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THE EFFECT OF A STORM SURGE ON NEAR-SHORE SEDIMENTS IN THE AMELAND-SCHIERMONNIKOOG AREA (N. NETHERLANDS)[1]

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ABSTRACT

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After a severe storm part of the sample localities have been resampled in the shallow off-shore (to about 20 m) and the beach of an area, which was previously surveyed under quiet conditions. It appeared that in the shallow off-shore: (1) the depth had not changed much, (2) half of the samples were finer after the storm, some were coarser and some had not changed much, (3) the garnet percentages as well as the mica concentrations had both decreased after the storm, (4) the post-storm sands were considerably less rollable than before and the Shape Distribution Character had changed into an upsloping type, which is characteristic for receiving deposits.

The observed features are explained by erosion of the shallow sea floor with transport by undertow towards deeper water. Subsequently, deposition took place of finer material that had been eroded in the tidal flat area and taken out in front of the coast by the first post-storm ebb tide. This material was reworked and spread out later on, loosing its mica and part of the fines by winnowing.

Since most of the depositional processes were due to capacitive overloading rather than to competency, the grain 'size' largely failed as a diagnostic criterion and the conclusions reached in this paper are mainly based on grain-shape and density differences.

INTRODUCTION

In January 1976 the Dutch coast suffered a very severe storm surge which had a strong erosive effect on the islands bordering the tidal flat area along the north coast of Holland. Since the present authors had studied this area formerly after long periods of quiet weather (WINKELMOLEN & VEENSTRA, 1974; VEENSTRA & WINKELMOLEN, 1976) they decided to resample part of their old sample localities to investigate what influence such a storm could have on the sediments (Fig. 1).

The Rijkswaterstaat Survey Dept. at Delfzijl collected a series of 26 grab samples on 18 and 20 February 1976, about 7 weeks after the storm. Thanks to a Hi-Fix system, the samples have been taken within a few metres of the old localities. The water depth measurements were reduced to N.A.P., i.e. Dutch Ordnance Datum, with an error of about 0.1 metre.

In the interval between the main storm and our sampling, the weather remained rough with a minor storm on January 20th. Furthermore, additional beach samples were collected 12 days after the storm and this sampling was repeated in summer 1976 after a period of quiet weather.

It is held that storm surges give rise to most changes of the beaches of the West Frisian Islands. The sands of beaches and dunes are removed and redeposited in the shallow off-shore area. Measurements of the coast line of Ameland indicate that the high-water mark of the central part of the beach retreated 200 m between 1900 and 1960, which implies a yearly erosion of about 3 metres or approx. 150.000 m^3.

In comparing post- and pre-storm deposits, special emphasis was laid on size, sorting, grain-shape and heavy-mineral content. Our sampling possibilities did not allow a structural analysis.

Description of the storm of 2-3 January 1976

A deep depression moved rapidly eastward on Jan. 2nd 1976. A trough of low pressure developed near Ireland and passed The Netherlands between 0.00 and 3.00 GMT on January 3rd (Fig. 2), during which period occasionally force 12 Beaufort was recorded (Fig. 3). The storm coincided with spring tide (Fig. 4).

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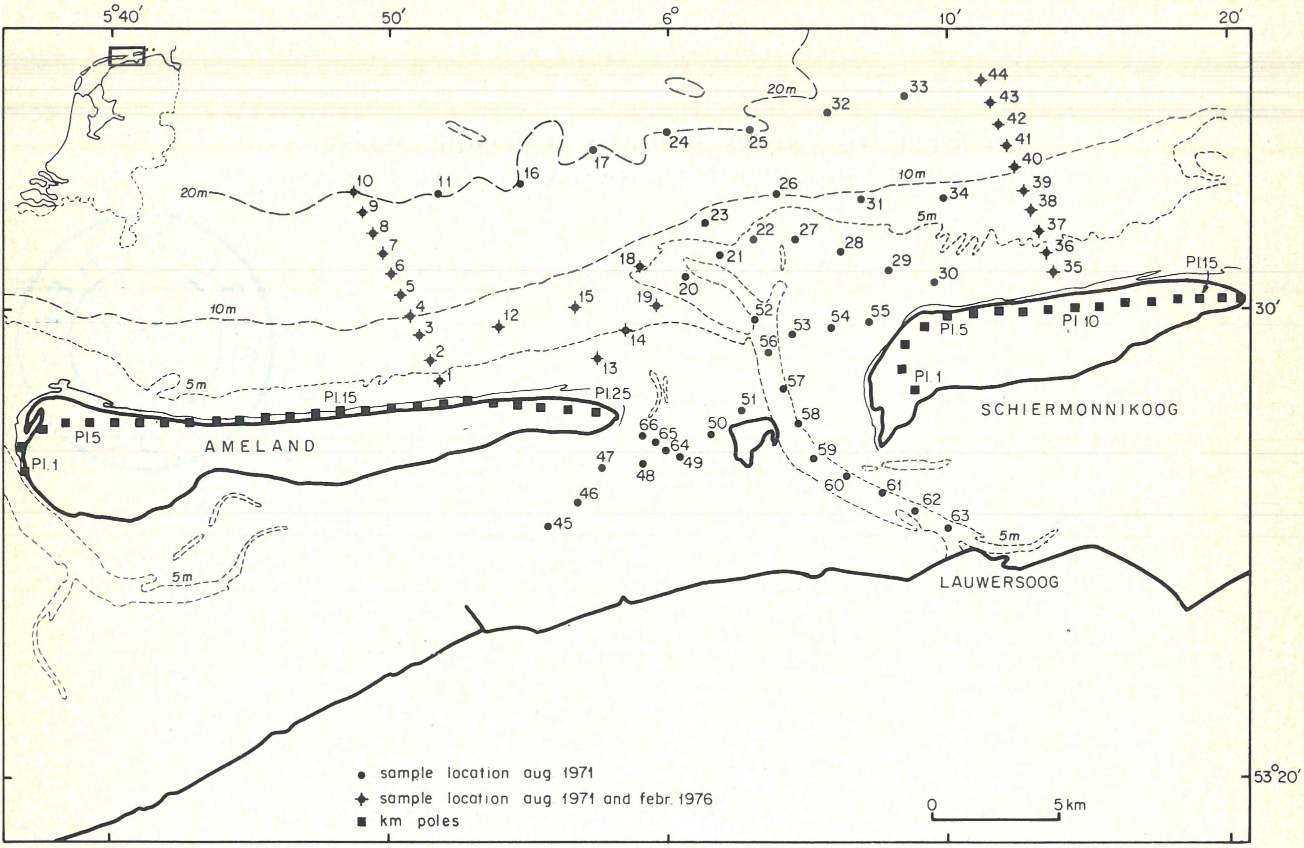

Fig. 1
Sample location map.

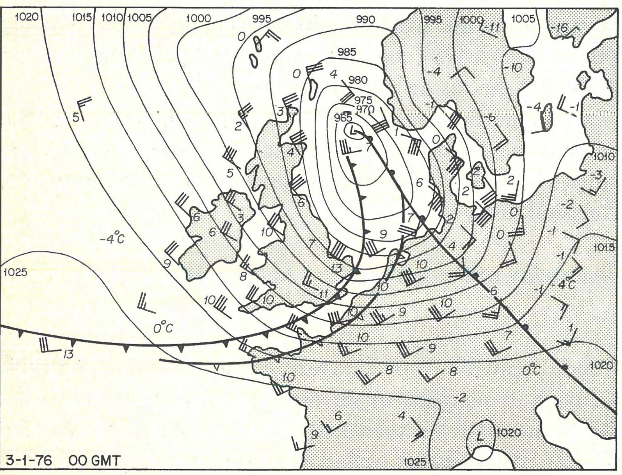

Fig. 2
Weather map.

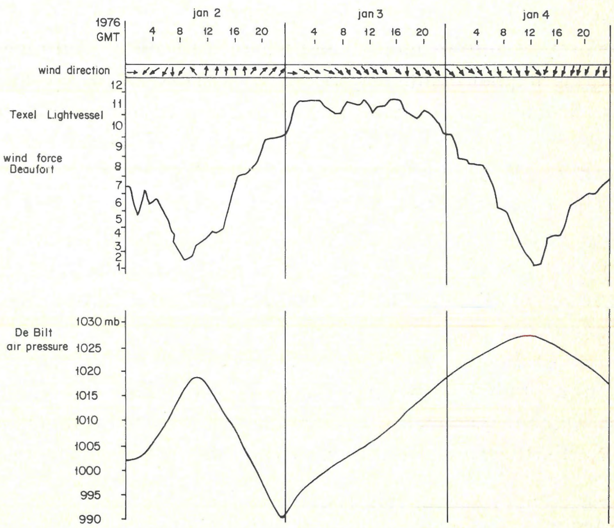

Fig. 3
Air pressure, wind forces and directions during storm.

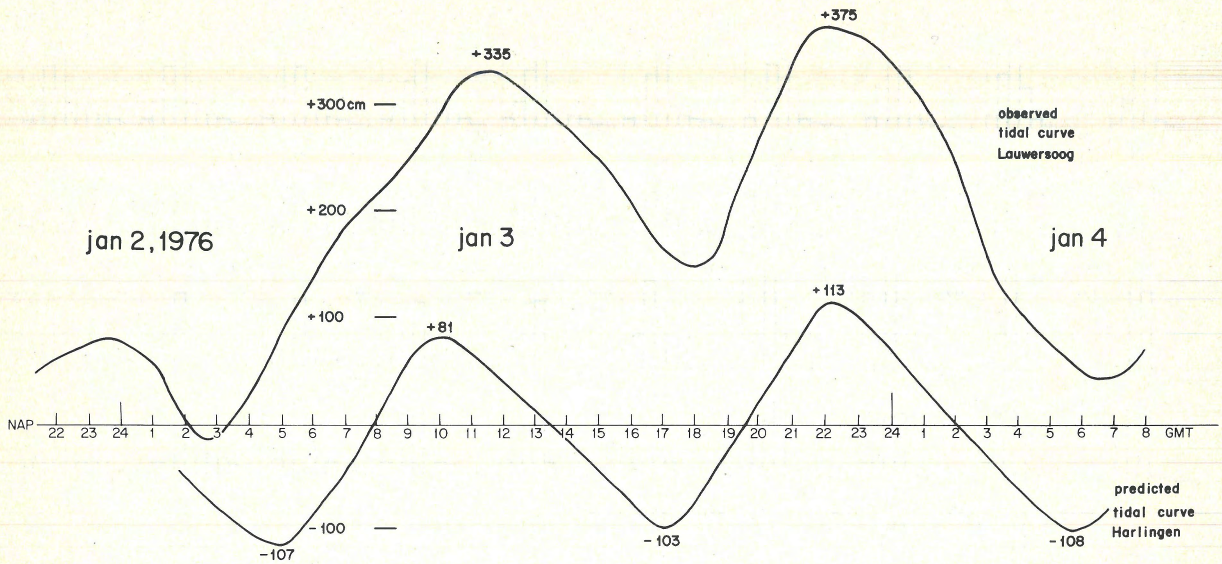

Fig. 4
Tidal curve during storm.

Description of the storm of 20-21 January 1976.

The centre of the depression moved to Northern Norway. A trough of low pressure developed over the North Sea and went to the Kattegat. The wind reached 9-10 Beaufort in the afternoon of January 20th. This storm also coincided with spring tide.

OUR HYPOTHESIS

After a storm surge irregularities on the beaches are smoothed out and the coastal dunes form cliff edges. Therefore, during the storm material is removed from the beach, the dunes and from the shallow off-shore to be redeposited somewhere in the neighbourhood. We expected therefore to encounter typical deposit-redepository relations (KUENEN, 1964; WINKELMOLEN, 1969), i.e. to find lag-type deposits in the higher-energy environments and more receiving deposits in more quiet water. Both should then have complementary charactcristics.

In the study area (Fig. 1) the median grain sizes vary roughly between 150-200 μm and the coarsest grains present in samples vary from 300-800 μm. Under heavy storm conditions, the energy of the waves and currents will be more than sufficient to transport (in principle) all the available size classes. Transport and deposition, therefore, will occur mainly due to the capacity. Under such conditions, the *grain size* as a parameter will not be the nostrum in judging the processes. Therefore, grain shape and density had to be used as additional evidence.

Furthermore, one could expect that when the competency of the water is far beyond the threshold for the available grain sizes, not much selection will occur during the removal of the material in the high energy environments. Only in the last phase of the storm, when the energy declined, could the competency threshold be approached again for certain sizes. This could eventually leave a thin layer of lag-type deposits in the high-energy environments.

We expected that the water gradient which was created, especially when the wind turned from W to NW, would induce a pronounced undertow and rip-currents with an easterly component towards deeper water. This should be the principal mechanism to remove the sediment from the zones of most severe erosion (VAN STRAATEN, 1961). If not, a capacitive equilibrium would soon have been reached and the erosion could not have been that catastrophic. We expected such undertow and rip-currents to be loaded to maximum capacity in the high-energy near-shore zone. In reaching deeper and less agitated water, their capacity will diminish with a subsequent fall-out of sediment in zones according to settling velocities. Hence, our expectations were to find the coarsest, densest and most spherical material closest to the shore in the somewhat deeper water and gradually finer and less spherical grains with dccrcasing hcavy mincral content towards dccpcr water.

Another point we considered has been, that the barrier islands retreat over tidal flat deposits. It seemed likely, therefore, that during storm erosion in the shallow off-shore this type of deposits become exposed and eroded and could contribute to the new sedimentation.

METHODS

Sampling

The beach and dune samples were taken with a stopping-knife

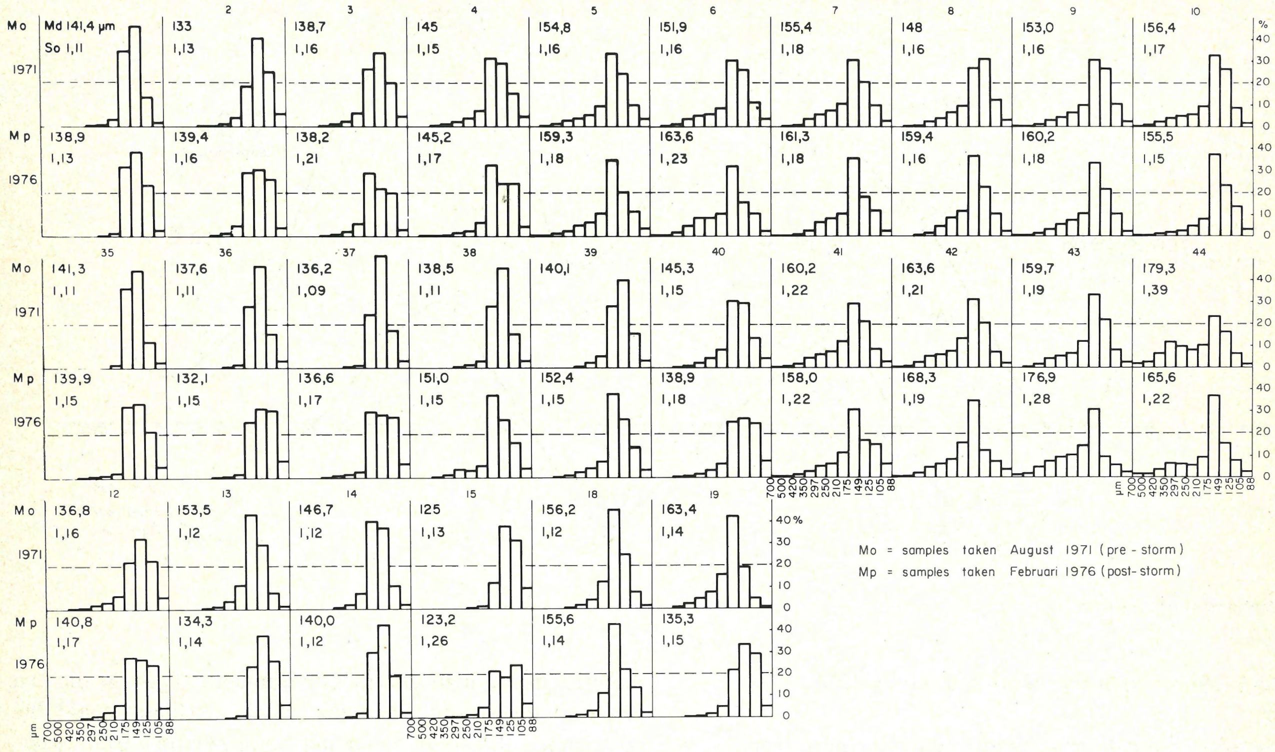

Fig. 5
Size distributions before and after the storm.

in such a way that what looked in the field as one influx lamina was sampled. The numbers of the beach samples refer to km-poles.

The off-shore samples have been taken with a Van Veen grab sampler, which took about 25 cm of sediment depth. In general such a sample will contain several influx laminae.

Size analysis

Size analysis has been performed by rotap sieving using ¼ phi size intervals. Before sieving, the samples have been treated with HCl and H_2O_2 to remove $CaCO_3$ and organic materials. The sorting values presented are the Trask values $\sqrt{Q_3/Q_1}$.

In modern litterature more sophisticated sorting expressions are often used. In our opinion, this only makes sense when the samples are well defined as regards e.g. number of influx laminae, position in a layer etc. Since we compare grab samples with carefully taken beach and dune samples, it is not meaningful to express the sorting in a more refined way. We prefer to present the grain-size distribution as histograms (Fig. 5).

Shape analysis

The grainshape was determined with the rollability apparatus (WINKELMOLEN, 1969-1971) on ¼ phi fractions. As in former surveys, relative rollability values are used. For each size fraction, the rollability values measured in individual samples in the area are averaged and the individual measurements are expressed as percentual deviation of the average. Normally, the averages change by taking additional samples. We did not recalculate new averages but, instead, used the old ones to calculate the relative rollability values of the additional samples. This procedure does not detract from their value for comparison.

Density

Different mineralogical fractions have been separated with a Frantz Isodynamic Separator (MCANDREW, 1957).

As in our study of 1976, the instrument was used with a foreward inclination of 30° and a side slope of 20°. The properties of the isolated fractions, viz with 0.4, 0.8 and 1.2 Amp are discussed in VEENSTRA & WINKELMOLEN (1976). The reasoning in the present paper is mainly based on the percentages of 0.4 Amp minerals (mainly garnet) and 1.2 Amp (muscovite-saussurite) in ¼ phi size fractions.

Due to its high density and equidimensional shape, the garnet of a certain sieve fraction is the hydraulic equivalent of the ½ phi larger quartz grains.

COMPARISON OF THE SAND PROPERTIES BEFORE AND AFTER THE STORM

The shallow off-shore

Size aspect – It appeared that the median of half of the off-shore samples had become finer and the other half coarser (Fig. 6). In most samples the size fraction <88 μm had decreased after the storm (Fig. 7). The Trask sorting of the post-storm samples generally became poorer (Fig. 5).

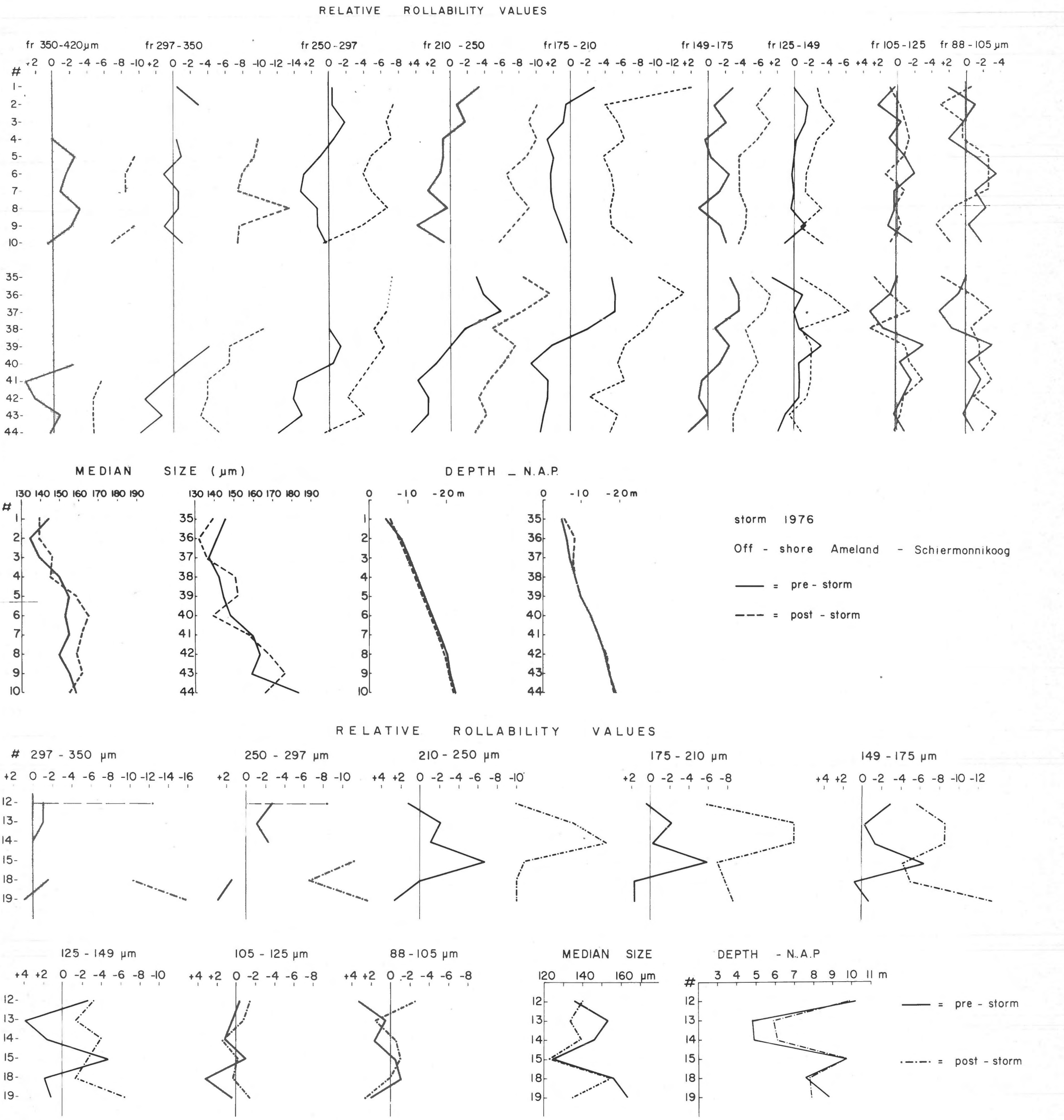

Fig. 6
Shape, size and depth of shallow off-shore samples before and after the storm.

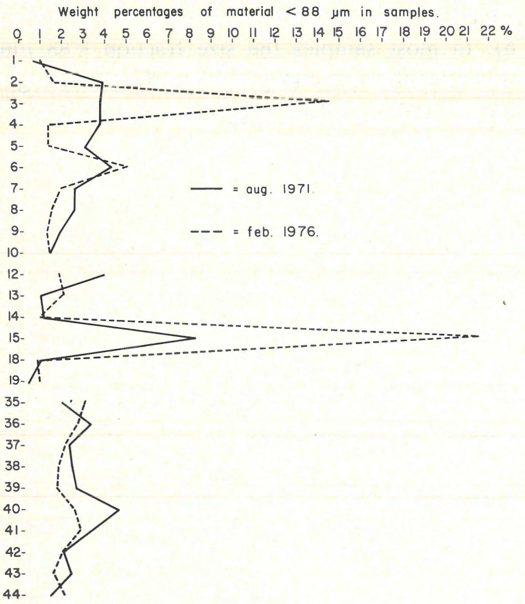

Fig. 7
Contribution of material smaller than 88 μm in off-shore samples.

Shape aspects – In figure 6 the relative rollability values before and after the storm are shown. The most salient feature is the pronounced decrease in rollability after the storm. The phenomenon is most marked for the coarsest size fractions. The differences diminish with decreasing size. In the 149-175 μm size interval it is still about 4%, the fraction 125-149 μm shows differences around 2%. In the 104-125 μm fraction the differences become very small and in a few samples this size fraction became even more rollable after the storm. The same holds for the 88-104 μm fraction, which is the smallest one investigated.

The samples taken in the influence reach of the tidal inlet (12-19) show the same picture, except for sample 15, which remained nearly unchanged.

In figure 8 the Shape Distribution Character (S.D.C. in the following) is shown. This is the graph obtained by plotting the relative rollability values of one sample against the size classes. Such graphs give an indication about the depositional processes (WINKELMOLEN, 1971).

The post-storm samples nearly all show a pronounced receiving S.D.C., i.e. they have low rollability values for the coarsest grains present and increasingly higher values towards the fines (WINKELMOLEN, 1969; WINKELMOLEN & VEENSTRA, 1974). This is especially so for the samples in the off-shore till about a depth of 10 m and less so for the deeper samples. In the deepest samples (10, 43 and 44, depth 18-20 m) the curves become more complex and show a lag character in their coarsest parts (downsloping curves). Although nearly all samples show an overall receiving trend, many of them possess one or two truncations. One of the truncations starts nearly everywhere in the 246-294 μm size interval, where the upsloping trend is interrupted for one or more size classes. In general it can be said that truncations in the S.D.C. curve point towards the presence of more populations in the sample. This is analogous to the inflexions in the cumulative size curves plotted on log-probability paper (VISHER, 1969).

Remarkable, furthermore, is that sample 15, which is situated in the outlet of the tidal channel, has a very pure receiving character and that its S.D.C. (and its size distribution) after the storm is almost identical to the pre-storm situation. The S.D.C. of all other samples changed considerably by the storm.

For reasons explained further below, we shall refrain from a detailed comparison between pre- and post-storm characteristics.

Density aspects – From 20 off-shore samples, the percentage of the 0.4 and 1.2 Amp minerals was determined in 5 size intervals of ¼ phi. The results are shown in figure 9 and compared with the pre-storm situation. For the samples in the reach of the tidal inlet (12-19) only the 105-125 μm interval was measured in this way.

For the content of the 1.2 Amp minerals (mica) it can be observed that the concentrations became considerably less in all size fractions of nearly all samples. Often the concentrations became more than halved. But also the concentration of the 0.4 Amp minerals (garnet) decreased after the storm in nearly all samples. Here as well, sample 15 (in the reach of the outflow of the tidal channel) is an exception since its concentration remained nearly unchanged.

The beach samples from Ameland

Size aspects – Comparison of beach samples taken along the beach of Ameland on January 14th 1976, i.e. 12 days after the severe storm, proved that between the km-poles 7 and 12 the median was higher, but between poles 12 and 15 lower than in 1973 (Fig. 10).

Shape aspects – In figure 11 the rollability values are given. The main features are:

(1) For the coarsest grains on the beach, the L.W.L.[3] samples are considerably more rollable than the H.W. samples. The size fractions between 105-175 μm do not show much difference between H. and L.W.M. and the very fines show better rollabilities in the H.W. samples.

(2) The pre-storm samples showed a trend of increasingly better rollability values towards the east in this stretch of the beach. This trend got lost during the storm.

(3) There appeared to be not much difference in the general level of the rollability values before and after the storm. But it should be remembered that the comparison has only limited value because of the different sample positions.

The S.D.C. of the beach samples is shown in figure 12. The

[3] L.W.(L.) = Low water (level).
H.W.(L.) = High water (level).

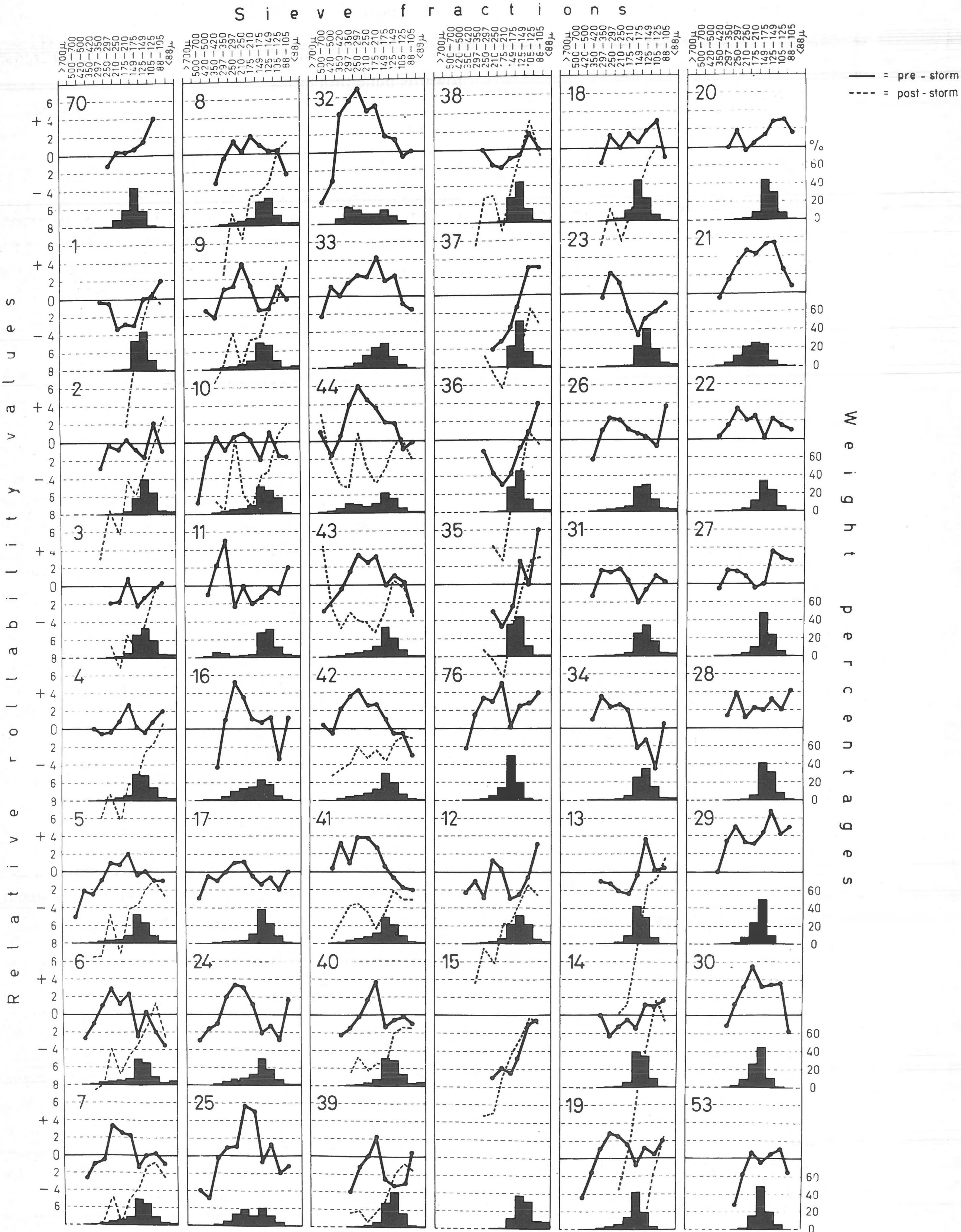

Fig. 8
Shape Distribution Character of off-shore samples. Pre-storm situation fully drawn, post-storm as broken lines. (histograms underneath S.D.C. curves).

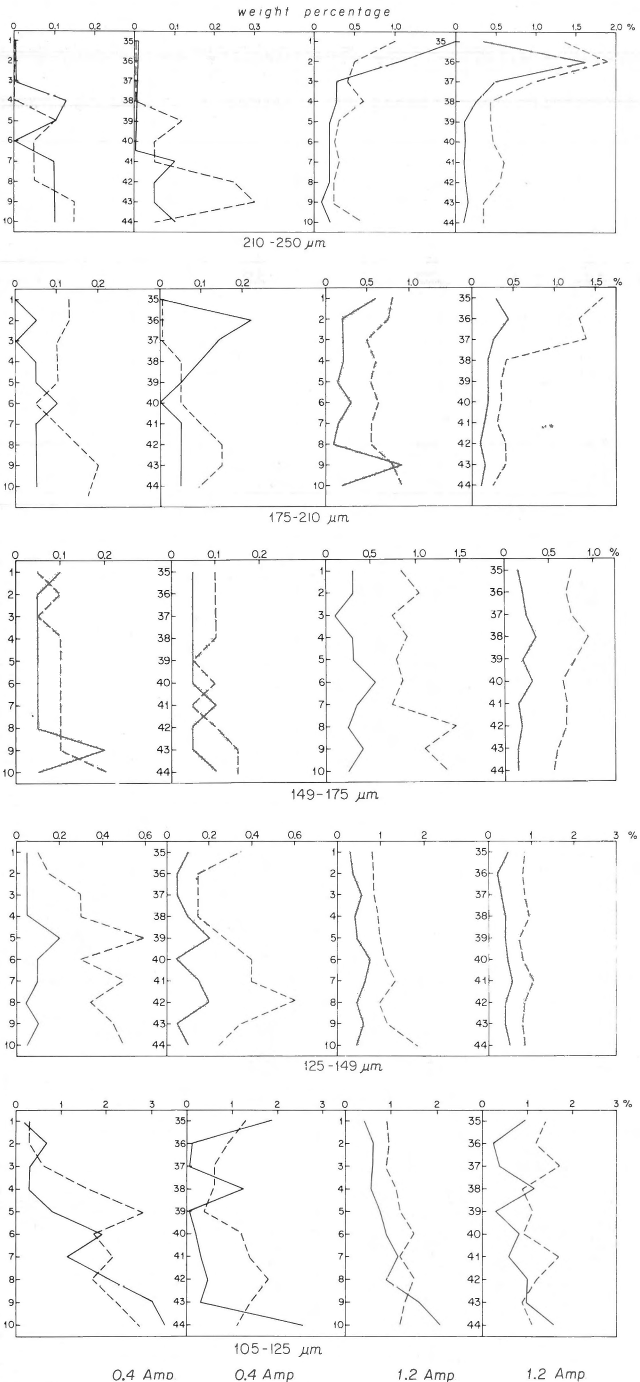

Fig. 9
Concentration of 0.4 Amp (garnet) and 1.2 Amp minerals in five size fractions of off-shore samples. Broken line = before storm; fully drawn = after storm.

differences before and after the storm are not spectacular. The same can be said for the differences in S.D.C. between the H. and L.W.L. samples.

By averaging the individual rollability values for each size fraction of a series of samples, a composite S.D.C. can be constructed for the group. In figure 13 this is done for the beach samples between PL. 5.5-15.5. For comparison a group S.D.C. is included for the dune sands of Ameland. It appears that the character of the post-storm beach material shifted towards dune properties.

Density aspects – In figure 14 the percentages of the 0.4 Amp minerals (garnet) are shown for the 104-125 µm size fraction. Although our data are scanty, it looks as if the H.W.L. samples tend toward higher garnet concentrations compared to the L.W.L. For comparison, some values are shown of pre-storm beach samples. The beach and dune samples of the island of Ameland are always rich in garnet compared to other sands in the vicinity (VEENSTRA & WINKELMOLEN, 1976). It looks as if the storm did not change this situation significantly.

CONCLUSIONS

Internal correlations

In general, there exist marked correlations between the parameters of size, shape and density within one sample and in the samples of a genetically coherent population of samples. This is because all three parameters are equally involved in the processes of transport and deposition. Size, shape and density are the ingredients from which the susceptibility concept is built up.

If in an area the available material is reworked, e.g. by currents, there will be erosion and redeposition. The eroded spots will be typified by relatively coarse, spherical and dense material, while in the sites of redeposition the sediment will be finer with less spherical grains and with relatively low heavy-mineral content. The split-up populations are called deposit and its repository. Such a deposit and its repository show complementary characteristics and have logical and predictable internal and mutually related properties.

A prerequisite for such internal correlations in an area is that the sediment is homogeneous as regards its source and that the processes of reworking act in the whole area under consideration in an analogous way. If e.g. part of the original sediment is reworked by waves and currents and part by turbidity currents, the correlations we find in the first environment will be largely missing in the latter.

The internal correlations in the area discussed in this paper have been worked out earlier (VEENSTRA & WINKELMOLEN, 1976). In figure 15 this is repeated for the 26 marine samples for the pre- and post-storm situation. The samples are arranged in order of increasing garnet content in the 105-125 µm size interval. This property is compared with the relative rollability values of the 149-175 µm size interval (this is the hydraulic equivalent of the ½ phi smaller garnet) and with the median size of the samples. It can be noted that for the pre-storm situation there exists a rather good correlation between these properties, i.e. an increase in garnet goes hand in hand with better rollabilities and larger sizes. It has already been argued

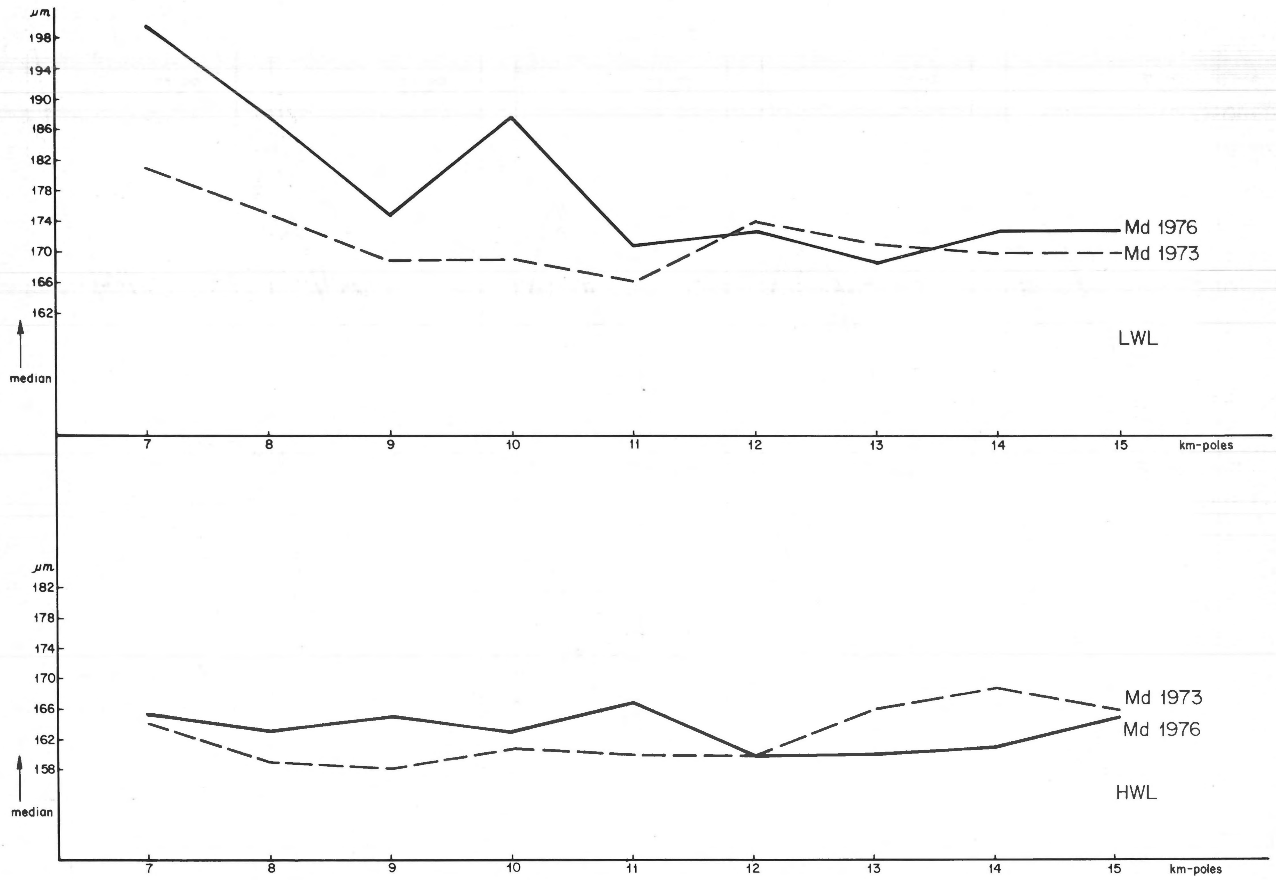

Fig. 10
Median grain size of beach sands in the central part of the island of Ameland.

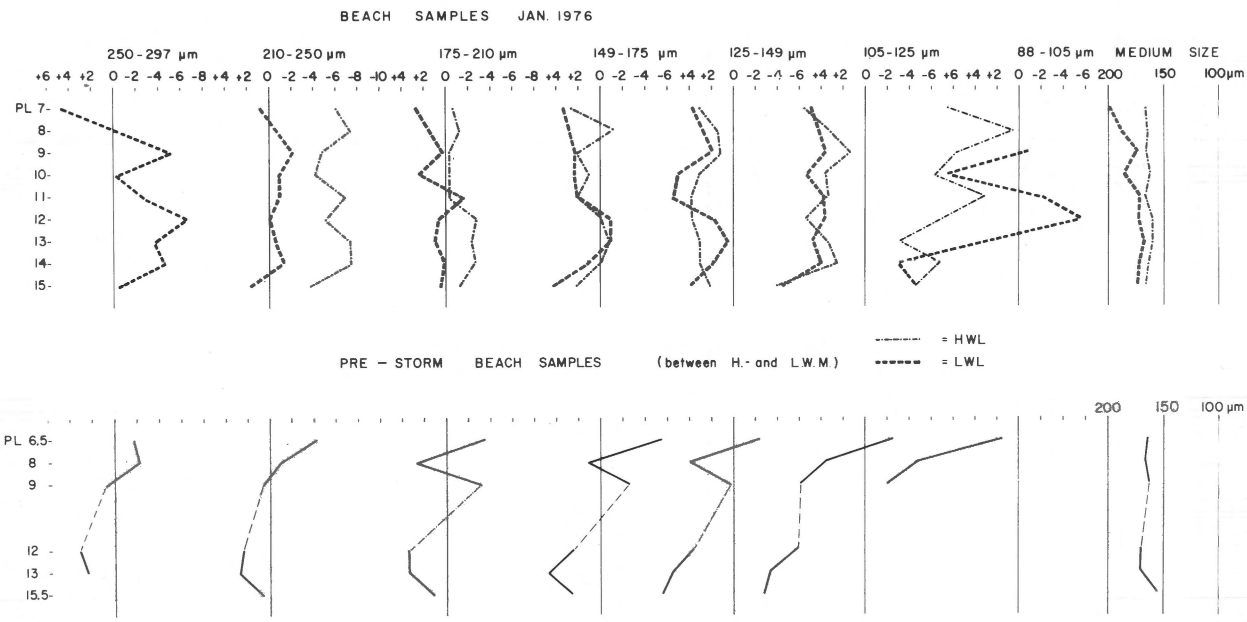

Fig. 11
Relative rollability values for beach sands of Ameland before and directly after the storm.

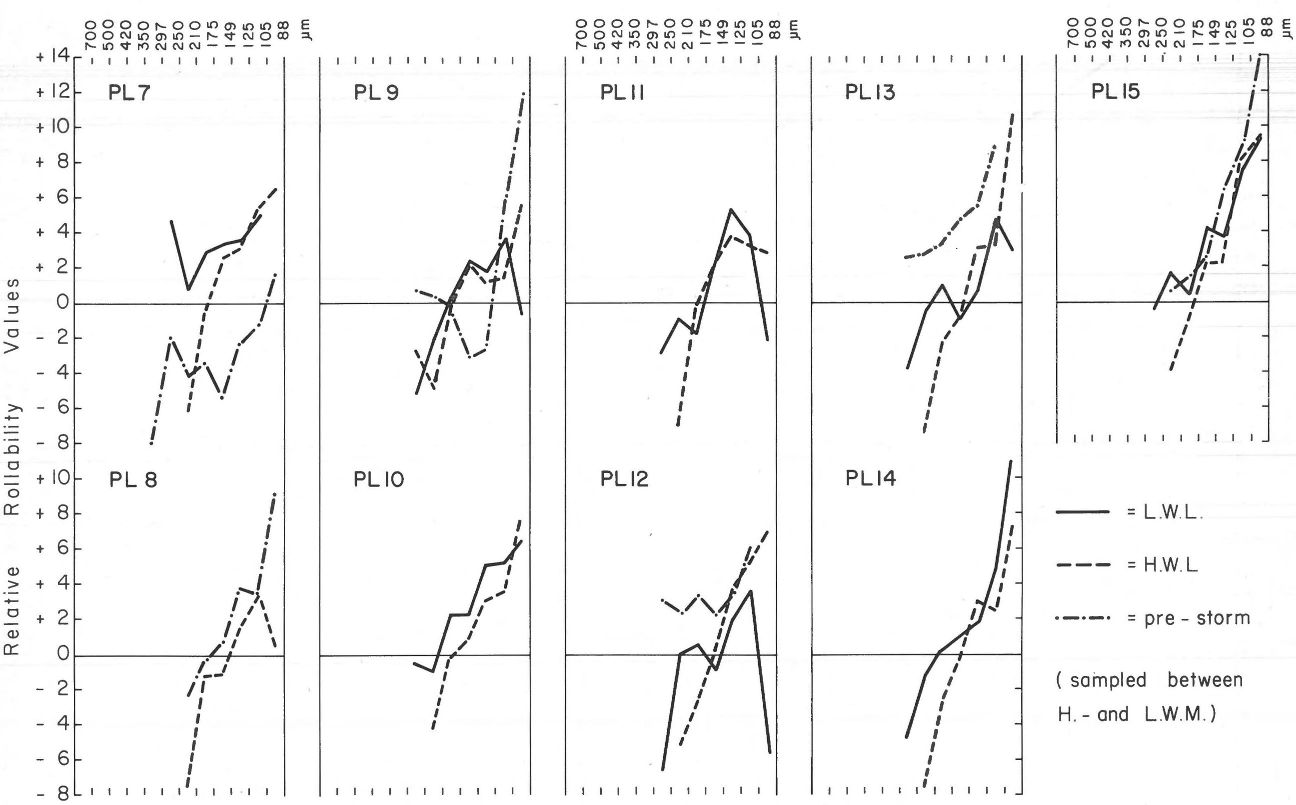

Fig. 12
Shape Distribution Character of beach sands of Ameland.

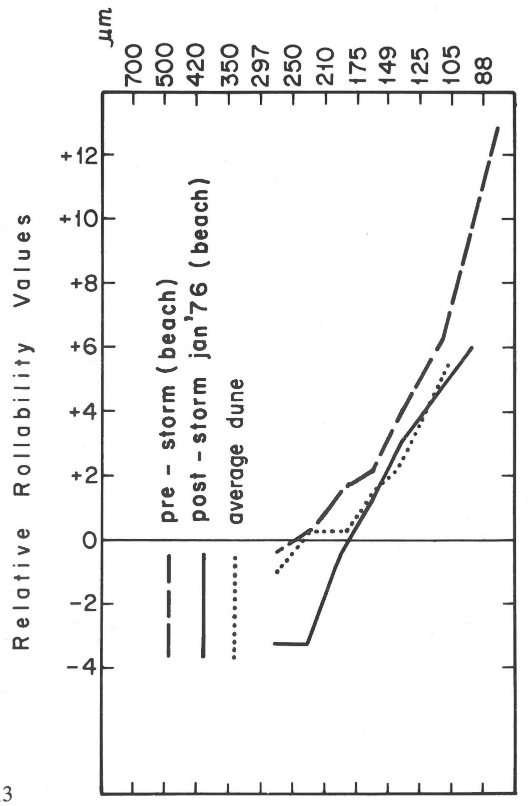

Fig. 13
Composite S.D.C. graphs of Ameland pre- and post-storm beach sands compared to the S.D.C. of average dune sands.

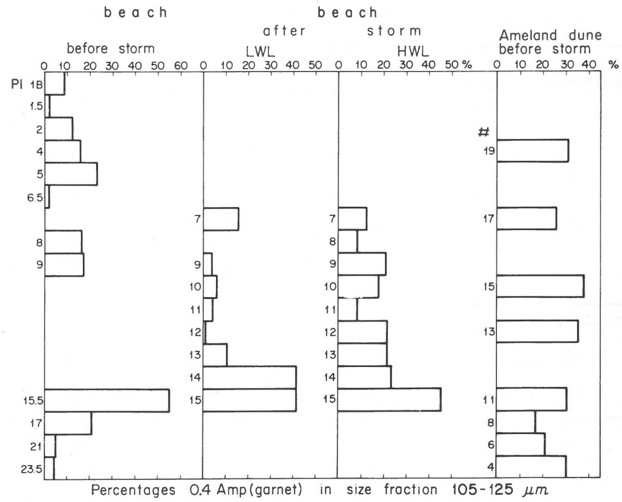

Fig. 14
Concentration of garnet in beach sands of Ameland compared to dune sands (right column).

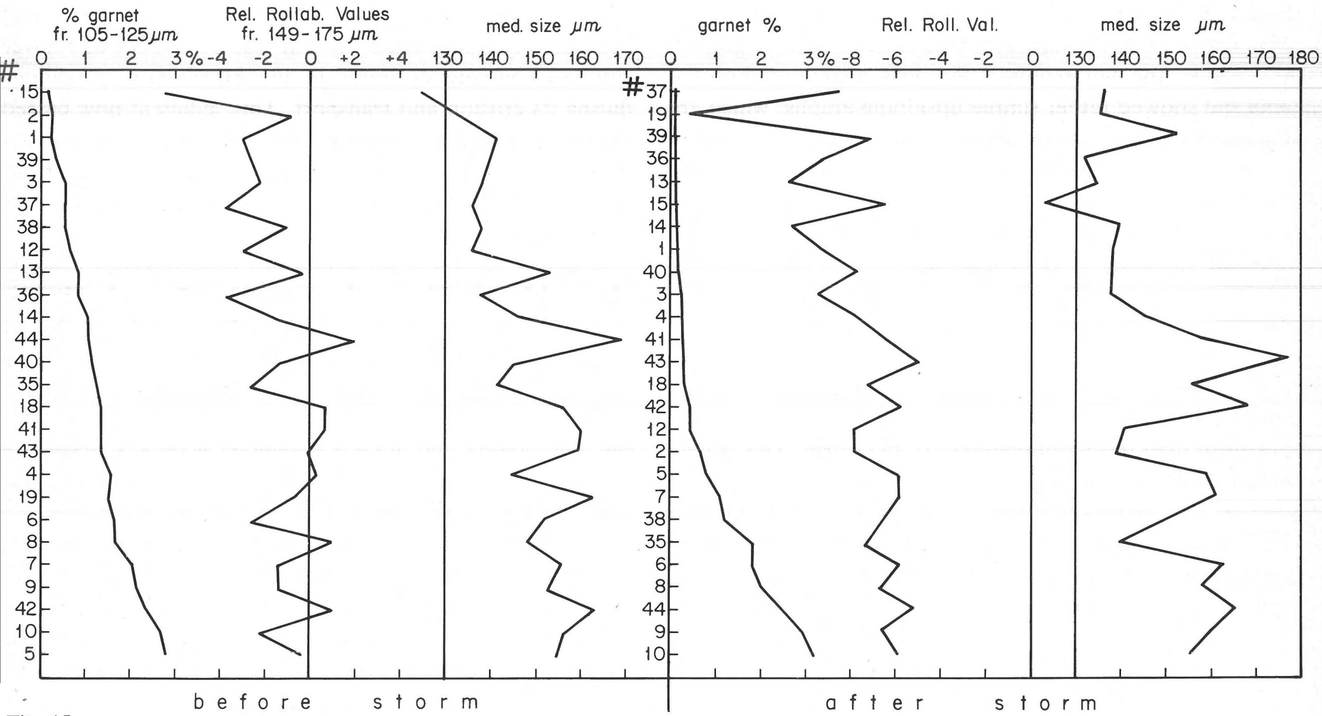

Fig. 15
Internal correlations in off-shore samples before and after the storm.

in VEENSTRA & WINKELMOLEN (1976) that the correlation with size does not continue well in the coarser sizes, because there simply are no coarser grains in the area.

The same procedure is followed for the post-storm samples, which are also arranged in order of their present garnet content. It is clear at one glance that the correlation is far less or even non-existent for many of the post-storm samples.

Two conclusions can be drawn, viz:

(1) Since the studied area is so restricted, it can be assumed that the processes operating during the storm have been of an analogous type all over the area. Hence, the disruption of the correlations must have been due to the introduction of new sediment in the area with a deviating genetical history. Such an introduction could be due either to lateral supply or to e.g. subaqueous outcropping and/or erosion of older sediments such as underlying tidal flats, boulderclay etc.

(2) Since heavy storms like those discussed in this paper are by no means exceptional in the area (ROHDE, 1977) it can be concluded that there must occur considerable transport and reworking in short periods so that the internal and areal correlations can be restored in timespans, which should be measured in months rather than years.

Depth

We had expected a considerable deepening of the off-shore in front of the beach with a slight diminishing of depth in the more remote off-shore due to redeposition.

To our surprise, the depth in the shallow off-shore did not appear to have changed significantly during the storm (the errors in depth sounding being about 0.1 m) (Fig. 6). Hydrodynamically, the absence of deepening during high energy conditions could be made plausible, for during the storm the actual water depth was about 3 m above normal due to stowage and the coinciding of storm and spring tide. But on the other hand it is known that during lesser storms sand is lost to the off-shore. This sand re-enters the shallow off-shore and beach during moderate conditions as prograding sand bars of about 3 m height, which approach the beach obliquely (REINECK, 1976). Therefore, the absence of deepening in the shallow off-shore requires an additional explanation.

Grain size

The median grain size in the off-shore had not changed much after the storm. Neither had the storm produced a marked zoning as predicted in our hypothesis. By contrast, the samples closest to the beach (1, 35 and 36) appeared to be of smaller size than before (Fig. 6). Most sizes in the off-shore were smaller than those occurring on the beach and dunes. This could hardly be explained by lag in a high-energy environment.

Grain shape

After the storm, the relative rollability values in the off-shore sands were significantly lower than before. This was most marked for the coarsest grains present in the samples. Also, the S.D.C. of the off-shore samples had changed considerably. The pre-storm samples showed rather truncated graphs. As a whole, the new sediment that was encountered on the same site showed rather simple upsloping graphs, which are characteristic for receiving deposits. Only in the coarsest size classes of some off-shore samples could indications of lag conditions be recognised. The shape characteristics of the post-storm sediments are also incompatible with lag conditions in a high-energy environment.

Heavy-mineral content

In general, the sands sampled after the storm in the off-shore contained considerably less garnet, but also less mica and saussurite than those sampled before the storm. This is very remarkable, since in most other cases an *increase* in garnet (due to lag conditions) goes hand in hand with a sharp decrease in the susceptible 1.2 Amp minerals. This again could never match with deposition under lag conditions in a high-energy environment.

THE NEW HYPOTHESIS

The new picture we propose is as follows: during the storm, much material will have been removed from the beach, the dunes and the shallow off-shore. The energy conditions have been so extreme that all the material could be removed without much selection. There must have been a stage at which the shallow off-shore was deepened out by waves and undertow. Much of the eroded materials will have been transported towards deeper, less agitated water by undertow and rip-currents. But also part of this material will have been brought as suspended load in the highly agitated water by the flood into the tidal flat area.

During the storm, the low tide remained so high due to wind stowage that the lowest water level reached remained about one metre above normal H.W.L. (Fig. 4). This implied that for hours the shoals in the tidal flats remained covered with very shallow but highly agitated water with breaking waves and swift currents. This must have given rise to an enormous erosion.

In the mean time, part of the material brought in by the preceding extremely strong flood must have settled out due to diminishing capacity during this 'ebb'. This relatively coarse material will have been deposited mainly in the channels. The finer material eroded from the plates and bluffs will have been deposited on top of this coarser material.

When the storm finally waned, the enormous watermasses piled up by the wind and the spring tide in the tidal flat area flowed back to sea, carrying a full capacity load of sediment. But this sediment will have been mainly the sediment that was eroded in the tidal flat area. The outcoming first post-storm ebb must thus have brought enormous quantities of sediment into the shallow off-shore zone. This sediment, however, had retained the characteristics of tidal flat sediments since it had been mainly transported 'en vrac' (as bulk load) and never suffered competency limits in the high-energy conditions during its erosion and transport. This sediment now passed the outer tidal delta and was deposited in the shallow off-shore and filled the erosional lows freshly made by the storm, reducing the depth to about a normal quiet-weather equilibrium profile.

A strong argument to sustain this new hypothesis can be obtained by considering the properties of sample 15. It is situated in the near off-shore in the pathway of the outflow of the tidal inlets. Before the storm, sample 15 had pronounced tidal flat characteristics (Fig. 8), i.e. an upsloping negative shape distribution curve (WINKELMOLEN & VEENSTRA, 1974). It is the only sample that did not change its character during the storm, i.e. at the site of sample 15 also under normal conditions tidal flat sediment was deposited by the outflowing water. Since this is what happened directly after the storm as well, the properties did not change at this site. And *all other* sand samples in the shallow off-shore zone tended to resemble this sample 15 after the storm, viz. fine, short in garnet, low rollability values and an upsloping S.D.C. graph indicating receiving conditions.

It is only in this way that the present authors can explain their paradoxical finding after the storm. Also the remarkable correlation between decreasing garnet and decreased mica content finds its solution by such a process. For the tidal flat sands are poor in garnet, which cannot reach the higher plates and bluffs but instead is concentrated in channel floor and outer tidal delta deposits (VEENSTRA & WINKELMOLEN, 1976). But they are rich in mica. During their transport towards the shallow off-shore, the very susceptible 1.2 Amp minerals have been preferentially washed out, because the water was still rather agitated. Also the very fines which normally make up a substantial part of the tidal flat material, were washed out in this way. This becomes apparent in figure 7, where the percentages smaller than 88 μm are compared. Although many sands in the shallow off-shore became a bit finer after the storm, the percentage of the fraction smaller than 88 μm became less in many samples.

It becomes clear now why no explanation could be found by considering the *same* sand going through high-energy processes in the shallow off-shore. The sand that covered the sea floor after the storm was not the same sand as before, not even part of it. The top of the former sand was stripped off to be replaced later on by a completely different sand which brought with it the inherited characteristics of its former genesis as tidal flat sand. It is for this reason that a detailed comparison between the two series of samples was unfruitful.

We are left with the question then of where the sands have been deposited that have been eroded by the storm from the beach, dunes and shallow off-shore. Our own samples do not give much indication to solve this question. In figure 8 it can be seen that most of the shallow samples, viz. 1-8, 12-19 and 35-39, have obtained the typical receiving S.D.C. of the tidal flat sands. Only the deeper samples (9-10, 40-44) show more complicated and truncated curves. Although the S.D.C. graphs from the deeper samples possess stretches with receiving and with a lag character, they show as a whole considerably lower rollability values compared to the situation before the storm. Also their garnet content is lower after the storm for most size fractions (Fig. 9). The sands that have been eroded from the beach and dunes must have been deposited elsewhere in deeper and less agitated water. Such a fall-out occurs gradually, viz. the least susceptible material first. Since the beach and dune sands have a rather good rollability, the first deposition of such material should have a better rollability than the average source. As such rollability values have not been encountered in the zone in between the beach and the 20 m depth line, it seems probable that the main deposition took place in water deeper than 20 m.

REINECK c.s. (1969, 1972) found rhythmic sand bands on the shelves in the southern bight of the North Sea as far as 50 km from the shore in water depths of about 40 m. He attributed such sandy layers, which were interbedded in much finer shelf sediments, to storm surges. It could very well be that the eroded beach and dune sands and the sand which has disappeared from the shallow off-shore have been deposited outside the sampled area in water deeper than 20 m. It would be worthwhile to sample this deeper zone with a boxcorer and to investigate the size, shape and density composition of such storm-surge layers, if any.

As regards the sediments newly deposited in the shallow off-shore, it seems probable that they were primarily deposited in the main pathway of the outcoming tide to be reworked and spread out over a broader area later on and eventually to be mixed with a lag-type of sand that must have remained back there. Indications for this can be found in the S.D.C. of the shallow off-shore sands (Fig. 8). Only few of the curves show the pure tidal flat type (e.g. 1 and 36). Most curves show minor truncations with alternating lag and receiving parts. This is attributed to later reworking. Also the garnet percentages show here and there higher values than before the storm. This also points towards reworking and local mixing with a thin band of lag-type sand that should have remained there while the storm was waning.

In figure 14 composite S.D.C. graphs are shown for the pre- and post-storm beach sands and compared to the S.D.C. of the dune sands of Ameland. As regards the Ameland beach, it is clear that the overall beach characteristics after the storm became almost identical to those of the dunes, thus supporting our former argument. Only the western beach samples show an aberrant picture (Fig. 11) especially for the L.W.L. samples. The grain size increased here and the rollability values became more positive. This is attributed to an influx of material from the outer tidal delta region. This outer tidal delta is a shallow, high-energy environment and is characterised by coarser material with high rollability values (VEENSTRA & WINKELMOLEN, 1976). During the storm, the outer tidal delta was strongly eroded and part of the material will have reached the west beach of Ameland which, due to the shielding effect of the outer tidal delta, remained relatively protected.

There is no trace of lag deposits to be found on the beach. Under moderate N.W. wind conditions with slight beach erosion, the beach becomes locally coarser and rich in garnet. That this was not the case after the 1976 storm proves that the energy of waves and currents was more than sufficient to remove everything without selection. After the storm a size maximum against the dunes was found, which is attributed to winnowing when the wind declined and the competency threshold for the coarsest grains was reached.

Interpolation

It is difficult to trace the site of deposition of the material that was eroded from the beach and dunes. We have already argued that it must have largely by-passed the 20 m depth line. But there are indications in the S.D.C. of our deepest samples that the deposition started near this depth.

In general, the interpretation of truncated S.D.C. graphs is rather difficult. It would be too time-consuming to go through each procedure with the reader. However, figure 16 indicates how it works. This shows the S.D.C. of sample 44 (18.5 m depth), together with the S.D.C. graphs of the sands which presented themselves as possible sources for the new deposition in site 44. These are an average beach sand and an average tidal flat sand.

The coarsest part of the S.D.C. of sample 44 is clearly lag and can be explained by a hanging back of the least susceptible material during the storm. From the eroded beach and dune sands, the coarsest material will fall out first when it is transported towards gradually deeper water. Since the beach material has a rather good rollability and since from this material the least susceptible grains will fall out preferentially, the remarkable peak in the 246 μm size interval can be explained as such a drop-out. Finer grains of this population of beach sands could largely by-pass the site during the deposition and their influence will therefore gradually diminish towards the fines. The fines washed out from the tidal flat sands and which are supposed to be deposited there somewhat later in time, are of very poor rollability, especially for the coarsest grains in this population. This could have produced the sharp minimum in the S.D.C. in the 175 μm region, since they are about the coarsest grains present in tidal flat sands.

In this way, a hypothesis can be checked and eventually rejected, at least in a qualitative manner. The authors are aware that this way of thinking is not a mathematical proof. It is more like putting the pieces of a jig-saw puzzle together. Maybe a certain piece could mechanically fit-in somewhere else as well. But when the final picture is completed, one can be pretty sure that the disputed piece is also in its correct position.

Additional evidence can be found in figure 9, which shows the garnet concentrations. We see that in the deepest samples (9, 10 and 44) the garnet percentages, which decreased in most

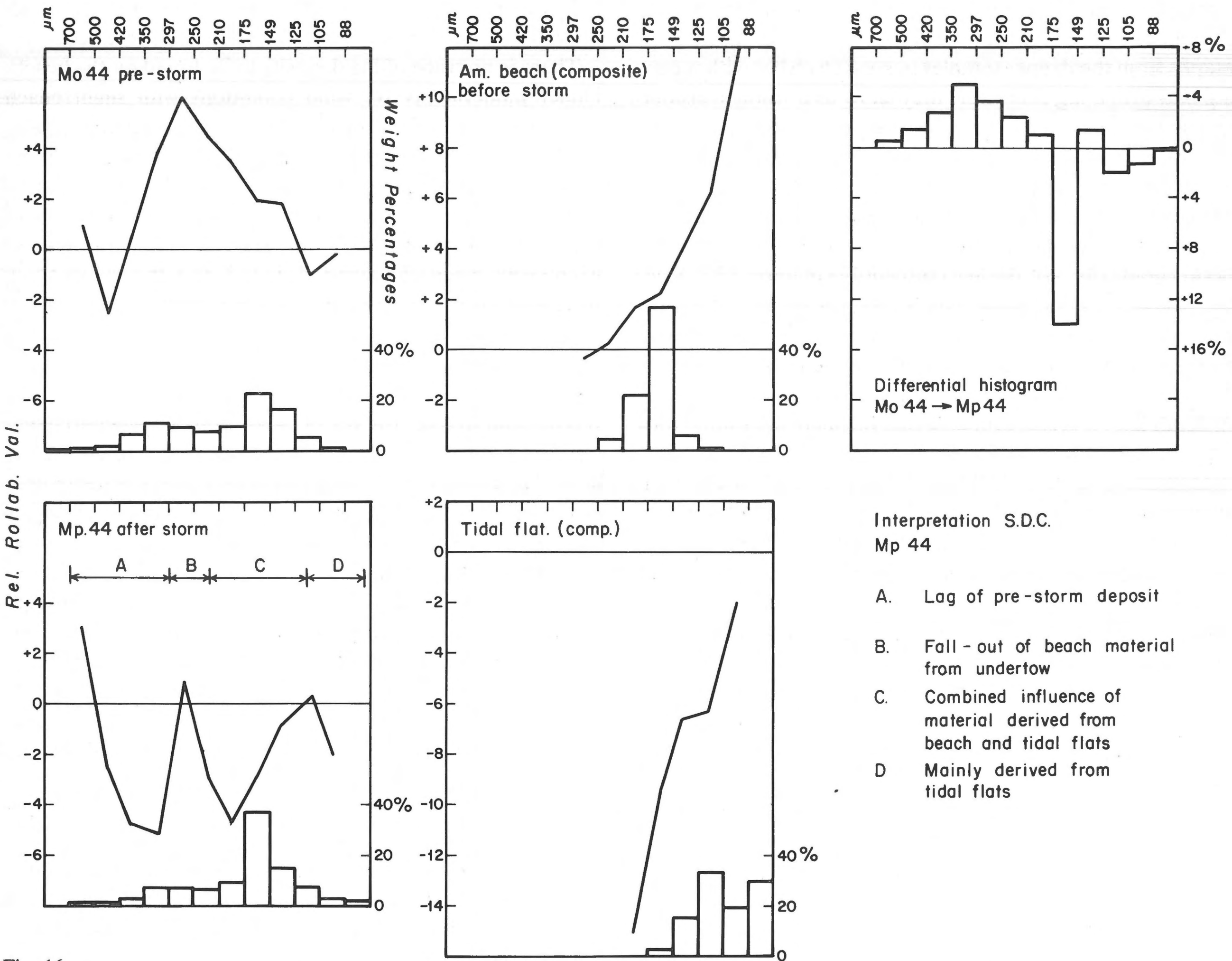

Fig. 16
Example of interpretation of the truncated S.D.C. graph of sample 44.

samples, increased sharply in these deep samples, but only in the size-fraction 105-125 μm. And it is exactly this size fraction which is extremely rich in garnet in the beach sands. The coarser beach sand fractions have rather normal garnet percentages (VEENSTRA & WINKELMOLEN, 1976). One could attribute this garnet concentration in the deep water samples to lag during the storm of the pre-existing sand. But in that casc, such a garnet increase would be even more pronounced in coarser sizes. This is not now the case as the 125-149 and the 149-175 μm fraction appeared to have a considerably lower garnet content after the storm.

A final question which presents itself is 'what happens with the sand that is deposited during the storm in the shallow offshore?' To answer this question, it would be convenient to know the thickness of this sand. We have no direct evidence for this. Although the tidal flat area is very extensive and could deliver enormous quantities of material, we must assume that most of the tidal flat material is brought outside by the first ebb tide after the storm. We can now make a simple calculation. By looking at the map, it seems justified to assume that the material which is brought outside by the ebb will be spread out in an area of about ¼ of that of the tidal flat area. We know that the waterdepth during the storm was 3 m above normal. If we assume now that the sediment concentration has been in the order of 1 g/l (larger values are quite possible) then every m^2 tidal flat area could produce 5 m^3 of sediment laden water with 5 kg of sediment. If this is spread over an area of only one quarter of the tidal flat surface, we can get a sediment thickness of about 20 cm on average. Although this estimation is rough, it should be in the correct order. Since the samples were taken with a grab, a thinner layer would have been penetrated and we could never have obtained such pure and homogenous results. On the other hand there are indications that here and there the underlying lag sand became mixed up a bit with the new cover. We believe therefore that this new cover of the shallow off-shore will have an overall thickness which should be measured in decimetres.

It is known that during moderate conditions there is some accretion of the beaches. Sandbars are moved by wave action towards the shore and join the beach. We want to stress, however, that the material that covered the shallow off-shore after the storm will not reach the beach in this way. It is in part finer, much more angular and very much poorer in garnet than the beach sands. Should such material reach the beach as prograding bars, then even finer less rollable grains should reach the beach preferentially and also the garnet would tend to hang back in the sea. Since the beaches become more rollable during moderate conditions, this possibility is ruled out. We think it much more probable that the tidal flat sand cover of the shallow off-shore is stripped-off again in a relatively short time to be redeposited by currents with an easterly component. In this way much of it will be brought in front of the tidal inlet again and could re-enter the tidal flat area. There it will be sorted out as described in VEENSTRA & WINKELMOLEN (1976) and part of it can reach later the outer tidal delta of the next island. In this respect it is remarkable that the tidal deltas restore rather quickly. E.g. 'de Richel', part of the outer tidal delta east of the island of Vlieland, disappeared completely during the storm in november 1972. This outer tidal delta was completely restored in summer 1973!

It is thought that the restoration of the beaches is mainly achieved with material that approaches the beach from the northwestern outer tidal delta regions. This explains the beach properties better since the sand in the outer tidal delta region is somewhat coarser, rich in garnet and of a good rollability.

POSTSCRIPT

This survey makes it once the more clear that the grain 'size' is not an ideal parameter to judge the processes of transport and deposition. Sieving separates size classes mainly on volume (mass) characteristics, whereas the transport forces act on the surface of the grains.

The conclusions drawn in this paper could never have been reached by considering size parameters only. The processes of erosion, transport and deposition are equilibrium processes. Mass forces in most cases resist erosion and transport, whereas the shear and impact forces of the transporting medium act on the surface of the grains to move them.

It is the conviction of the present authors that it is better to consider sediment parameters that are hydrodynamically significant, rather than to stick one's head in the sand.

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