal inlets with rather deep tidal channels, which form outer tidal deltas. In the past, the barrier has been closed at least locally and peat was deposited in the present tidal flat area.

In historical times, some of the islands have been very mobile (Schiermonnikoog and Rottumeroog) while others remained at the same site (Ameland, Vlieland), see Veenstra, 1969. The grain-size diminishes stepwise from island to island towards the east.

The aim of this survey has been to obtain more insight into the dynamics of the sandtransport and the shift of the islands. This article is a sequel to the article 'Size and shape sorting in a Dutch tidal inlet" by Winkelmolen and Veenstra (1974).

POSSIBILITIES OF SANDTRANSPORT

During the transgression following the last stage of the Ice-age there has been active sandtransport towards the south. A barrier was built up, which has been closed for some time, but more often it was breached. Since the transgression came to a standstill it is questionable if at present there is still a net transport towards the south. More probable is that an equilibrium profile has been established since, and that today supply and removal of sand are more or less in balance in coast-normal direction.

Longshore transport in the shallow off-shore certainly plays a part. The material is fine and waves and currents are strong enough to move this material regularly. This follows as well from the occurrence of ripples and sand waves. According to general opinion this longshore transport has an eastward surplus. Beach drift could also be one of the transport mechanisms. Furthermore, there often occurs wind transport along the beaches. The strongest winds are prevailingly from western directions. Along the west coast of Holland this leads to transport of sand from the beach directly into the dunes. On the islands, there is much more transport parallel to the beach and oblique to the dunes. However, we cannot say apriori that there should also be a net transport towards the east. Next to wind strength and frequency, also the humidity

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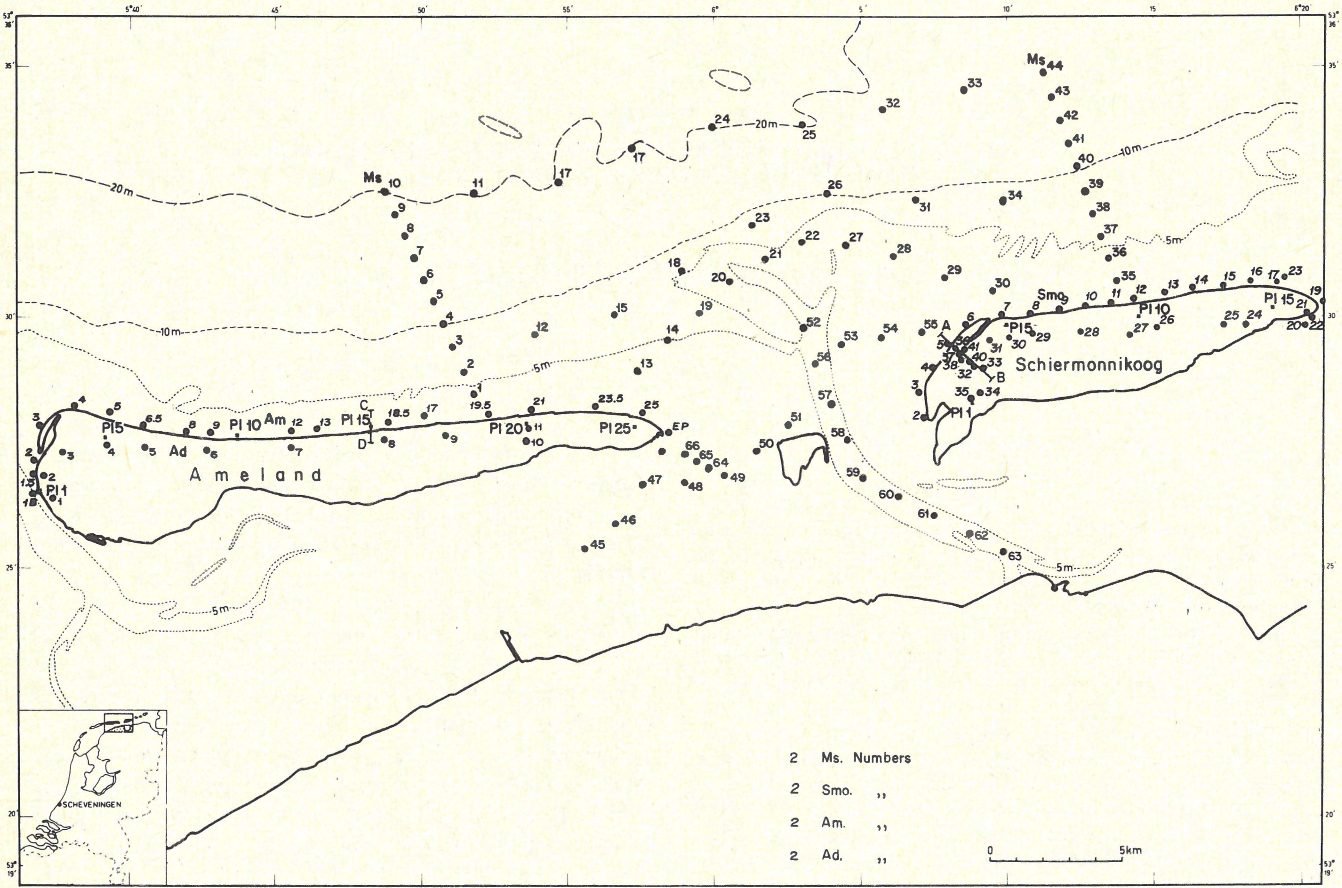


Fig. 1
Sample location map.

plays a part and the westerly gales often go hand in hand with rains while the eastern winds are dryer.

Furthermore, there is considerable sand transport to and fro the tidal inlets. Here, the largest current velocities and the highest turbulencies prevail.

The material making up the islands and the shallow offshore zone is so fine (medium between 140 and 185 mu) (Fig. 2), that most of the time it can be transported as saltation load. Competency seldom is the limiting transport factor. Most of the transport is governed by capacity phenomena. Quantitative equilibrium is reached then between the transported load and the material left behind. Such processes have a qualitative aspect as well. But since the sand in the area is fine and rather monotonous in size distribution, qualitative selection mainly occurs on shape and density criteria. Under such conditions, grain-size largely fails as a criterion for the transport conditions and additional shape and density data are needed to complete the reasoning.

METHODS

Size analysis

All samples have been treated with diluted hydrochloric acid before sieving. Sieves between 0.50 phi and 4.00 phi with a $\frac{1}{4}$ phi interval have been used. The median, the quartiles, in some cases the percentiles and the Trask sorting coefficient of each sample have been determined. The standard deviation of the size parameters of each series of samples have been calculated too.

Shape measurement

The shape of the sand grains was measured with the rollability apparatus on $\frac{1}{4}$ phi size fractions. For a description of the method, the reader is referred to Winkelmolen (1969) and (1971) and for the special application in this area to Winkelmolen and Veenstra (1974).

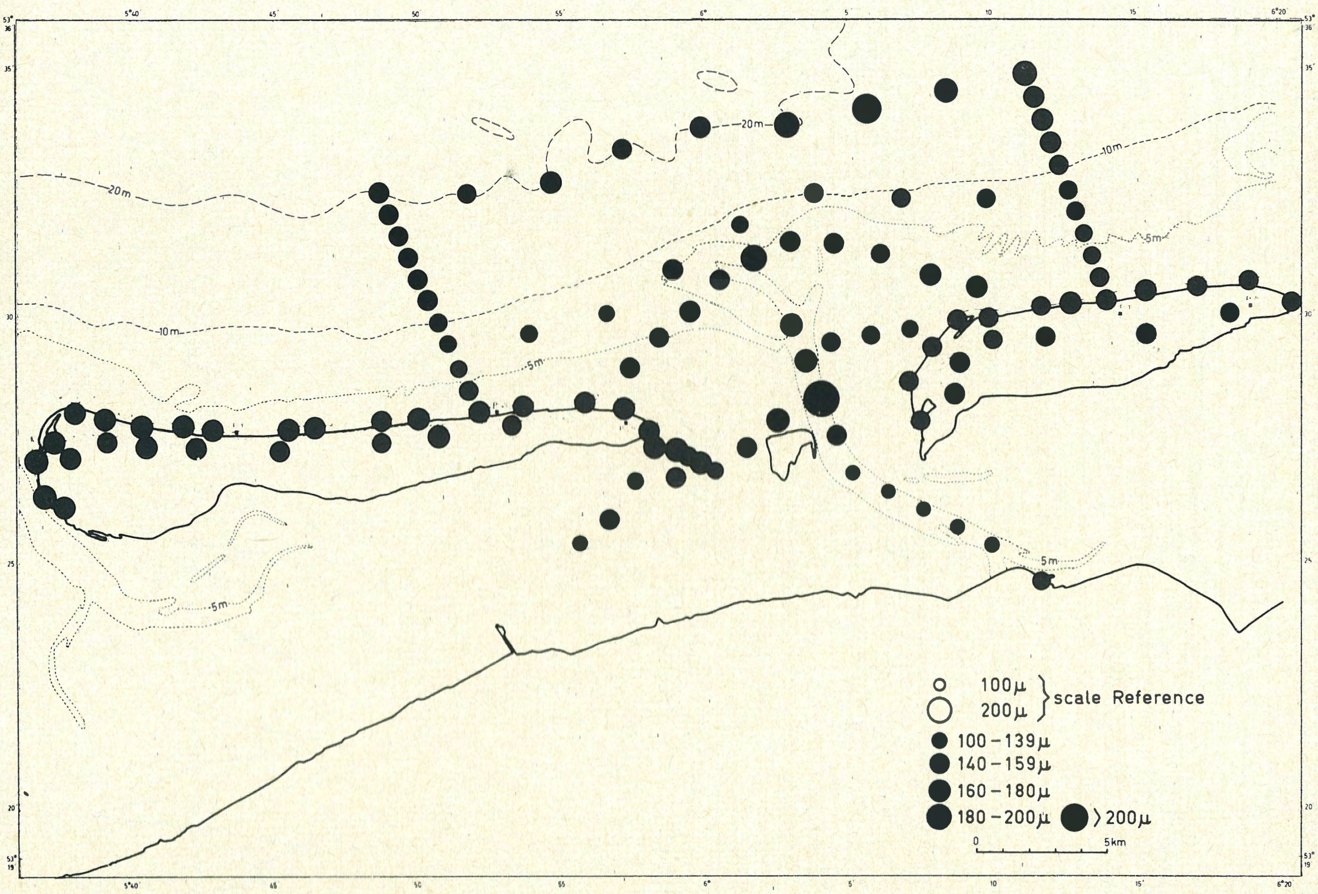


Fig. 2
Areal distribution of median grain-sizes.

Density measurement

The density separation was performed on $\frac{1}{4}$ phi size fractions with a Krantz Isodynamic Separator (McAndrews, 1957). The instrument was used with a foreward inclination of 30° and a side slope of 20°. Three magnetic fractions have been separated from the non-magnetic fraction, which usually formed the bulk of the samples. The properties of the magnetic fractions are listed in Table 1. The setting of the apparatus has been chosen so, that the three fractions had a distinctly different hydraulic behaviour. The 0.4 Amp. fraction (mainly garnet) is hydrodynamically equivalent with a ½phi larger quartz fraction, the 0.8 Amp. fraction with an approximately $\frac{1}{4}$ phi larger quartz fraction. The 1.2 Amp. fraction has such a poor rollability, that it nearly compensates for the somewhat higher density, so that this fraction more or less behaves like the quartz fraction.

GENERAL ASPECTS OF DENSITY STUDIES

There appeared to be quite large differences in heavy mineral contents between samples, quantitatively as well as qualitatively. These differences are most pronounced is the finer size fractions (smaller than 150 mu). The coarser sieve fractions contain much less heavy minerals and show less mutual variations.

When fractions of the same fine size interval are considered, those derived from coarser sediments show higher percentages of heavy minerals than those obtained from finer samples. Moreover, the fine fractions of coarser sediments show a relative enrichment of the heavier 0.4 Amp. minerals.

In the area, most samples have their size mode in the 149-175 mu interval, which means that this size is regularly moved and redeposited. The 104-125 mu garnet grains are the hydraulic equivalence of this mode. For this reason, most

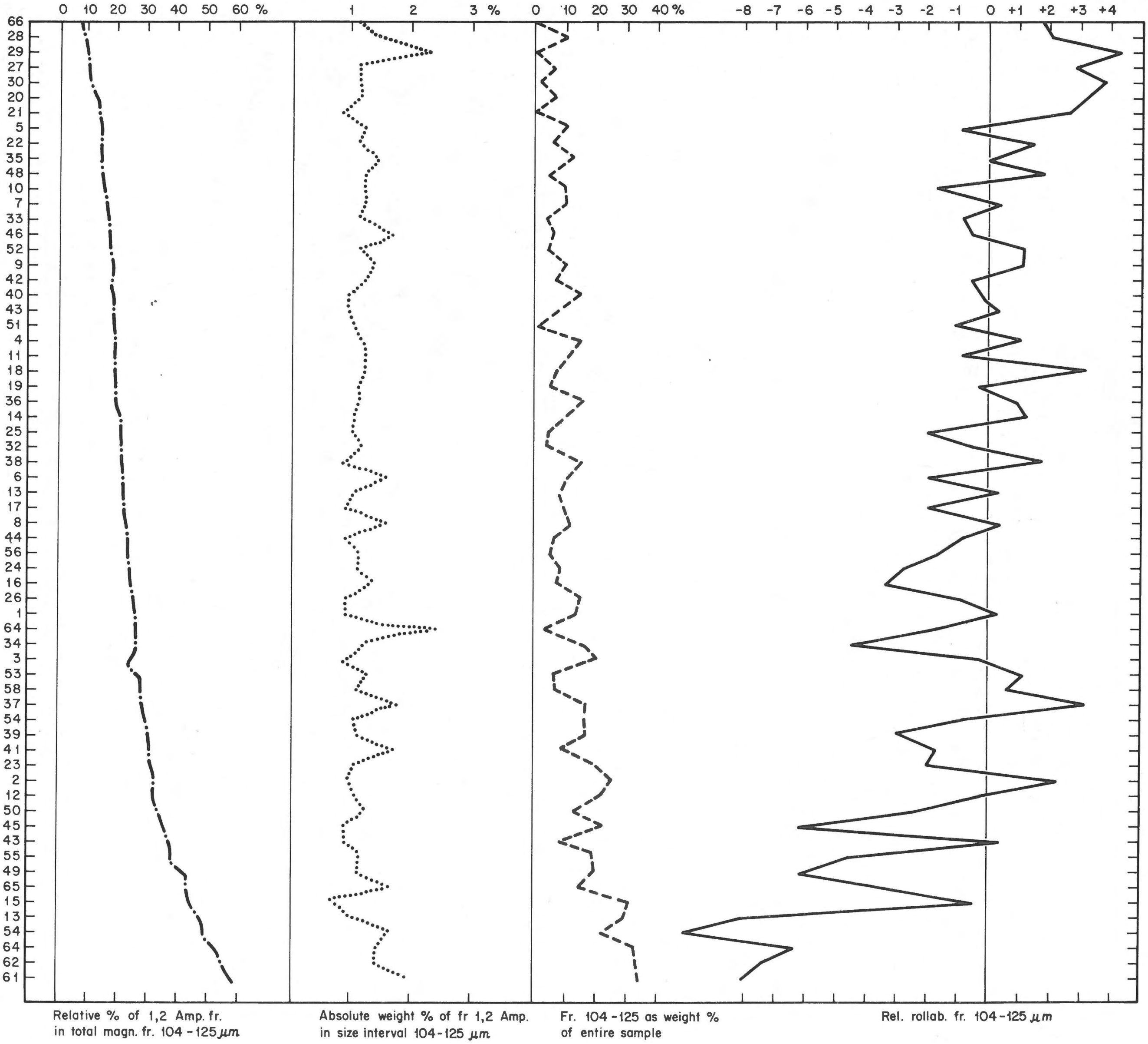


Fig. 3
Correlation between relative percentages of the 1.2 Amp. magnetic fraction in the total magnetic fraction of the 104-125 mu size interval with other sediment properties.

Table 1
Properties of the separated magnetic fractions (104-125 mu)

	0.4 Amp.	*0.8 Amp.*	*1.2 Amp.*	*Entire fraction*
	83% Garnet 15% Hornblende 1% Epidote 1% Tourmaline	32% Epidote 30% Hornblende 31% Tourmaline 5% Disthene 2% Staurolite	57% Muscovite 40% Saussurite 2% Epidote 1% Hornblende	84% Quartz 10% Feldspars 6% Heavy Minerals
Density	3.67	3.27	2.78	2.70
Rollab.val.	166.5	170	178.5	177
Term.fall.v.	1.85 cm/s	1.65 cm/s	1.32 cm/s	1.39 cm/s
Eq.Qtz.Sph.	182	167	147	145

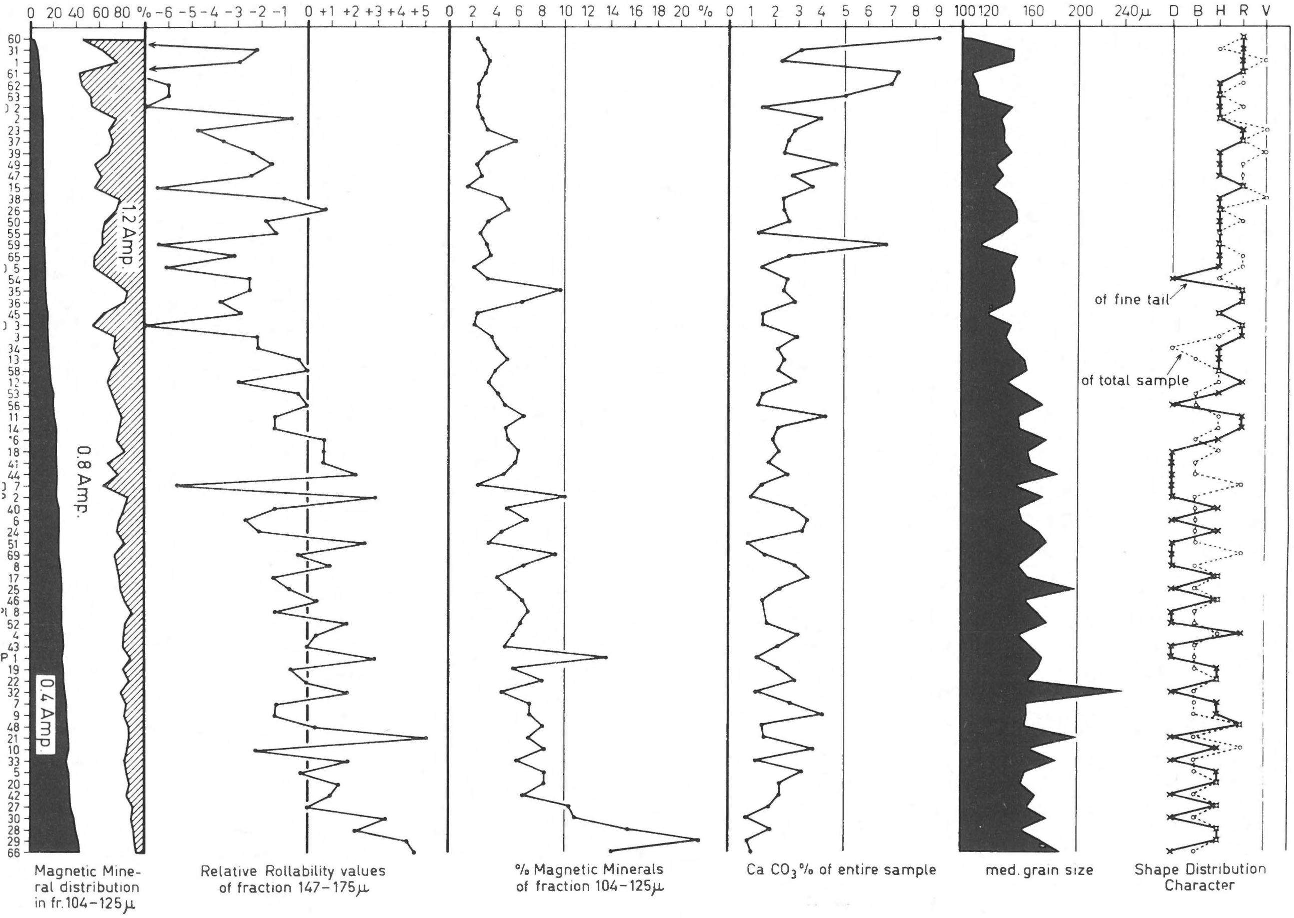


Fig. 4
Interrelations between mineral distribution, size, shape and depositional character.

attention has been paid in this study to the density distribution in the 104-125 mu size interval.

Before discussing the special density distribution in the area in a later chapter, we must look first at the general phenomea. In Fig. 3, some general aspects of the heavy mineral distribution in the 104-125 mu size interval are shown. The (marine) samples are listed in order of increasing weight percentages of the 1.2 Amp. fraction in the total of the magnetic fractions. There is a variation from 6-60%. In the second column, in which the absolute percentages are plotted, the 1.2 Amp. magnetic fraction makes up of the entire sample fraction. The percentages vary from 0.9 - 1.3%, with a few gusts to 2%. This was to be expected, since the 1.2 Amp. fraction is very similar in hydraulic behaviour to the quartz fraction.

In the third column, in which the percentages are plotted, the 104-125 size fraction makes up of the entire sample. Since the modes of the samples are coarser, this means that the lowest percentages occur in the coarsest samples. There is a rather good correlation between the coarseness of the samples and the relative scarcity of the 1.2 Amp fraction in the total magnetic fraction.

In the fourth column, the relative rollability values are plotted of the entire 104-125 mu fractions. There is a rather good negative correlation here. Well rollable grains in the fines mean lag conditions, which goes hand in hand with somewhat coarser sediment and relative richness in the heavier minerals, hence a paucity of the 1.2 Amp. fraction in the total magnetic fraction,

It is clear therefore that the 1.2 Amp. magnetic fraction in itself will be of little significance for a hydrodynamic interpretation and the heavier minerals are more promising, especially the garnet. However, when heavy minerals are used to distinguish between different source areas, it follows from the foregoing that preferentially those minerals should be used which are the hydraulic equivalence of the quartz fraction. The more a mineral is of a deviating nature, the more it is apt to specific selection compared with the bulk of the

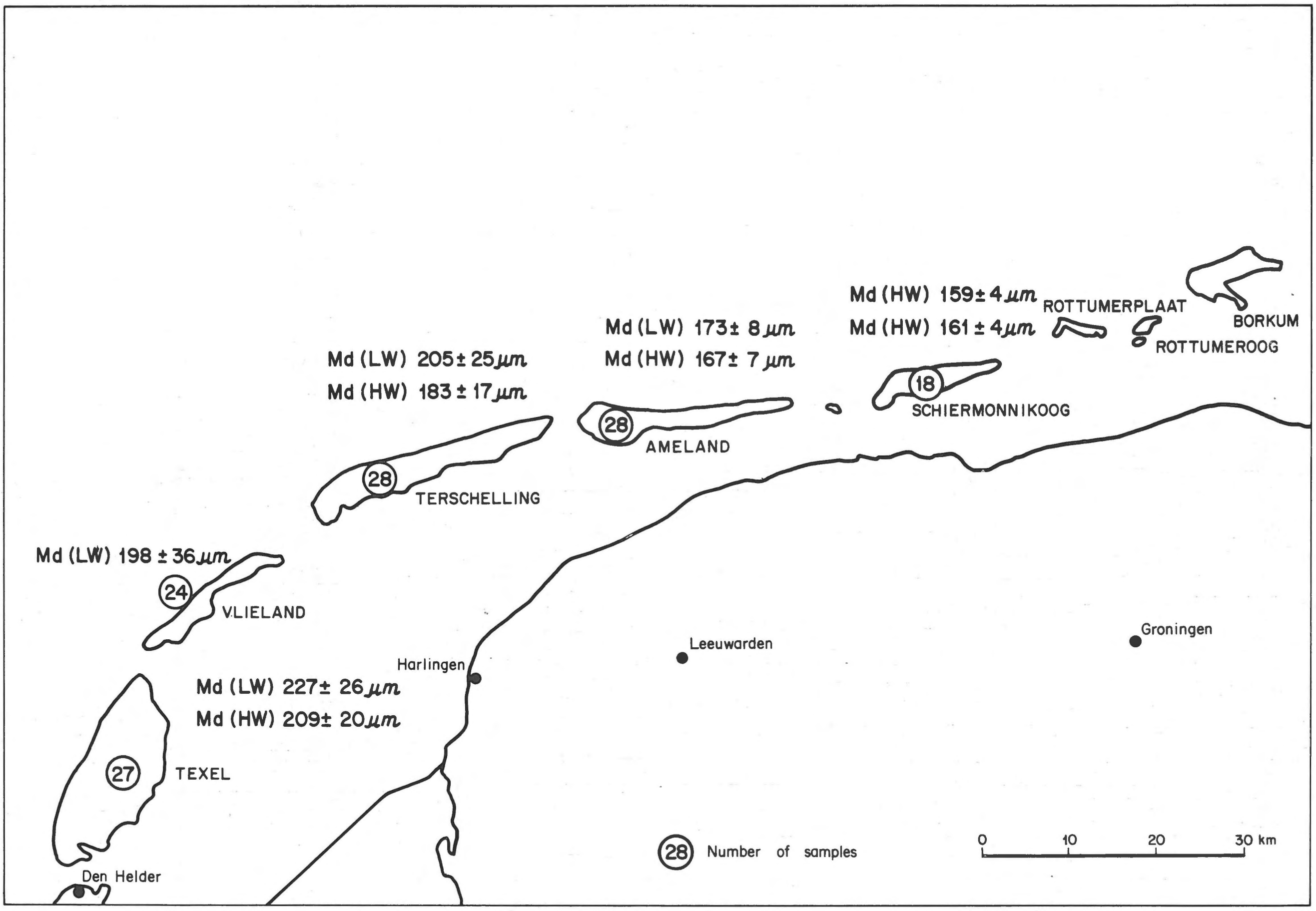


Fig. 5
Average median grain-size of L.W. and H.W. samples for five successive islands.

Table 2. Average size distribution of beach samples, taken 1 km apart

		P1	Q1	Md	Q3	P99
Schiermonnikoog						
17 beach samples,	HW-line	216 ± 19 mu	176 ± 8 mu	161 ± 4 mu	147 ± 4 mu	109 ± 5 mu
19 beach samples,	LW-line	303 ± 37 mu	176 ± 10 mu	159 ± 4 mu	144 ± 4 mu	105 ± 3 mu
Ameland						
26 beach samples,	HW-line	257 ± 22 mu	185 ± 11 mu	167 ± 7 mu	152 ± 5 mu	111 ± 8 mu
27 beach samples,	LW-line	301 ± 28 mu	198 ± 11 mu	173 ± 8 mu	156 ± 5 mu	116 ± 8 mu

sediment. Its occurrence and distribution in the sediment will then be related not only to its origin, but also to a high degree to the character of the depositional processes.

Since we are now after these depositional processes, we concentrate on the garnet percentages in this study. In Fig. 4, the same samples as in Fig. 3 are arranged in order of increasing garnet percentages of the magnetic fraction of the 104-125 mu size interval. There is a very good correlation with the rollability values of the 149-175 mu quartz fraction, which is the hydraulic equivalence. There is a positive correlation with the absolute heavy mineral percentages in the size fraction. There is a negative correlation with the CaCO3 contents of the entire sample. This is logic, because the carbonate particles are in general of a high susceptibility and low density, which give them opposite hydraulic characteristics compared to garnet. In the fifth column, a positive correlation with median grain-size is shown. But this correlation is only visible in the upper part of the column. The

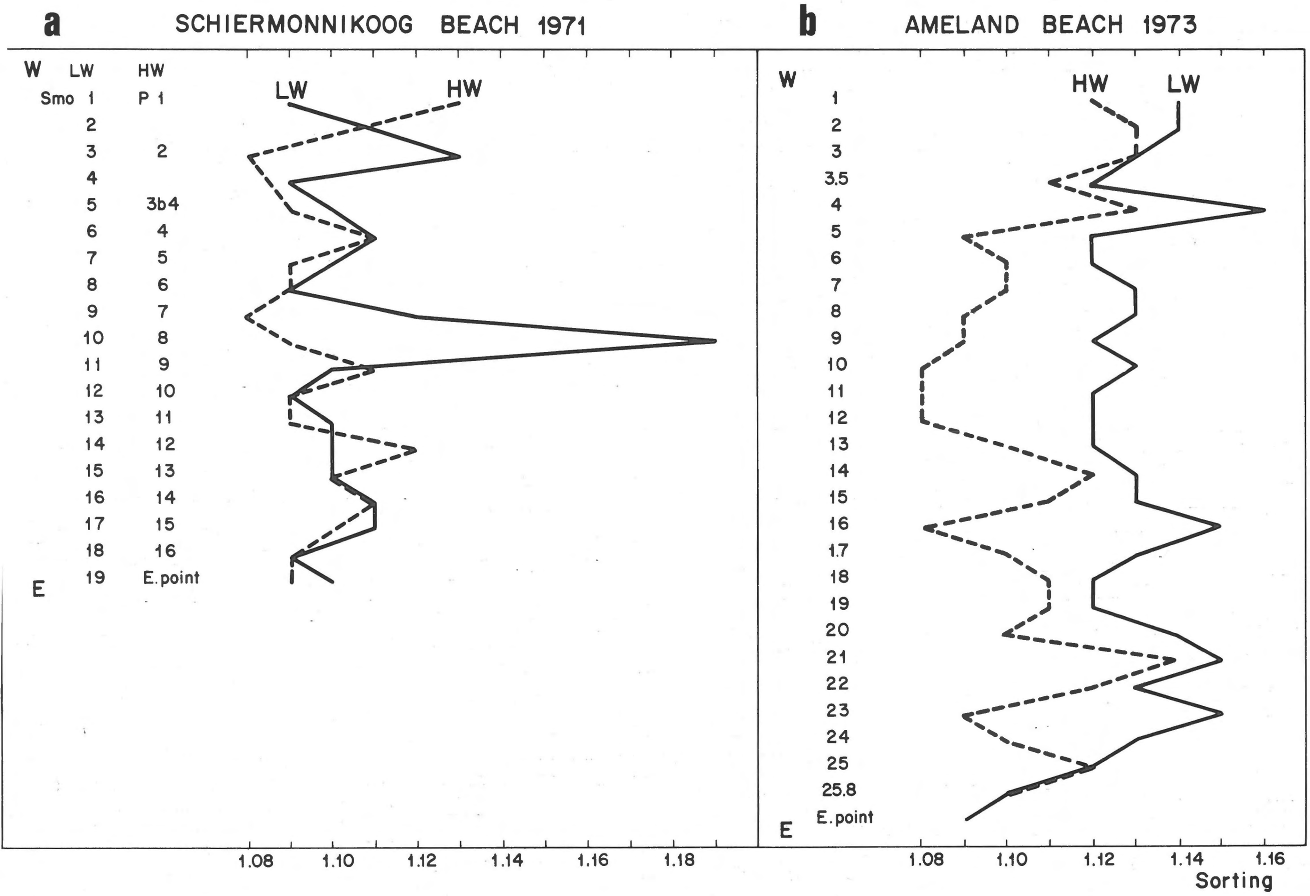


Fig. 6
Sorting values in W–E direction of L.– and H.W.L. samples for Schiermonnikoog (A) and Ameland (B).

reason is, that there are no coarser sands in the area. Here we have thus a good indication of the limited value of size for the dynamic interpretation. All other correlations continue over the whole sample list except size. In the last column, the shape distribution character of the samples is shown (see Winkelmolen, 1971). Low garnet percentages occur in the receiving deposits, high ones in the lag deposits.

DESCRIPTION OF THE ISLANDS

Size data

Grain-size analyses of beach sands of Schiermonnikoog show that the coarsest sands occur at the western point of the island and at the central part. The sorting of the sand at these locations is poorer than at the other parts of the beach. The beach sands of Ameland show the same phenomenon.

In most cases the average median grain-size of each foreshore of the dutch West Frisian Islands is finer than that of its western neighbour (Fig. 5, Table 2). The explanation is that the coarse part of the sediments of the foreshore and nearshore is trapped in the shoals and gullies of the outer tidal deltas. Only a part of the sediments of these deltas is taken up in the beach sands of the western ends of the islands.

The 5% value of the LW samples of Ameland is 252 ± 28 mu and of 19 LW samples of Schiermonnikoog 237 ± 27 mu. This shows that, although grains of 800 mu occur, the size fractions coarser than about 250 mu are scarcer on the beach of Schiermonnikoog than on Ameland.

The beach of the central part of Schiermonnikoog shows a variation in sorting between 1.09 and 1.19 at the LW line and between 1.08 and 1.11 at the HW line. The average sorting of all LW samples is 1.106 and of all HW samples 1.097 on Schiermonnikoog; thus sorting is better in HW samples. (Fig. 6A).

The beach of the central part of Ameland shows a variation in sorting between 1.12 and 1.15 at the LW line and between 1.08 and 1.12 at the HW line. The average sorting of

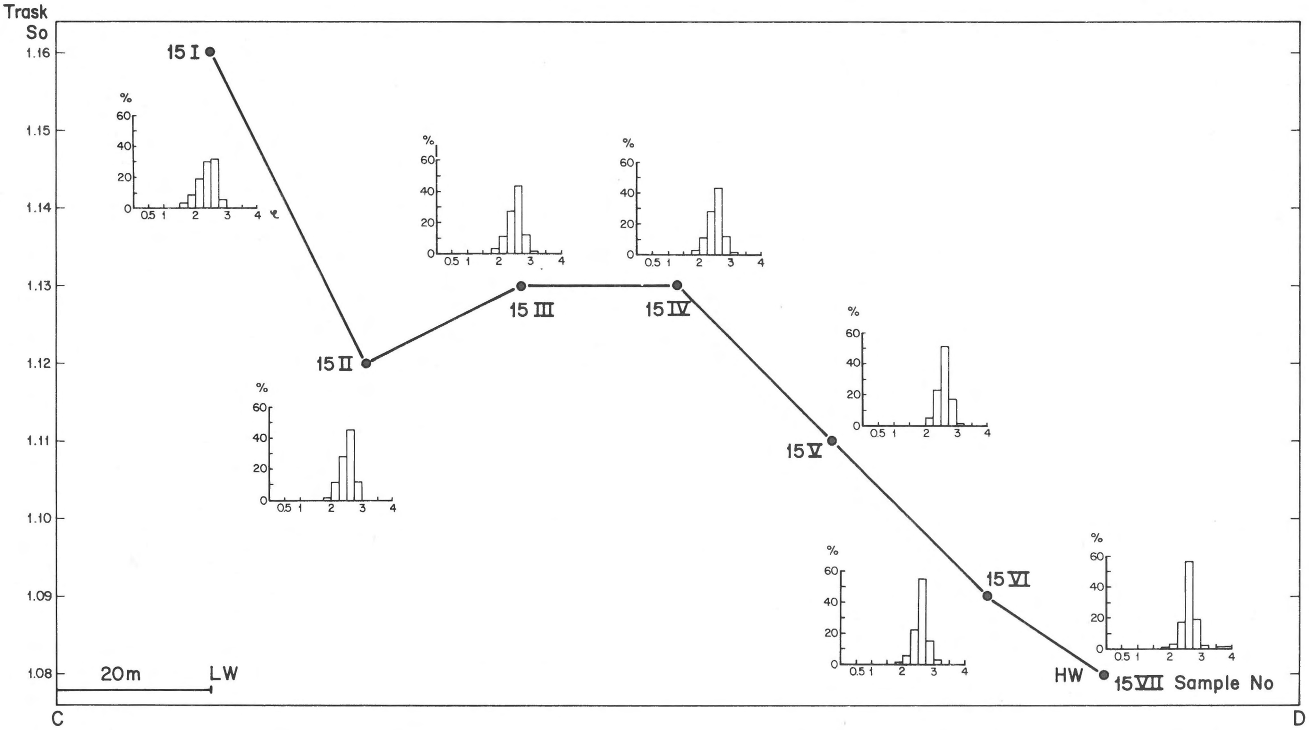


Fig. 7
Size distribution and sorting of samples in a run normal to the beach in between L.– and H.W.L. near Pole 15, Ameland.

all LW samples is 1.132 and of all HW samples is 1.108 on the island of Ameland, sorting also being better in HW samples. (Fig. 6B).

Generally the beach samples taken near the LW line possess more coarse material than the HW samples. The difference in grain-size composition between the individual beach samples is mainly caused by variation of the quantity of coarse grains. Hence, the coarse percentile P1 shows a large standard deviation (Table 2).

The beach sands of the western ends of both islands contain more coarse grains, because coarse size fractions from gully- and outer tidal delta sediments can be deposited there during westerly gales. The outer delta protects the western part of the islands from the full wave energy and deviates the long-shore current. Therefore, the influence of both these agents increases towards the eastern end of the islands.

Although the general slope of the beach is small, 2°, this is sufficient to create a size grading. The velocity of the upwash decreases upslope on the foreshore, hence the transporting power diminishes gradually and the coarser size grades will be deposited at the lower part of the beach.

The size of the sand becomes gradually finer towards the HW-line (Miller & Zeigler, 1968). Grain-size analyses of samples from section C-D at right angles to the coast (pole 15, Ameland) support this. (Table 3, Fig. 7).

Table 3

sample	P1	Q1	Md	Q3	P99	So
15-I	344 mu	220 mu	187 mu	163 mu	125 mu	1.16
15-II	279	194	169	154	106	1.12
15-III	289	196	170	154	113	1.13
15-IV	284	196	170	154	107	1.13
15-V	255	183	164	150	109	1.11
15-VI	245	180	164	151	111	1.09
15-VII	238	173	160	148	107	1.08

Grain-size distribution in samples between LWL (15-I) and HWL (15-VII) in a section normal to the beach near pole 15 (Ameland).

As the backwash passes over successively lower portions of the foreshore, it is passing over an increasingly coarse bottom. Large particles put into motion higher on the beach come to rest downslope as the velocity of the backwash diminishes. Fine particles put into motion near the top of the foreshore are transported downslope by turbulent flow and are trapped in an irregular way between larger grains. Therefore the median size decreases from the HW-line to the LW-line. The sorting of sands of the foreshore is good near the upper limit, but is poor on the rest of the foreshore due to the irregular distribution of the coarser size grades.

Table 4

sample	type	P1	Q1	Md	Q3	P99	max. grain-size
SMO 23	suspension	264 mu	170 mu	156 mu	140 mu	106 mu	500 mu
SMO 17	LW-line	286	169	154	138	105	800
Pl 15	HW-line	236	168	155	139	106	400

Grain-size distribution of a suspension sample compared with beach samples at the same locality on the beach of Schiermonnikoog.

It appears that the maximum grain-size of the LW samples is 800 mu whereas that of the HW samples is 400 mu on both islands. Hence the size fraction 400-800 mu is practically absent on the backshore. Comparison of two beach samples with a suspension sample taken at the same locality shows that sizes up to 500 mu can be held in suspension (Table 4). Grain size analysis of these samples gives analogous results, although the quantity of coarse material varies considerably.

Dune sands

According to investigations in Germany (Sindowski, 1973) the dunes of the East Frisian Islands Langeoog, Spiekeroog and Wangeroog could be subdivided into four groups according to median, roundness and sorting. It has been tried to obtain similar results at Ameland, which possessed a rather stable position during the past centuries. Therefore a number of 37 dune samples have been collected all over the island. These samples had the following size parameters: Q1 = 186 ± 8 mu, Md = 168 ± 3 mu and Q3 = 155 ± 3 mu, thus showing a very small range. The Trask sorting coefficient of the samples varies between 1.07 and 1.12, but not systematically. Moreover, there is only a small difference in size distribution between dune and beach samples at Ameland. The size parameters of 27 LW samples were Q1 = 198 ± 11 mu, Md = 173 ± 8 mu and Q3 = 156 ± 5 mu, whereas those of 26 HW samples were Q1 = 185 ± 11mu, Md= 167 ± 7 mu and Q3 = 152 ± 5 mu.

According to size and sorting, the dunes of Ameland cannot be subdivided into different genetic groups. The size parameters of the sediments of the adjoining islands differ substantially from the values given above, thus demonstrating that the sands of Ameland belong together and that the island was not much influenced by transportation of new material by longshore currents and beach drift.

In general there is not much difference between beach and dune sands. This is to be expected, because all available grain-sizes can be transported by the wind. Northwesterly winds blow sands from the beach into the dunes, whereas southwesterly winds can bring the sand back to the beach. Moreover, the outer ridge of the dunes is subject to severe erosion during gales. The eroded sand will be deposited on the foreshore and the shallow offshore.

The dune sands of Schiermonnikoog are finer than those of Ameland, which is in accordance with the grain-size of the beach sands. The dunes of Schiermonnikoog are less sorted than the dunes of Ameland. Especially at the western part of both islands the sorting is poorer than at the rest of the island (Table 5).

Section A-B at right angles to the dune coast of Schiermonnikoog near pole 3 shows that the median grain-size diminishes from LW mark to HW mark as predicted, but increases again towards the dunes. The section runs NW-SE, which is the prevailing wind direction. It is held that the coarse grains form a lag deposit, as the fines are selectively removed either by wind or during spring tide. (Fig. 8)

The sorting of the samples from this section shows that the HW samples are better sorted than the LW samples, but that beyond HW mark the sorting gets poorer gradually. There is no difference in grain-size or sorting between the upper part of the beach and the dunes.

The CaCO3 content

The CaCO3 content of 28 LW samples of the island of Ameland was 1.3% and 1.2% of 28 HW samples. The difference is caused by the somewhat larger amount of shell hash in the LW samples, in which it forms a substantial part of the coarse fractions. The lower CaCO3 content of the older dunes of Ameland, which amounts 0.5% in 9 samples collected over the island, must be attributed to weathering. These old dunes were situated at least 400 years at the same locality.

Shape data General remark

During the elaboration of the measurements, especially those on shape and density, it became clear that Ameland and Schiermonnikoog must have run through a completely different genesis, though topographically they seem rather similar. Ameland e.g. has ten times more garnet in the 104-125 mu size interval than Schiermonnikoog. These results were very unexpected. Since our sampling program has been based on the presumption of a large similarity, only the outer tidal delta in between both islands has been sampled. From preliminary results from other wadden islands we got the impression that Schiermonnikoog represents the more "normal" type of development in the area and that Ameland has more extraordinary features. For this reason we shall start with the eastern island.

Table 5 Average size distribution and sorting of dune samples.

	Q1	Md	Q3	average sorting	sorting range
Ameland					
1968 11 dune samples	183 ± 9 mu	166 ± 6 mu	154 ± 4 mu	1.095	1.07 – 1.11
1974 37 dune samples	186 ± 8 mu	168 ± 3 mu	155 ± 3 mu	1.088	1.07 – 1.12
Schiermonnikoog					
1971 11 dune samples	180 ± 11 mu	163 ± 4 mu	149 ± 3 mu	1.098	1.08 – 1.17

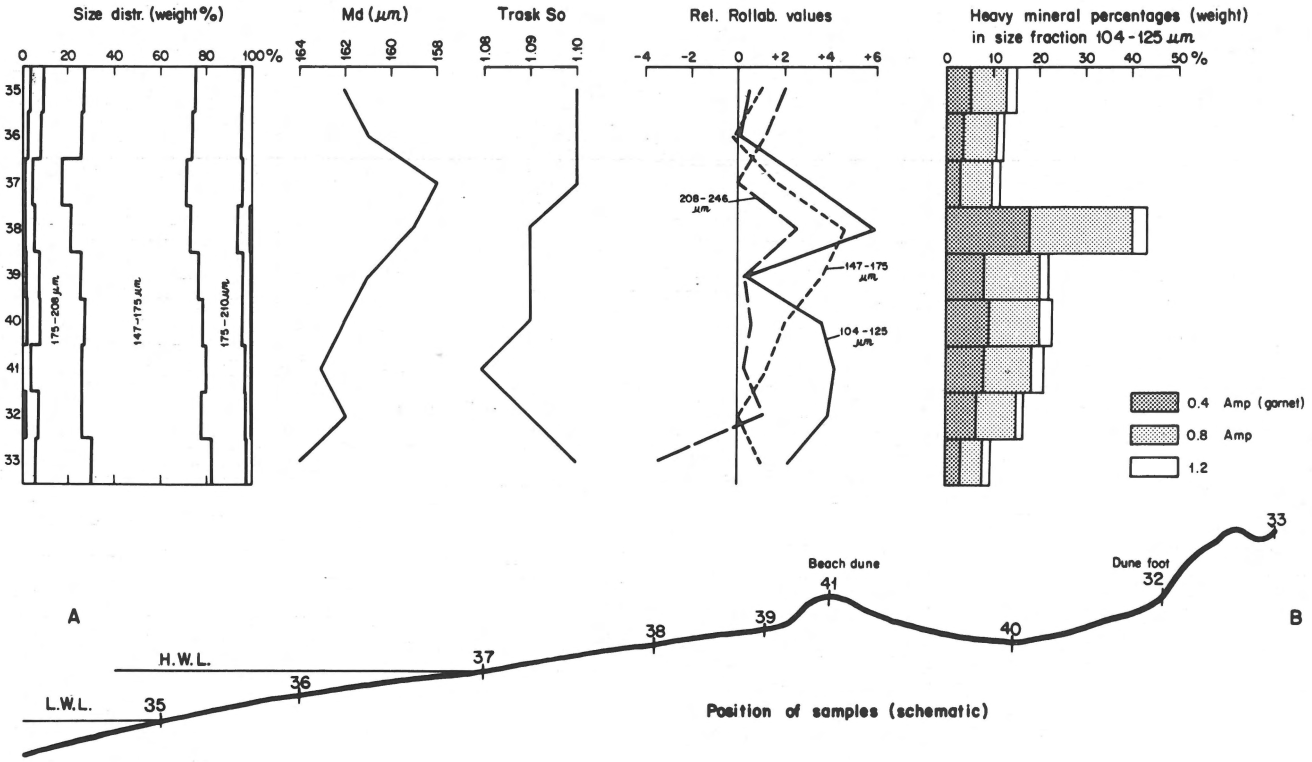


Fig. 8
Rollability values, heavy mineral distribution and size-values in a section normal to the beach near Pole 3 on Schiermonikoog. (A-B on sample location map).

The island of Schiermonnikoog

In Fig. 9, the S.D.C. of the individual samples are plotted, together with their size distribution as histograms. The beach samples show a wider variation in S.D.C. than the dune samples. This is a general phenomenon, because of the usually much broader spectrum of local depositional processes along the beach, especially near the low water line.

When the S.D.C.'s are averaged for groups of samples, such local variations are smoothed-out and such a composite diagram gives a better insight in the more collective properties of the beach samples. In Fig. 10A, such composite S.D.C. curves are given for the western L.W.L. beach samples (S.M.O. 1-5) the north coast beach samples (S.M.O. 6-18), samples of the outer tidal delta, the inner tidal delta and the shallow off-shore.

At one glance it is clear that the beach samples show a very close resemblance with those of the outer tidal delta. This is especially so for the samples of the north coast.

Along the west coast of Holland, the beach sands originate mainly by wave action from the shallow offshore. A deposit-repository relation can be demonstrated there (Wkm ,1971). A same mechanism is excluded for the bulk of the beach sands of Schiermonnikoog. If an analogous mechanism would

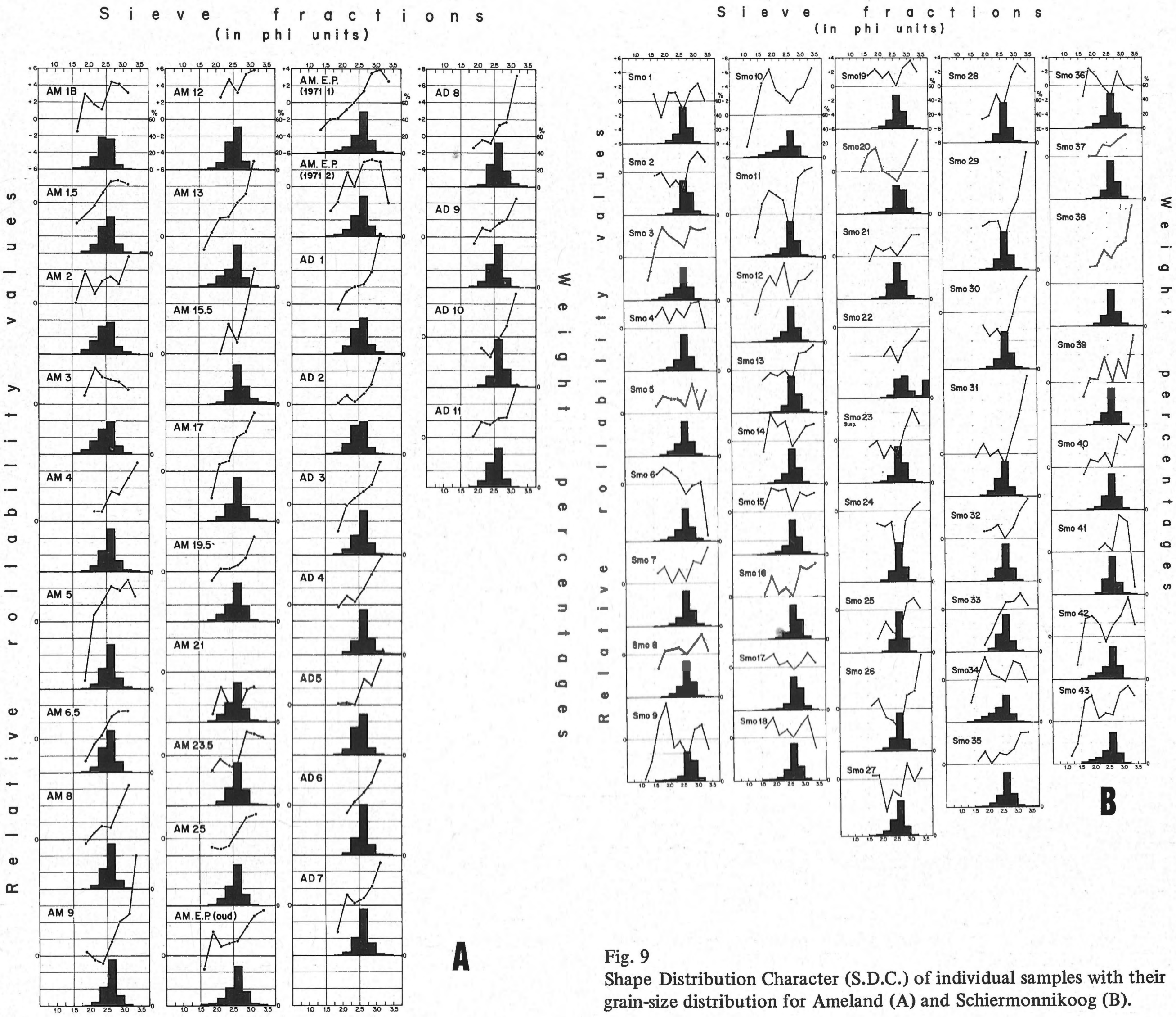


Fig. 9
Shape Distribution Character (S.D.C.) of individual samples with their grain-size distribution for Ameland (A) and Schiermonnikoog (B).

have acted here as well, the beach sands would have been of lower relative rollability than the delivering offshore sands, for the most susceptible grains would have been preferentially removed by the waves. Contrary, the beach sands are considerably better rollable than the shallow offshore sands, which excludes the latter as a source.

The outer tidal delta remains then as the only reasonable source for the beach sands. As was pointed out in W and V (1974) the high energy conditions prevailing on the outer rim of the tidal delta form there a lag deposit, characterised by high rollability values. The material that is winnowed out is partly deposited in the inner zone of the delta, which causes the low rollabilities there. The beach sands of Schiermonnikoog, however, have rollability values which are only 1-2% less than the sands from the outer tidal delta. It remains to be explained then why both sands do not have a clear deposit-repository relation, expressed as complementary shape characteristics. One reason could be that selection on the outer rim of the tidal delta is so severe, that no susceptible grains at all are left. The high rollability values on the outer tidal delta represent then the average of a very narrow spread. From such a narrow shape spectrum, later transport processes have little choice and can only slightly modify the shape characteristics, resulting into an "inherited" S.D.C.

If the present outer tidal delta is the source of the beach (and dune) sands, then a west-east transport mechanism must exist. Now, beach drift is a common mechanism, observed on many coasts. Such a mechanism leaves its mark in the sediment as a distinct trend in size, shape and density in the transport direction (e.g. MacCarthy, 1933, Wkm, 1969).

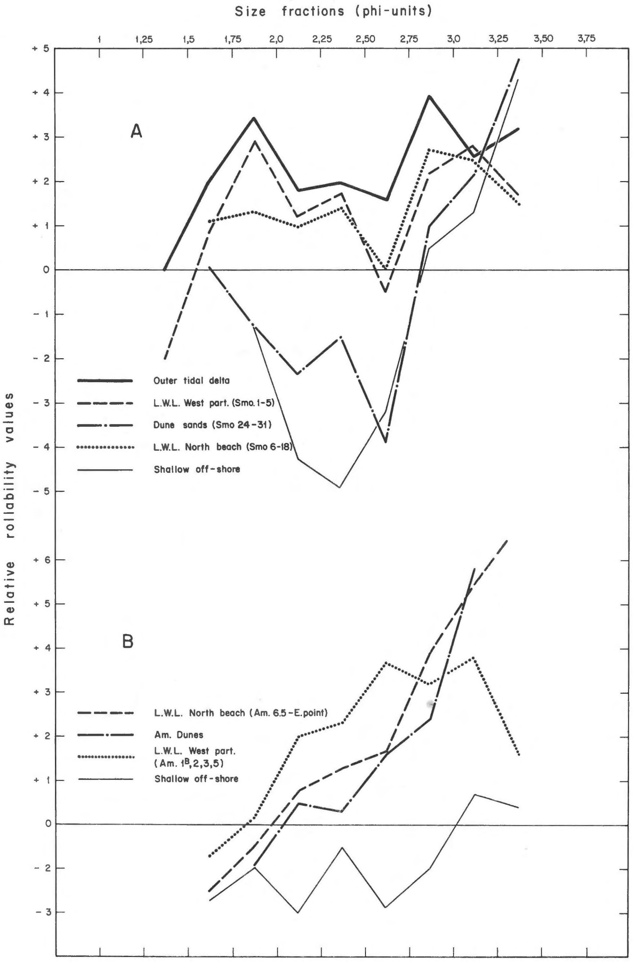


Fig. 10
Composite S.D.C. graphs for different environments for Schiermonnikoog (A) and Ameland (B).

In Fig. 11, the rollability values of the different size fractions are shown in the west-east direction. There appears to be no distinct trend. The western side and the middle of the island show rather large variations, while the eastern samples are all close to an average.

Also the sizes (Fig. 2) and the heavy minerals (Fig. 12) do not show a clear transport trend towards the E. From the map and from aerial photographs it appears that a system of sand waves, striking SW-NE is approaching the beach from the outer tidal delta. Such a way of transport is not very suited to achieve much selection. Most of the time, the material is immobile in the sandwave and selection can only occur during the short time interval the sand moves from one wave to the other. Although such a mechanism could explain the lack of trend in the beach sands, there is still another possibility, which to our insight is more likely.

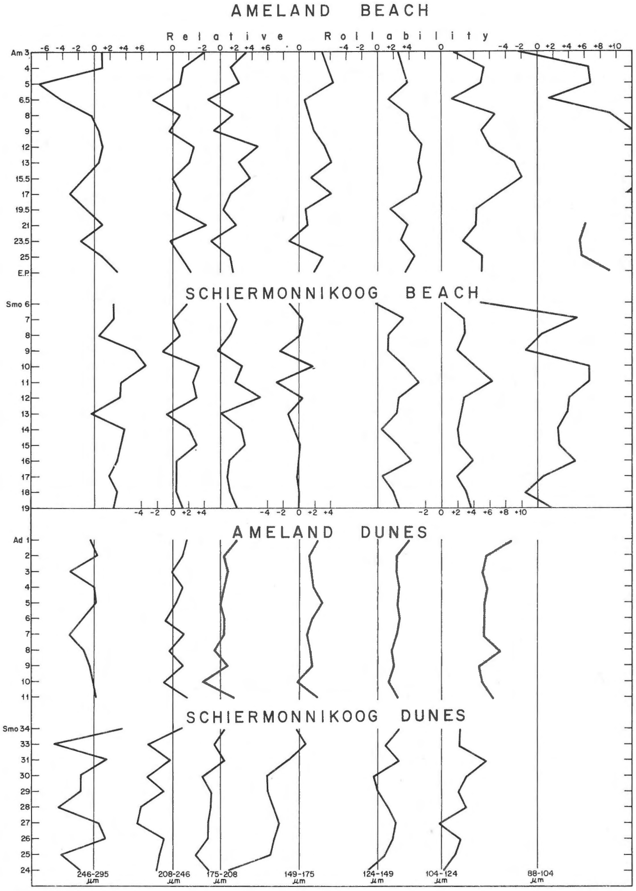
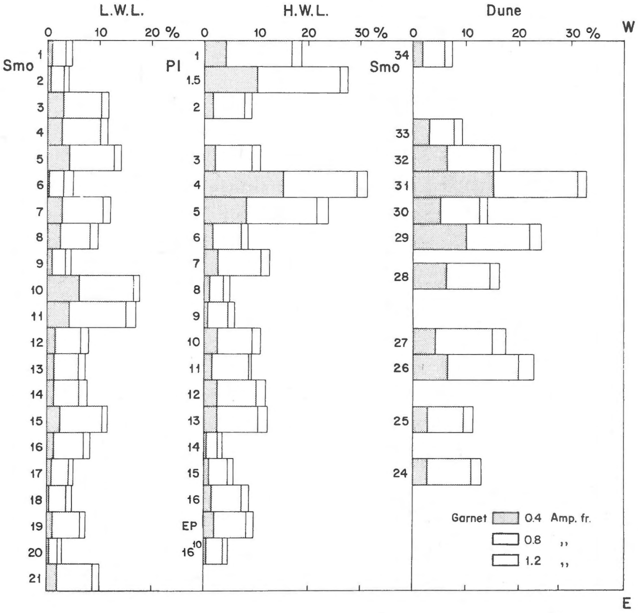


Fig. 11
West-east trends in rollability values for different size-fractions.

Fig. 12
Heavy mineral distribution in the 104-125 mu size fractions in W–E direction for L.W.L., H.W.L. and dune samples on Schiermonnikoog.



From the old maps it is obvious that the island has been very mobile in the last three centuries. Each time the tidal channel outlet shifted, also a new outer tidal delta will have been built-up and the former delta, having lost its supply, will have been eroded and delivered material for the beach. We think it most probable therefore that the character of the beach sands is for a large part inherited from former tidal deltas and only to a small extent from the present one.

The dune sands of Schiermonnikoog are considerably less rollable than the beach sands, except for the 88-105 mu size fraction, which is better rollable (Fig. 10A). This picture is in accordance with our results in all other beach-dune combinations. Everywhere, the wind picks up the most susceptible grains, leaving the better rollable behind on the beach. However, the dune sands on Schiermonnikoog show a S.D.C. which deviates from most other dune sands. Practically all other dunes so far investigated and also the eolian coversands showed a rising curve type, i.e. they had their lowest rollabilities in the coarsest fraction with increasingly better rollabilities for successive finer sizes. The dune sands on Schiermonnikoog show for the size fractions from 300-175 mu a downsloping trend. Normally, such a downsloping trend is typical for lag deposits. It is impossible that the coarsest sizes of these dune sands belong to a separate population with lag characteristics, for especially the coarsest grains that reach the dunes should have the most pronounced receiving character. And indeed they have, because their rollabilities are considerably less than those of the delivering beach sands. Remarkable is that in this size interval the S.D.C. curves of the dune sands run parallel with those of the beach and the outer tidal delta (Fig. 10A). Therefore, a same explanation as for the beach S.D.C. can be used, i.e. that the lag character is inherited from the former origin as outer tidal delta with too narrow a spectrum of shapes that a normal dune S.D.C. could be developed.

Contrary to the beach sands, the dune sands on Schiermonnikoog show a west-east trend. This is especially clear for the rollability values (Fig. 11) which gradually become more negative towards the east for all size fractions. But also the heavy mineral concentrations in the 104-125 mu size fraction show the same trend, viz a decrease in garnet content and in absolute heavy mineral content towards the east (Fig. 12). Especially the oldest dunes on the west side of the island have high garnet percentages.

There must be a net transport by wind from west to east, causing a lagging behind of better rollable and heavier grains in the west. At present, the dune vegatation is preserved by men. In former centuries, much more sand movement by wind in the dune area must have occurred. However, in between the high water line and the foot of the dunes, this mechanism could still be active.

Density aspects

In Fig. 12, the absolute percentages are shown for the three magnetic fractions in the 104-125 mu size interval of L.W.L., H.W.L. and dune samples from west to east.

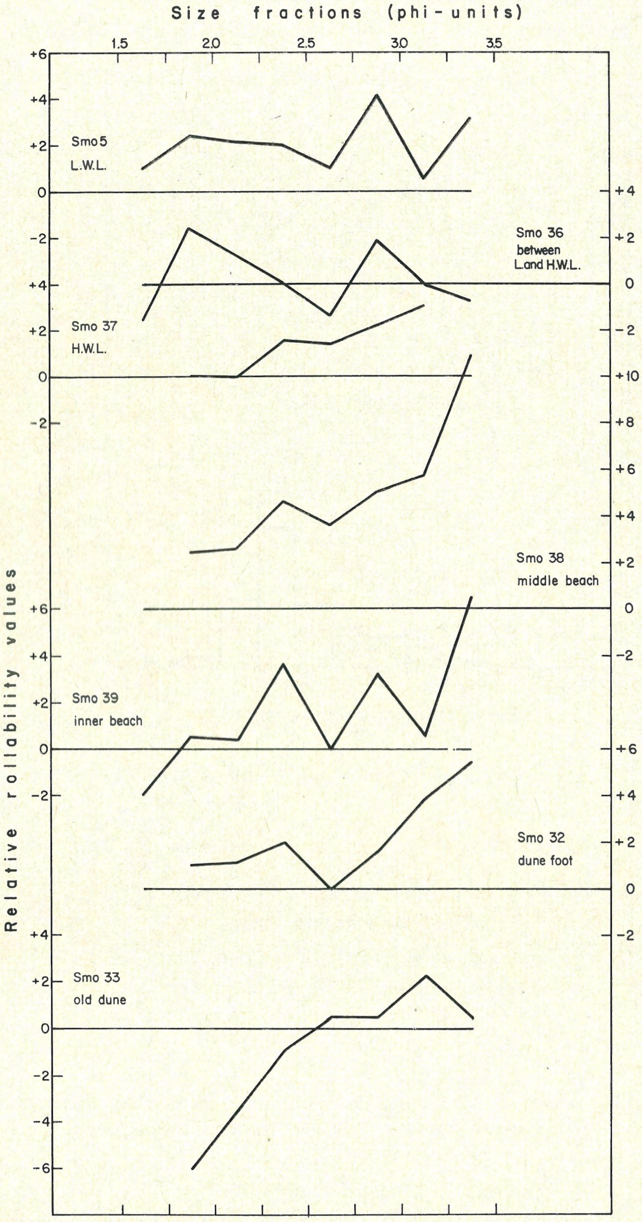
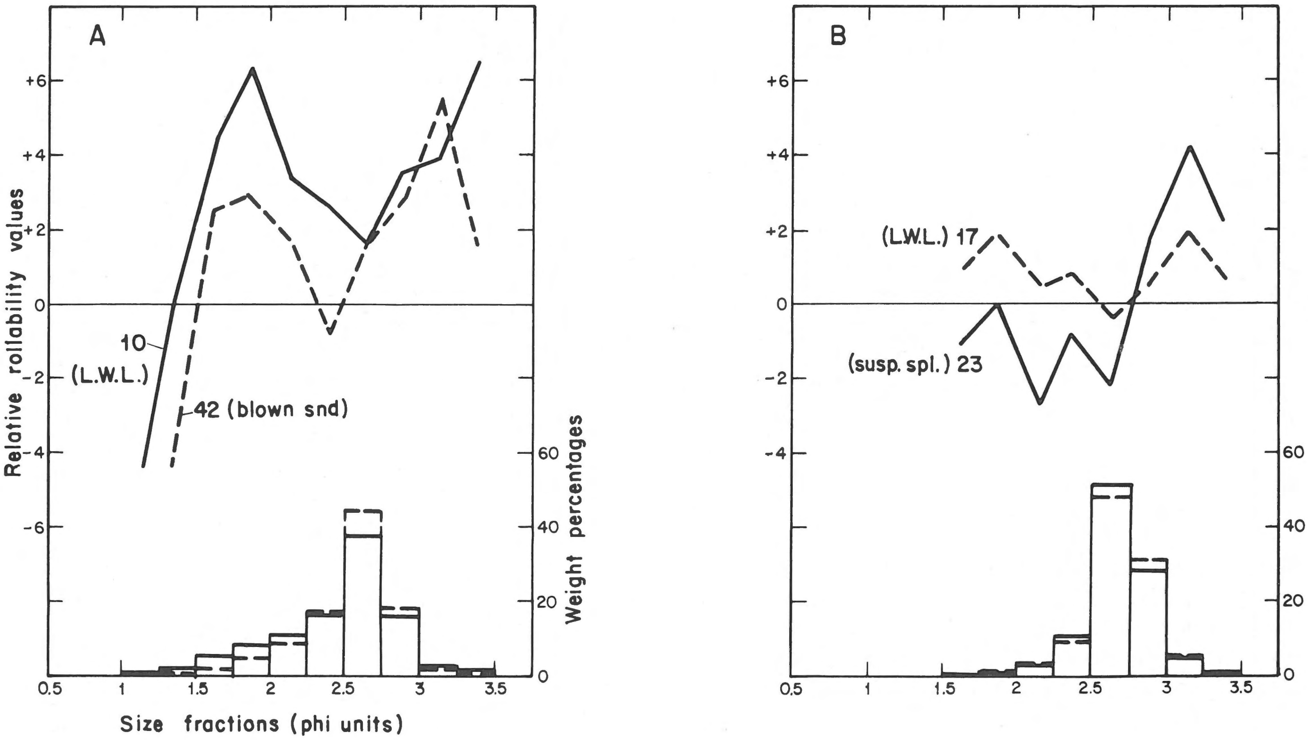


Fig. 13
S.D.C. of samples in a run normal to the beach near Pole 3 on Schiermonnikoog. (for situation of samples, see Fig. 8).

The percentages of the 1.2 Amp. magnetic fraction are very monotonous, due to its similarity in susceptibility to the quartz fraction of this size. The garnet percentages show the largest variations.

In all three types of samples, the garnet (0.4 Amp.) percentages are highest in the samples from the western part of the island. The L.W.L. samples show a more regular pattern than the H.W.L. samples. Although the general trend is the



	Sample 10 (L.W.L.)	Sample 42 (blown. snd.)
Md	170µm	165µm
So	1.19	1.13
Density Distrib. fr. 104 – 125µm		
0.4 Amp.	6.2 %	1.1 %
0.8 Amp.	10.0 %	2.0 %
1.2 Amp.	1.5 %	1.3 %

	Sample 17 (L.W.L.)	Sample 23 (Suspension)
Md	154µm	156µm
So	1.11	1.10
Density Distrib. fr. 104 – 125µm		
0.4 Amp.	0.65 %	0.3 %
0.8 Amp.	3.10 %	2.1 %
1.2 Amp	1.10 %	1.1 %

Fig. 14
Comparison of S.D.C., size distribution and heavy mineral content between (A), a blown sand with the underlying beach sand and (B) a suspension sample from the surf-zone with the adjoining L.W.L. beach sample.

same for both, the H.W.L. samples are locally very rich in garnet. In detail, the sites of high percentages in H. and L. water samples do not correlate.

The garnet percentages in the dune samples are higher than those in the beach samples. This goes hand in hand with high relative rollability values for this size in the dunes and a relative paucity of this size in the dunes. This was explained (Wkm, 1969) by assuming that during the sand storms, the more susceptible grains of this size can by-pass the dune area, leaving the well rollable and heavier grains selectively behind. Size, shape and density data suggest a net eastwards transport of sand in the dune area. This should be held responsible as well for the higher garnet percentages in the western dunes.

In order to obtain a closer insight in the selection processes, a section was sampled normal to the beach near pole 3 on the west side of the island. The section had a NW-SE direction, thus parallel to the prevailing winds. The run contains a L.W.L., a halfway H.W.L., a H.W.L., a middle beach, an inner beach, a dune foot an a real dune sample.

The S.D.C. of the sample is shown in Fig. 13 and the heavy mineral percentages of the 104-125 mu fraction in Fig. 8.

The L.W.L. sample gives a more or less neutral curve. The midwaterline sample shows a receiving character for the coarsest grains and a pronounced lag character for the grains from 149-250 mu. In the H.W.L. samples, the coarse grains are very rare. For the grains from 125-250 mu, the character is receiving. From low to high water line, there is a decrease in heavy mineral content.

The greatest contrast we find in the middle-beach sample. The S.D.C. is strongly receiving with high positive rollability values. This is most probable due to the blowing out of the more susceptible grains either towards the dunes or back to sea. This shows as well in the sharply increased heavy mineral content of this and all other dry-beach samples, which also show positive rollability values.

Clearly, the main selection takes place on the dry beach between the H.W.L. and the dune foot. This explains as well the large variations in the H.W.L. samples in Fig. 12. A few meters deviation from the H.W.L. could lead one already in the area of main selection.

During a visit on the island there was a strong south-western gale which blew sand from the higher beach on the wet beach during the low tide, forming there a thin layer of a few cm thick. Fig. 14A show the S.D.C. of this blown sand, compared with the underlying wet beach near pole 8. The curves are almost parallel.

In the coarsest sizes, the blown sand is about 4% less rollable than the underlying beach sand. The blown sand is a trifle finer as well.

Furthermore, there is a marked paucity of the heavier minerals in the blown sand. All this shows that even short wind transport is a very effective mechanism to achieve selection.

Another experiment was made near pole 15. During N.W.wind (about 5 or 6 Beaufort scale) repeated water samples were taken of the uppermost water layer in the surf zone at about one meter water depth. The samples were taken in a plastic bag and each time the water was decanted. A rough estimation gives about 5 gram sand per liter. The properties of the suspension sample are shown in Fig. 14B and compared with the adjoining L.W.L. beach sample. The suspension sample is slightly coarser than the beach sample. For the grains down to 149 mu, the suspension sample is about 2% less rollable, for the smaller grains the reverse is true. The garnet concentration of the 104-125 mu size interval is for the suspension sample about half, for the 0.8 Amp. magnetic fraction it is 2/3 and for the 1.2 Amp. fraction is the same as for the beach sample.

Admittedly, one sample under one weather condition is not much to base a story on. But the results with this sample fit into the whole picture hydrodynamically as well as regards the areal size, shape and density distribution. Apparently, in the surf zone the material is very mobile. The most susceptible and lightest grains are preferentially in transport and can be removed either laterally or back towards deeper water. The slightly increased median grain-size points towards the removal of the finest material, which is apparent as well from the high rollabilities of the grains smaller than 125 mu.

The island Ameland

In Fig. 9 it can be seen that there is a marked difference in S.D.C. between the samples at the west part (Pole 1-5) and those of the rest of the island. In Fig. 10B composite S.D.C. diagrams are shown for both parts separately, together with one for the dune sands. It appears that the S.D.C. of the westernmost beach samples show an analogy to those of the outer tidal delta in between both islands. (10A). The rest of the beach samples show steeply rising S.D.C. curves, which are very similar to those of the dune sands. The dune sands are only a trifle less rollable than the beach sands. Very remarkable are the rather high relative rollability values of the 149-175 mu size interval, which is the mode in the beach as well as in the dune sands.

Like on Schiermonnikoog, also the beach sands of Ameland are considerably better rollable than the sands in the shallow off-shore in front of them, which excludes the latter as a source. Obviously, along the barrier islands in the north another transport mechanism is working than along the west coast of Holland.

Since it can be presumed that the outer tidal delta west of Ameland will have similar characteristics as the tidal delta west of Schiermonnikoog, the westernmost sands of Ameland will have been derived from the adjoining tidal delta, like on the other island. But the rest of the beach samples on Ameland is completely different from those on analogous places on Schiermonnikoog.

If we look at old maps of the area, we can see that the north coast of the island Ameland has been eroded considerably. In the middle of the island e.g. the H.W.L. retired 900 m since 1809. This implies that most of the recent beach sands must formerly have been dune sands. Furthermore, the combination beach-dune must have supplied large quantities of sand to the shallow off-shore area.

In Ameland, as in Schiermonnikoog, there is no clear W–E trend in shape values along the beach and only a faint trend in the dune sands. Beach drift therefore cannot be responsible for the removal of sand.

From the recent history we know that after strong storm surges, large quantities of sand disappear in a very short time to the shallow off-shore. During normal, more quiet conditions, a part of the sand is transported back to the beach as slowly prograding bars, built up by wave action, but a large part of the lost sand cannot reach the island again.

During the last 400 years, Ameland has retained its same longitude. Since the width of the dune belt is only a few hundred meters till at most one kilometer, it can be estimated that this process of dune-beach-dune-beach transformation must have occurred several times during the last four centuries.

The close resemblance between beach and dune sands on Ameland is therefore very understandable. For, dune sands always have a strong receiving character. When such a sand is removed "en vrac" to the shallow off-shore and worked back to the beach, this receiving character will be preserved, because this process as well produces a beach sand with a receiving character. Be blown out again to the dunes will then hardly alter the characteristics, since from origin these sands have already the characteristics inherited from former wind transport.

Density aspects. The most salient feature in Fig. 15 are the

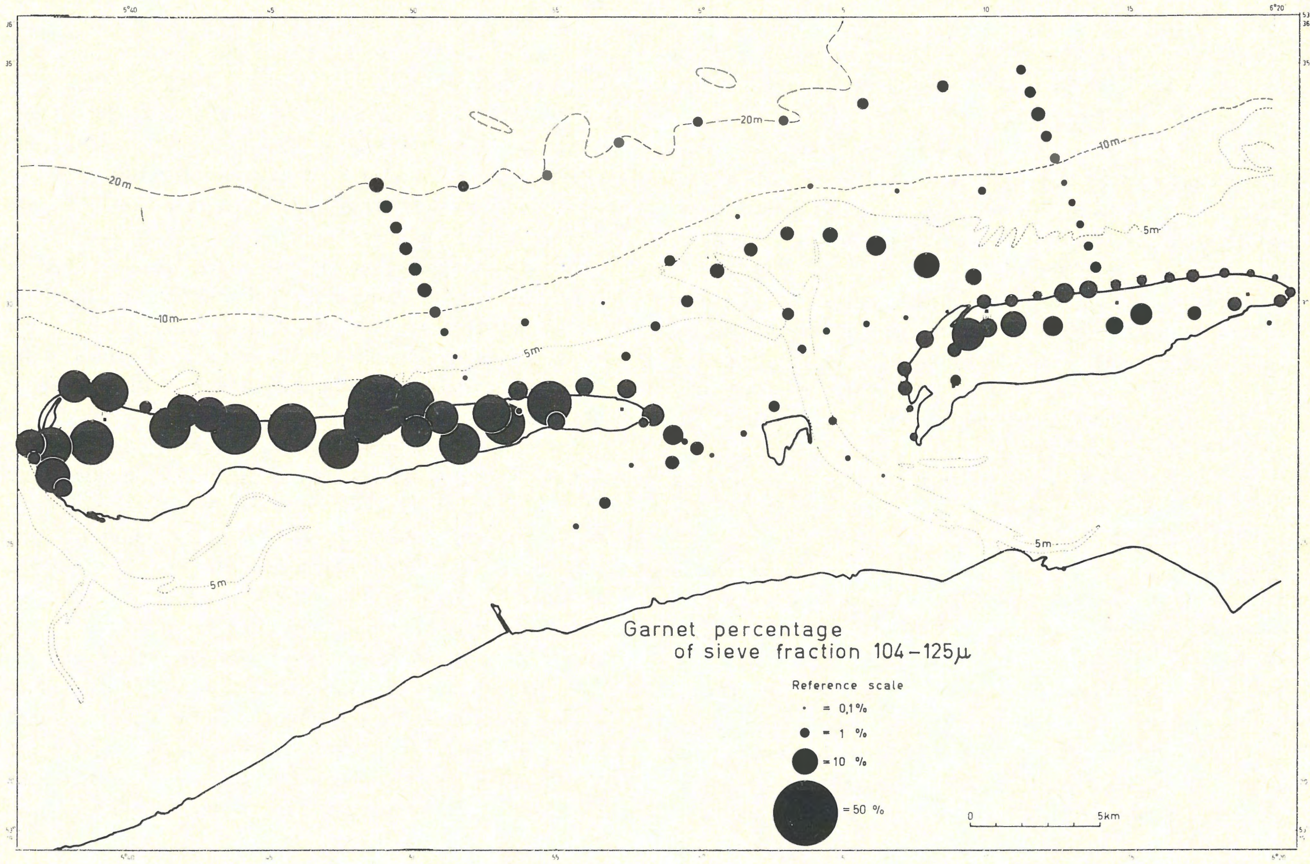


Fig. 15
Areal distribution of the 0.4 Amp. (Garnet) percentages in the 104-125 mu size fractions (compare with Fig. 2).

extremely high garnet percentages in the 104-125 mu size interval in the Ameland samples. The dots on the figure are constructed with their radius equivalent with the square root of the percentages, to avoid exaggeration. These garnet percentages are eight to ten times higher than on Schiermonnikoog. The two islands west of Ameland show again values, which are in the order of magnitude of those of Schiermonnikoog.

The garnet percentages in the 149-175mu size interval are extremely low for all samples in the whole area, including the marine samples. These values range from less than 0.1% to about 0.4% and no areal trend could be distinguished.

To explain the high garnet percentages in the fine size fractions (and the high rollabilities) we must assume that during the removal of sand from the beach and dunes under high energy conditions, there must occur selection viz a separation of the most susceptible grains especially in the finer size fractions.

Since the process of removal from the beach during storm surges will have a bulk character, this selection must occur in the zone of fading energy viz in somewhat deeper water.

The largest, densest and most rollable grains will settle closest to the shore and in gradually deeper water also smaller, less spherical and lighter grains can fall out. During more quiet conditions, the material that remained closest to the beach is transported in-shore again by wave action as prograding bars. To explain the separation, we must assume that the material that could reach deeper water is removed by long-shore currents, which do not affect the very shallow zone in front of the beach. Probably, the outer tidal delta, which sticks out on the west side of the island, produces a "shadow" in which no long-shore current can occur. Maybe even a vortex is created in this shielded zone keeping the selected material in front of the beach.

The proposed mechanism not only explains the shape and density sorting, but as well the step-wise diminishing grain-size from island to island. During such a process, not only the least dense and less rollable material is "sieved off", but as well the fines, which remain in circulation and can reach, via the tidal channels and reselection in the tidal flat area, the next island.

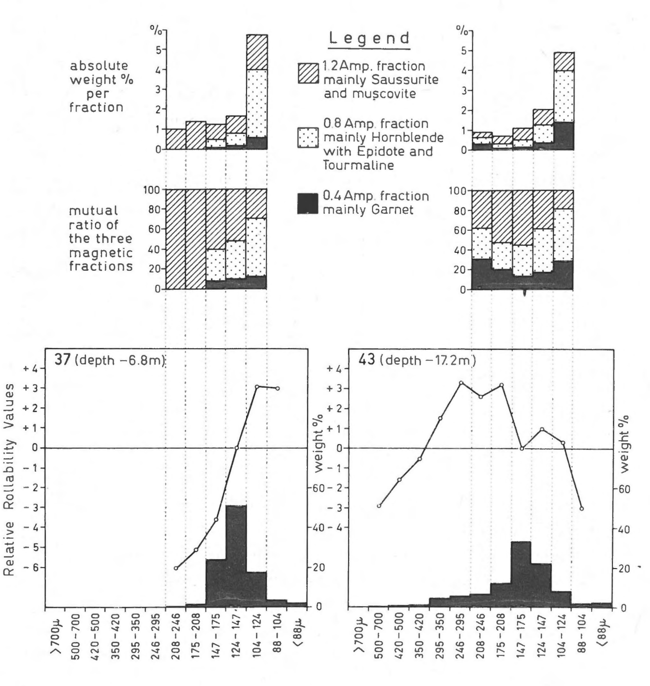


Fig. 16
Deposit-Repository relation as regards size, S.D.C. and heavy mineral distribution between a deeper off-shore sample (43) and a shallow off-shore sample (37). Size, shape and density distribution clearly reveal the bi-modality of sample 43. Only the fine population of this sample has complementary characteristics with the (fine) shallow sample.

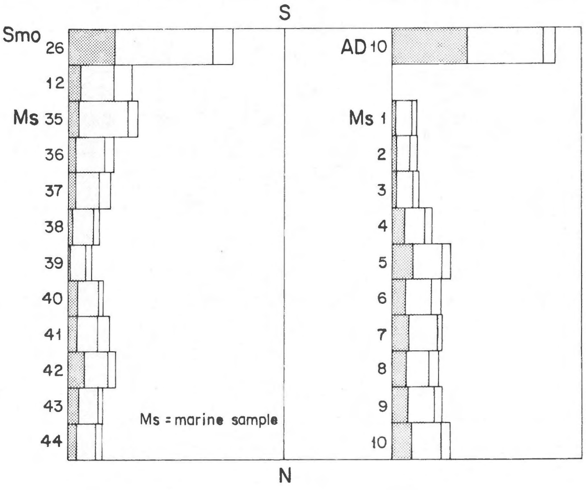


Fig. 17
Heavy mineral distribution trends in the 104-125 mu size class in two marine sample runs normal to the coast.
(for Legend, see Fig. 12.)

SUMMARY AND CONCLUSIONS

From data, discussed in W and V (1974) and the present article, the following overall picture can be developed.

In the off-shore area, deeper than about 12 m, the sediments are composed of two different populations. A coarse population shows inherited characteristics from an earlier, higher energy situation during the post-glacial transgression. The present currents and wave action are no longer able to change the character of the population, though ripple transport occurs.

North of Schiermonnikoog, this population shows properties identical to those of the present tidal channel deposits, while north of Ameland the properties are consistent with a barrier face facies.

The grains finer than about 250 mu form a separate population which can still be moved regularly, with a net transport towards the south and east. There exists a deposit-repository relation between the deeper and more shallow deposits of this size, which is expressed as complementary character in S.D.C. and in heavy mineral content (Fig. 16).

However, the sediments from the shallow off-shore (3-8 m depth) cannot contribute much to the beach deposition. This follows from their size (they are too fine to be the source for the coarser beaches) as well from their shape and density distribution. Most probably, this material is largely subjected to longshore currents. The beach sands are mainly fed by their own "hinterland" since the coastline is retreating. Only on the west side of the islands there is a direct supply from the outer tidal deltas. During storm surges, beach and dune material is lost to the sea. The coarsest, densest and best rollable material stays in the vicinity of the coast, where it remains in the protected area in the current shadow of the outer tidal deltas. The more susceptible material can reach somewhat deeper water (3-6 m?) and is subjected to longshore currents there and mixed with the receiving deposits arriving there from deeper water.

The material that is left in the very shallow off-shore re-enters the beach by wave action and can be blown out there to form new dunes.

On both islands, there are no indications of marked beach-drift. Only in the dune area, there could be some net transport towards the east. The material that is subjected to long-shore currents in the shallow off-shore is brought in front of the tidal inlets and, because of its fineness, can easily enter the tidal flat area. Here, it is subjected to severe selection again. The finest and least rollable and lightest material contributes to the tidal flat sedimentation, whereas the coarser, better rollable and denser material is either incorporated in the tidal channel deposits or is returned to sea, partly via the outer tidal deltas.

A special explanation is needed for the rigid longitude of Ameland compared to the high degree of lateral mobility of Schiermonnikoog. From older maps and from the Holocene thicknesses it follows, that the area of Schiermonnikoog has always been a main in- and/or outlet. The Pleistocene is deeply eroded maybe initially by early Holocene rivers (see e.g. Zagwijn, 1974). The sub-bottom therefore will consist of easily movable loose materials, which are no hindrance for the migration of tidal channels. The Borndiep, west of Ameland, is a deep tidal channel, which cuts through more consistent older glacial material. This could be prohibitive for active channel migration.

Since the protection of the islands in mainly achieved by the outer tidal deltas, which on their turn depend on the behaviour of the tidal channels feeding them, Ameland remains in a fixed longitude because the channel and the delta remained in a same position. This implies as well that Ameland is constantly retreating over tidal flat deposits, while Schiermonnikoog moves over tidal channel deposits and tidal deltas.

This material is eroded in the shallow off-shore and undoubtedly contributes as well to the sedimentation. An indication of this can be found in Fig. 17 in the sample runs normal to the coast. North of Ameland there is a paucity in heavy minerals from the 10 m depth line to the coast, whereas north of Schiermonnikoog, there is the same diminishing in garnet content from deep water till about the 5 m depth line, but closer to the shore the percentages rise again. Now, tidal flat deposits as eroded in front of Ameland are extremely poor in heavy minerals, while the older channel and delta deposits in front of Schiermonnikoog are on the contrary much richer and therefore can be held responsible for the augmented concentrations in front of the beach.

The forelying study clearly demonstrates that size, shape and density are equally involved in the sorting processes. Especially when the size spectrum is narrow and deposition mainly occurred due to capacity phenomena, density and shape selection can become the keys for understanding the transport processes, as teaches e.g. a comparison of Fig.'s 2 and 15.

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