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Magnetic Heavy Mineral Associations as Sediment Transport Indicators on a Beach of Norderney Island, Southern North Sea

With 13 Text-Figures and 6 Tables

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Abstract

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Extensive sedimentological investigations have been carried out on the beach of the island of Norderney in order to obtain more information about the erosional and depositional processes in the nearshore zone. The study of the hydraulic properties of different sediment particles such as quartz and heavy mineral associations as a function of density and grain size promotes the understanding of the dynamic beach processes. The erosional behaviour of beach sediments is mainly controlled by the critical threshold stress and depends mainly on grain density and only to a lesser extent on grain size. The deposition, by contrast, is mainly controlled by the settling velocity of the particles, i.e. a combination of grain size, grain shape and density. Heavy mineral sands and other sediment particles with a higher density have a higher critical threshold stress than quartz sands. The former are thus more resistant against erosional processes. As such, heavy mineral sands would be a suitable fill material for extending the longevity of artificially replenished beaches. Larger grain sizes, by contrast, have a much lower influence on the longevity of artificial beaches than hitherto assumed because grain size alone was found to have a subordinate influence on the threshold stress.

Introduction

Transport processes in the nearshore zone are a manifestation of the complex interactions between variable hydrodynamic forces, beach configuration and sediments.

The sandy beaches of the barrier-islands along the southern North Sea shoreline of Germany and the Netherlands (Fig. 1) are mainly composed of quartz sands. Locally important accessory components are heavy minerals and shell fragments.

Heavy minerals concentrate in beach sands in the course of physical sorting processes because of their higher density ($>2.89\ g/cm^3$). Such local placers were of economical interest in the past as sources for rare ores. Already MEYN (1876) mentioned heavy mineral concentrates from the North Frisian island of Sylt. Placers were also described from the inhabited island of Trischen (WETZEL 1924), from the East Frisian island of Wangerooge (TRUSHEIM 1935) and from the West Frisian island of Terschelling in the Netherlands (VAN DEN SLEEN 1912). LUDWIG & FIGGE (1979) give a detailed description of heavy mineral placers in the German Bight.

The settling velocity is a more useful parameter in the assessment of the transport behaviour of sediment particles in water than grain size alone because sediment grains with an identical size can have quite different hydraulic properties because of different densities and/or grain shapes. Data on the settling velocity of quartz and heavy minerals are, for example, published in VON ENGELHARDT (1937), SLINGERLAND (1977), HAND (1967), but these are of limited

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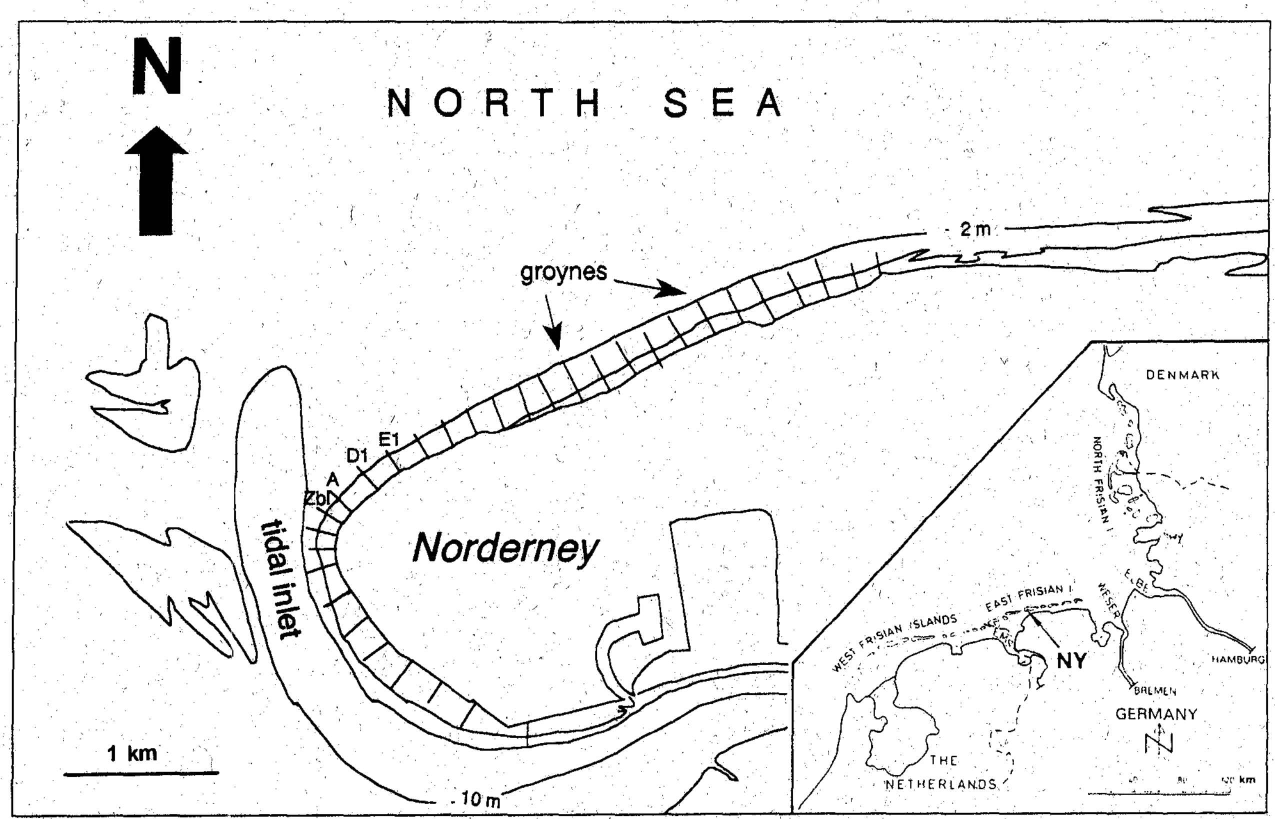

Fig. 1. Location map: Norderney Island, southern North Sea.

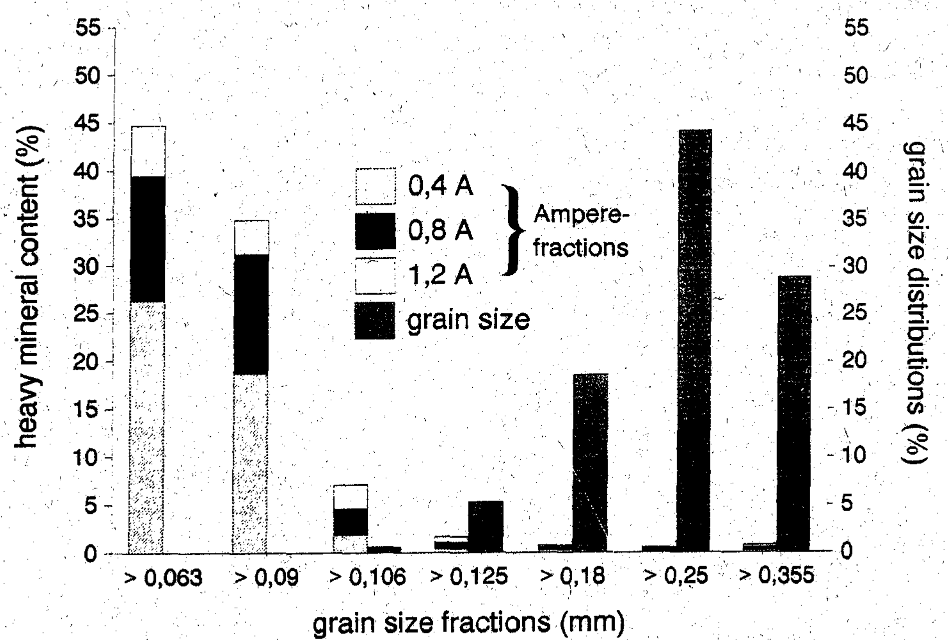

Fig. 2. Heavy mineral content of different grain size fractions of an examplary sediment sample from the high water line in the groyne field ZbI-A (April 7th, 1992). — Norderney Island, southern North Sea.

use in the case of Norderney because they span significantly different grain size ranges than those found on the beaches of the East Frisian Islands.

In the study area heavy minerals mainly concentrate in the finer sieve fractions (Fig. 2). As a result the relative heavy mineral content of individual sieve fractions increases with deceasing grain diameter. This is mainly due to the fact that heavy minerals have different hydraulic properties than larger and lighter minerals such as quartz (RITTENHOUSE 1943; McINTYRE 1959). The heaviest minerals concentrate in the finest grain size fractions and the slightly lighter minerals in the next coarser fraction (WEYL 1937). Because the main purpose of the studies was to investigate the physical processes in the nearshore zone, hydraulic properties of heavy minerals had to be determined by measuring their settling velocities.

A separate field experiment was thus designed to investigate the role of sediment distribution and properties on these dynamic beach processes specifically focusing on settling velocities of heavy minerals.

Study Site

Sediment sampling was conducted in the nearshore zone of a mixed-energy, tide dominated beach on the island of Norderney, Germany (Fig. 1). The mean intertidal slope approximated 0.02. The sediments generally comprise well-sorted sand with a mean grain size of 0.2 mm (EITNER et al. 1992; EITNER 1993; EITNER & RAGUTZKI 1994).

The hydrodynamic conditions in the area around Norderney are controlled by waves and tidal currents. Both are responsible for the typical appearance of the East and West Frisian coastline with its barrier islands. Norderney has a mean tidal range of approx. 2.4 m (mesotidal). The annual mean significant wave height varies from 0.7–1.0 m (NIEMEYER 1992).

Methods

The sediment samples were desalted before soil physical analyses. Grain size distributions were determined by dry sieving at 1/4 phi intervals.

Many heavy minerals have magnetic properties, so that they can be separated by a magnet, e.g. using a Franz Magnetic Separator as in this study. Although this method extracts heavy minerals from the sediment less efficiently than separation by heavy liquids because not all heavy minerals are magnetic, its application facilitates the analysis of large numbers of samples.

The Frantz Magnetic Separator splits heavy minerals from sediment according to their magnetic susceptibilities by an adjustable magnetic field (McANDREW 1957). In the present study the force of the magnetic field measured in Amperes was increased in three steps, corresponding to the 0.4 A, 0.8 A and 1.2 A levels respectively. The occurrence of heavy mineral associations in the individual Ampere-fractions, as observed in the beach sediments of Norderney Island, is summarized in Tab. 1. Although the minerals of these Ampere-fractions have different densities. It is possible to assign a mean density to each heavy mineral association. Thus, the 0.4 A-fraction contains minerals – especially garnets – with a mean density of 4.0 g/cm^3, the 0.8 A-fraction minerals with a mean density of 3.5 g/cm^3 and the 1.2 A-fraction with a mean density of 3.0 g/cm^3. In comparison, quartz grains have a density of ca. 2.65 g/cm^3.

The settling velocities were measured in a ca. 1.5 m long plexiglass tube with a diameter of 30 cm. The water temperature was 21°C. The velocities of individual grains from different size fractions were determined by a stop-watch. Ten to fifty grains per fraction, depending on the grain size, were used for each test. The small number of grains facilitated an almost undisturbed settling of each grain. The influence of other grains by collisions was insignificant. The results plotted in the diagrams are thus mean settling velocities. The reproducibility of the settling results were also tested. The variation of the mean settling results was small, less than 0.1 cm/s. The shape factor of sediment grains is an important parameter in their settling behavior. In the present the shape of the grains which are well-rounded is quite homogeneous.

Box cores were taken to investigate sorting and selection processes on the beach. After drying, the sediments in the box cores were stabilized by paraffin. By this method characteristic bedding structures can be documented. The paraffin was subsequently dissolved in hot water to allow a grain size analysis of each characteristic layer (cf. Fig. 3).

Review of Research on Heavy Mineral Transport Processes

The distribution and genesis of heavy mineral deposits on beaches have been the subject of several studies over the last few decades. MARTENS (1928, 1934) assumed that heavy minerals mainly concentrated on the upper part of the beach. The cut and fill processes on beaches expose heavy mineral lag deposits during periods of erosion. These are subsequently buried by lighter quartz grains and shell debris in the course of beach accretion. This is a continuous process which is accentuated during storms when beaches can be cut back several metres beyond the normal high-water mark, especially during spring tides.

RUBEY (1933) developed the concept that heavy minerals enrich due to higher settling velocities than the bulk beach material.

According to VON ENGELHARDT (1937), two forces are responsible for the development of heavy mineral placers: surf action along the beach and wind action on the beach and especially in adjacent dunes (VON BÜLOW 1929). Sand is transported by wave swash to the seaward slope of a berm. There the sediment is selectively sorted by wave action and is deposited on the berm. This sorting process is controlled by the settling velocity of the sand grains such that the grains with the highest settling velocities are deposited at the most seaward position. The higher the settling velocity the more seaward this point is situated.

RASMUSSEN (1941) also explained the higher percentage of heavy minerals on the upper beach with their higher density and hence also a higher settling velocity. The orbital velocity of incident waves increases with decreasing water depth. As a result, suspended sediments comprising particles of different densities will undergo gravity sorting along the energy gradient. Since the velocity of the return flow is smaller due to frictional energy losses, the backwash can only move particles with lower settling velocities at any particular position on the beach.

The enrichment of well-sorted heavy mineral sands seems to be an important feature of beach erosion and regression (RAO 1957; KOMAR & WANG 1983; KOMAR 1989; FRIHY & KOMAR 1991).

Other investigations, however, demonstrated that light and heavy minerals that were deposited together rarely have the same settling velocity (RITTENHOUSE 1943; HAND 1967; LOWRIGHT et al. 1972). In more recent studies the selective entrainment and the differential transport of light and heavy minerals due to density and grain size differences have been investigated by SLINGERLAND (1977, 1984), KOMAR & WANG (1984), TRASK & HAND (1985). It was shown that the sediments are sorted by selective entrainment and that the minerals are separated depending on grain size and density. During transportation the individual particles are then moved in varying speeds, thereby promoting further separation and selection in the course of deposition at different sites.

SLINGERLAND (1977) and KOMAR & WANG (1984) developed an empirical equation by which the selective entrainment of sediment grains can be calculated:

$$\tau_t = (\rho_s - \rho)\, g\, d \tan \Phi \tag{1}$$

where τ_t is the threshold stress, ρ_s is the sediment density, ρ is the water density, g is the gravitational acceleration, d is the diameter of the moving sediment grain and Φ is the pivoting angle. A derivation of equation (1) is given by RAUDKIVI (1976). Based on the experiments of Miller and BYRNE (1966) and LI & KOMAR (1986), the pivoting angle Φ can be determined by:

$$\Phi = e\left(\frac{d}{k}\right)^{-f} \tag{2}$$

where k is the bulk mean grain size of the sediment, e and f are empirical coefficients. An increase in the ratio of d/k leads to a decrease of Φ and thus to a reduction of the critical threshold stress τ_t.

In their investigations of beach placers in Oregon (USA), KOMAR & WANG (1984) used these following equations (notations as before):

$$\tau_t = 0.00515\,(\rho_s - \rho)\, g\, d^{0.568} \tan \Phi \tag{3}$$

$$\Phi = 61.5\left(\frac{d}{k}\right)^{-0.3} \tag{4}$$

Equation (3) was originally developed by MILLER et al. (1977) and is valid for uniform grains with diameters smaller than 1 mm. Equation (4) reflects the pivoting angle of natural beach sediments and goes back to MILLER & BYRNE (1966). LI & KOMAR (1992), who have tested these equations, state that minerals with a higher density and finer grain size have a higher critical threshold stress than minerals with a lower density and coarser grain size.

The causes for heavy mineral enrichment on beaches can be summarized in form of two hypotheses:

(1) The increasing influence of eolian transport processes during low tide causes the enrichment; i.e. the shorter the time of water covering, the larger the heavy mineral enrichment.

(2) Events associated with higher energy inputs on a beach that also flood wide parts of the backshore due to an increased water level (e.g. during storm surges) lead to intensive sorting and selection processes. The lighter and finer sediment particles are winnowed out, the heavier and larger particles left being behind.

Results

The results of the studies on the beach of Norderney confirm that heavy minerals mainly enrich on the upper beach during higher tides and stronger energy inputs. Box cores from the Norderney beach show well developed heavy mineral layers above backshore deposits (Fig. 3). These heavy mineral layers are not continuous alongshore, but form irregular patches of various extent that have the shape of extremely flat lenses.

The box core IA-1 illustrates the occurrence of two characteristic zones with variable structures commonly observed. The upper, approx. 6 cm thick zone consists of a laminated succession of heavy mineral layers (HM-I to HM-III) and quartz sand layers. The latter ones are not preserved by the paraffin in the profile because of their lower permeability. A sedimentological analysis of these was therefore not possible. This succession will in the following be called the **redeposited zone.** It has a mean grain size of 0.23–0.29 mm due to a higher content of medium sand. At 38–69%, the heavy mineral content is relatively high (Fig. 3).

By contrast, the lower zone does not show any characteristic sediment structures. Ripple marks are faintly

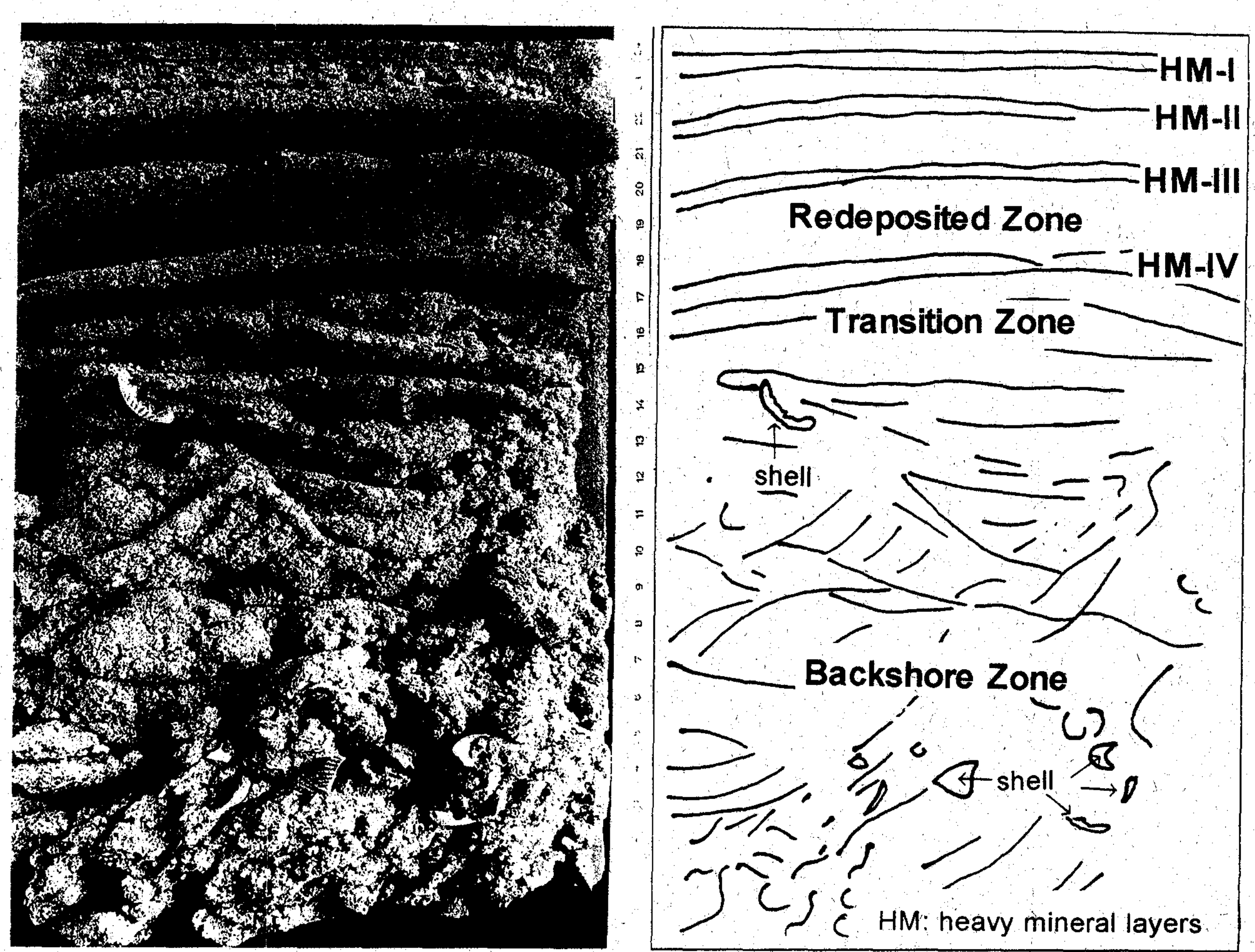

Fig. 3. Picture and sketch of the box examplary box core IA-1 taken within the groyne field ZbI-A in a distance of 10 m from the revetment after a tide with higher energy input (December 18th, 1992). — Norderney Island, southern North Sea.

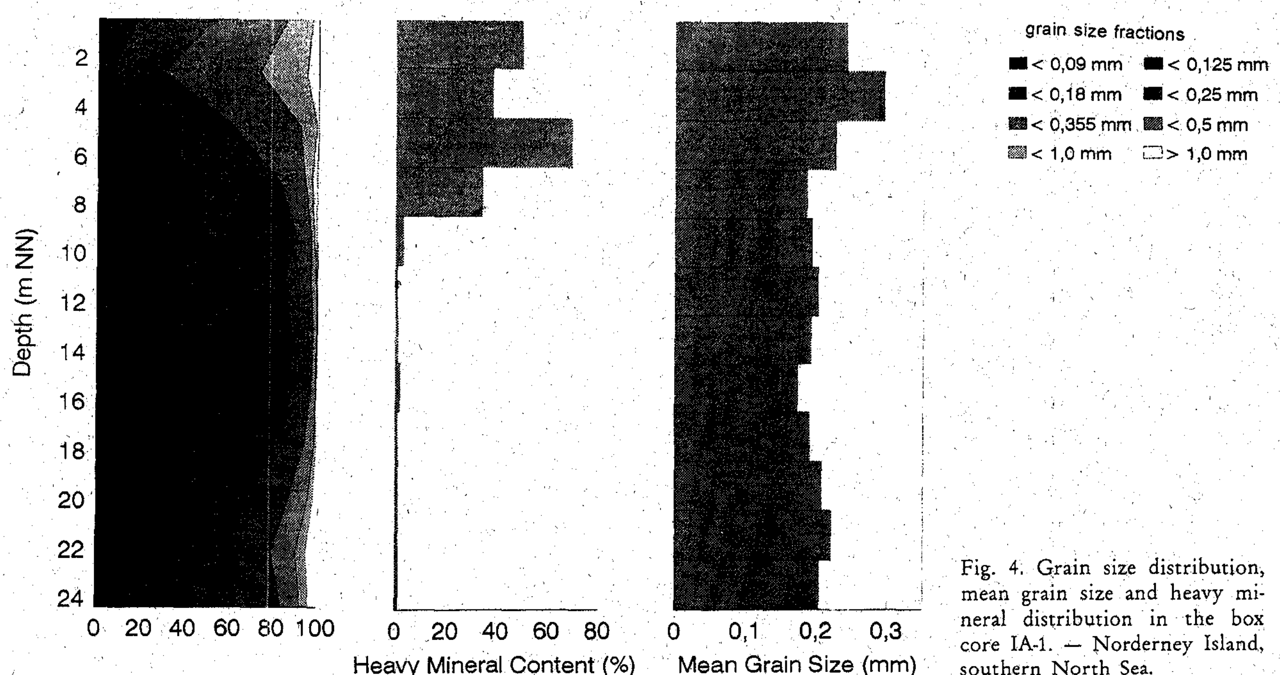

Fig. 4. Grain size distribution, mean grain size and heavy mineral distribution in the box core IA-1. — Norderney Island, southern North Sea.

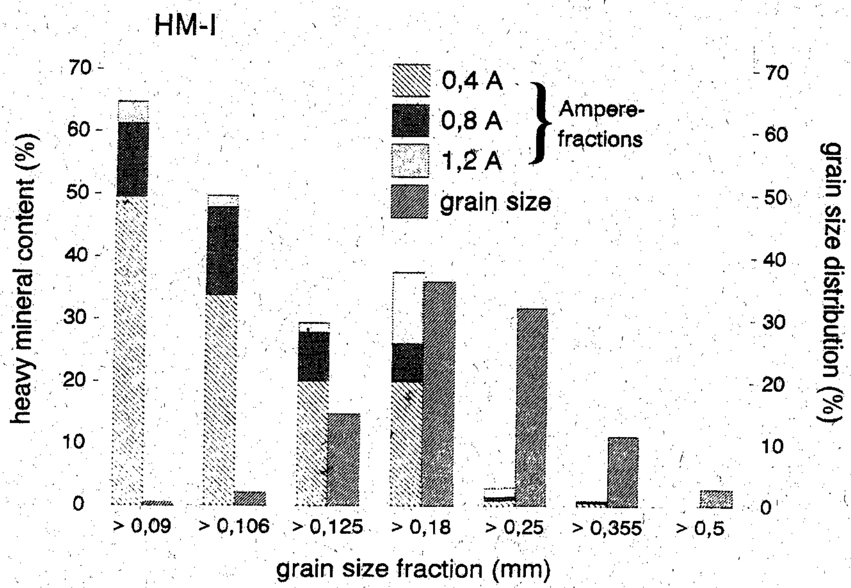

Fig. 5. Heavy mineral content of different grain size fractions of the heavy mineral layer HM-I. – Norderney Island, southern North Sea.

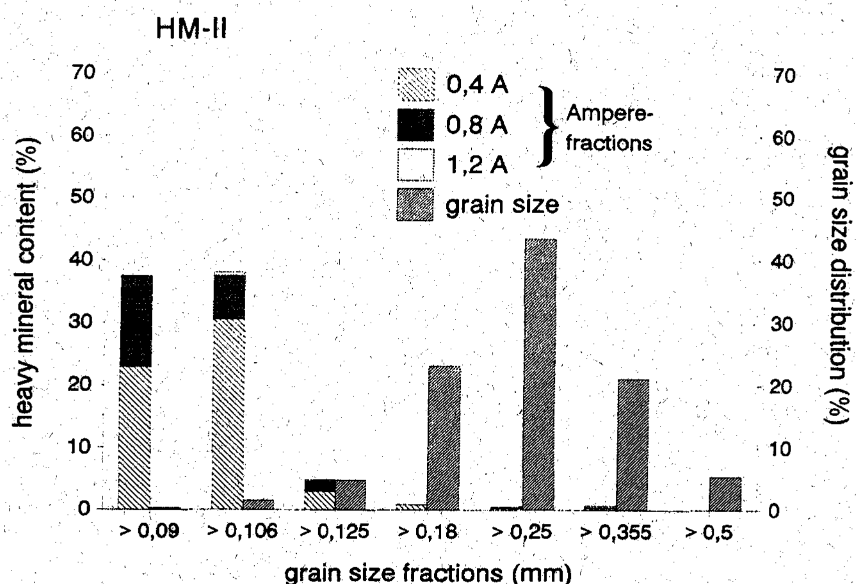

Fig. 6. Heavy mineral content of different grain size fractions of the heavy mineral layer HM-II. – Norderney Island, southern North Sea.

recognizable and single shell fragments may occur. The sediments belong to the backshore depositional environment. This zone will henceforth be called the **backshore zone.** The mean grain size of these sediments varies around 0.2 mm and the heavy mineral content is very small (1–2%) (Fig. 4).

Between the two section a 1 cm thick **transition zone** can be recognized. It incorporates a single heavy mineral layer (HM-IV) with a heavy mineral content of approx. 35% which is significantly higher than that of the backshore sediments. The mean grain size is similar to the grain size of the underlying backshore sediments (Fig. 4).

To determine the relationship between grain size and density of sediment particles the heavy mineral content of several sieve fractions was determined. The results are presented for the three heavy mineral layers of the redeposition zone and for the fourth layer of the transition zone as well as for the backshore zone (Figs. 5–9). In general, the heavy mineral content decreases from the finer to the coarser grain size fractions. There are, however, distinct quantitative differences between the three zones.

The individual heavy mineral layers are more inhomogeneous with respect to their composition than it appears at first sight. The uppermost heavy mineral layer (HM-I) has a relatively high heavy mineral content (30–60%) in the fine sand fractions (<0.25 mm) but a very small proportion (less than 3%) in the medium and coarse sand fractions (Fig. 5). The very fine grain size fractions (<0.125 mm) are mainly composed of heavy minerals (more than 50%). These fractions, however, contribute less than 3% to the total sediment, as do the coarse sand fractions. These fractions are therefore not important for the evaluation of heavy mineral enrichment processes. The more interesting parts of the grain size spectrum are

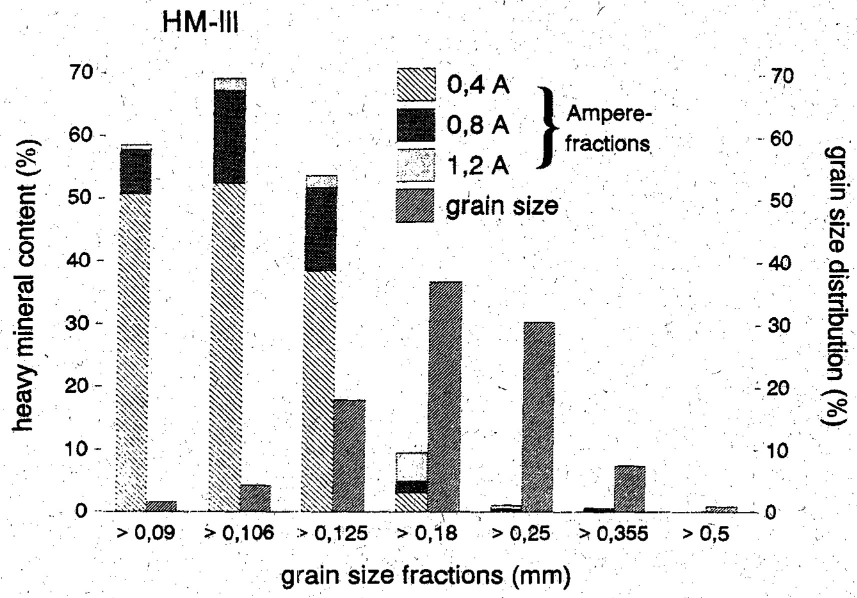

Fig. 7. Heavy mineral content of different grain size fractions of the heavy mineral layer HM-III. — Norderney Island, southern North Sea.

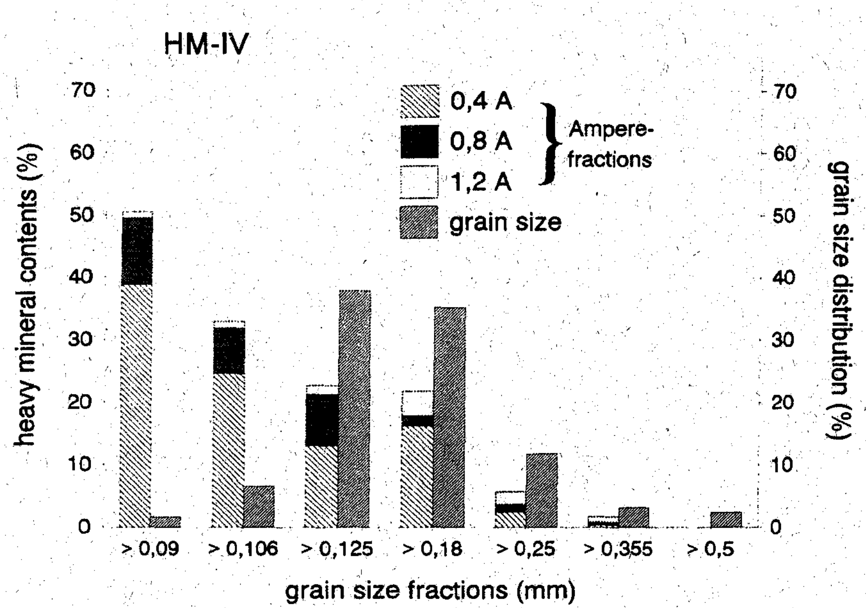

Fig. 8. Heavy mineral content of different grain size fractions of the heavy mineral layer HM-IV. — Norderney Island, southern North Sea.

the medium and fine sand fractions, the latter of which contains 30% heavy minerals. The medium sands, on the other hand, are almost devoid of heavy minerals.

In the second heavy mineral layer (HM-II) the heavy mineral content is much smaller than might have been expected (Fig. 6). Higher proportions are only found in the very fine sand fractions (<0.125 mm), which form less than 5% of the total sediment. The relatively high proportion of medium sand containing almost no heavy minerals as in the case of layer HM-I, is quite remarkable. Furthermore, the 0.18–0.25 mm size fraction contains less than 1% heavy minerals. By contrast, the heavy mineral content of the overlying layer HM-I amounts to almost 40%. This observation means that in this second layer fewer heavy minerals were enriched than coarser quartz grains.

The grain size distribution of the third heavy mineral layer (HM-III) (Fig. 7) is comparable to the first one (HM-I). Slight differences can be recognized in the heavy mineral content. The 0.125–0.18 mm fraction has a particularly high heavy mineral content (greater than 50%). By contrast, the next coarser fraction (0.18–0.25 mm) only contains 10% heavy minerals, although the relatively high proportion of the 1.2A fraction is quite remarkable, being similar to the HM-I layer.

The transition zone with the heavy mineral layer (HM-IV) shows some similarities to the underlying backshore sediments, e.g. relatively small amounts of heavy minerals, especially in the sieve fractions 0.125–0.18 mm and 0.18–0.25 mm (Fig. 8).

The sediments of the backshore environment are very homogeneous, comprising up to 80% of fine sand that is almost devoid of heavy minerals (Fig. 9).

The critical threshold stress for the sediment particles in the four heavy mineral layers and the backshore deposits

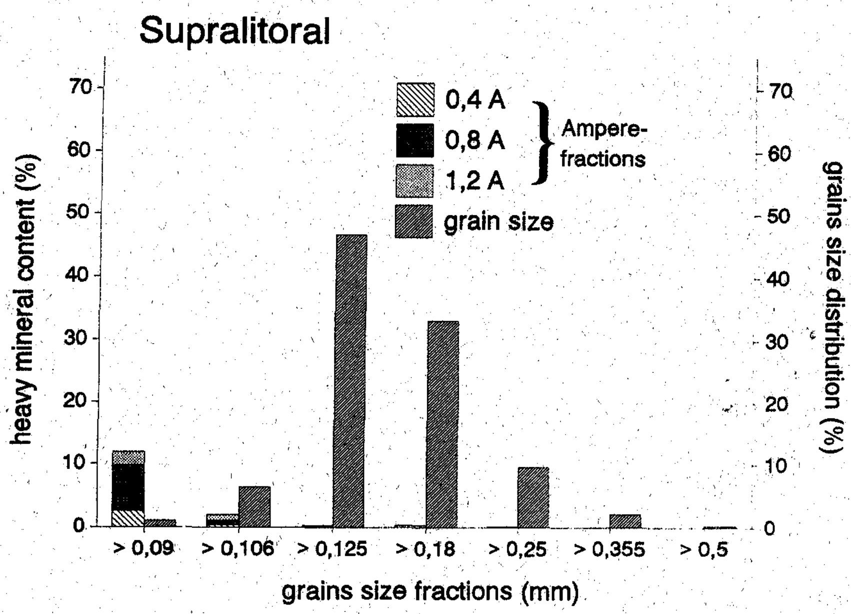

Fig. 9. Heavy mineral content of different grain size fractions of the supralitoral layer. — Norderney Island, southern North Sea.

Table 1. Heavy mineral associations in the sediments of Norderney, southern North Sea, determined by x-ray diffraction method (after WESTHOFF 1990) and their mean densities.

0.4 A Fraction	0.8 A Fraction	1.2 A Fraction
Garnet (Almandine, Spessartine)	Hastingsite	Tourmaline (Dravit)
Ilmenite	Epidote	Staurolite
Hastingsite	Saussurite	Epidote
	Staurolite	Muscovite
		Titanite
Mean Density 4.0 g cm^{-3}	Mean Density 3.5 g cm^{-3}	Mean Density 3.0 g cm^{-3}
Quartz with heavy mineral enclosures		

Table 2. Settling velocity according to grain size and density of heavy mineral associations and quartz grains for a water temperature of 21°C. — Norderney Island, southern North Sea.

Settling Velocity (cm s^{-1})				
Grain Size (phi)	Heavy Minerals			Quartz
	0.4 A	0.8 A	1.2 A	
3.5	2.39	2.30	2.13	1.23
3.0	3.27	3.18	3.03	1.72
2.5	4.38	4.21	4.04	2.65
2.0	6.75	5.71	5.71	3.58
1.5	9.09	8.06	7.67	5.90
1.0	10.00	11.11	10.30	8.60

Table 3. Threshold stress according to grain size and density of heavy mineral associations and quartz. — Norderney Island, southern North Sea.

Critical Threshold Stress (dynes cm^{-2})				
Grain Size (phi)	Heavy Minerals Associations			Quartz
	0.4 A	0.8 A	1.2 A	
3.5	3.12	2.59	2.07	1.70
3.0	3.29	2.74	2.19	1.80
2.5	3.52	2.93	2.34	1.92
2.0	3.76	3.13	2.50	2.06
1.5	4.05	3.38	2.70	2.22
1.0	4.39	3.65	2.91	2.40

was calculated according to the equations (3) and (4) (Tab. 3). On the basis of these equations, the smaller but heavier sediment grains have a higher threshold stress than the lighter and coarser particles in each size fraction of the Norderney beach sediments. Every Ampere-fraction clearly contains minerals of a different density range (Tab. 1).

Corresponding to their different mean densities, the settling velocities of the individual heavy mineral suites and the quartz as a function of grain size are shown in Fig. 10. The settling velocities of all mineral suites rise with increasing grain size and decreasing susceptibility (i.e. increasing Amperage). Moreover, it can be seen that heavy minerals with a higher density (0.4 A fraction) have notably higher settling velocities than lighter heavy minerals (0.8 A and 1.2 A fractions) and quartz of the same grain size.

These results differ in some respects from those reported in the literature. According to VEENSTRA & WINKELMOLEN (1978), heavy minerals of the 0.4 A fraction

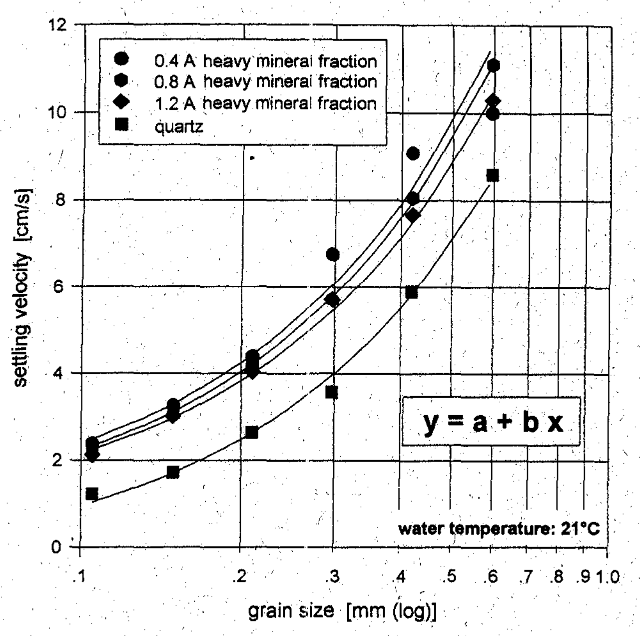

Fig. 10. Settling velocity of heavy minerals and quartz according to grain size. — Norderney Island, southern North Sea.

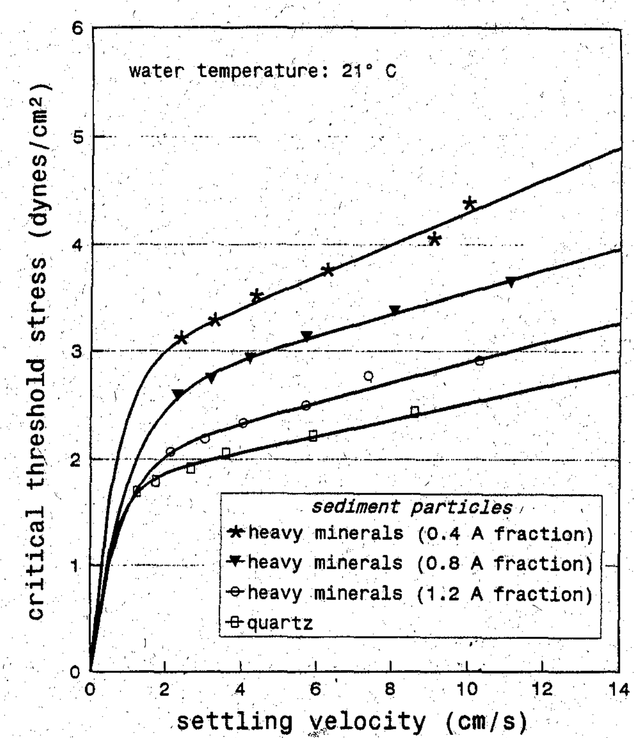

Fig. 12. Correlation of settling velocity and critical threshold stress of heavy minerals and quartz. — Norderney Island, southern North Sea.

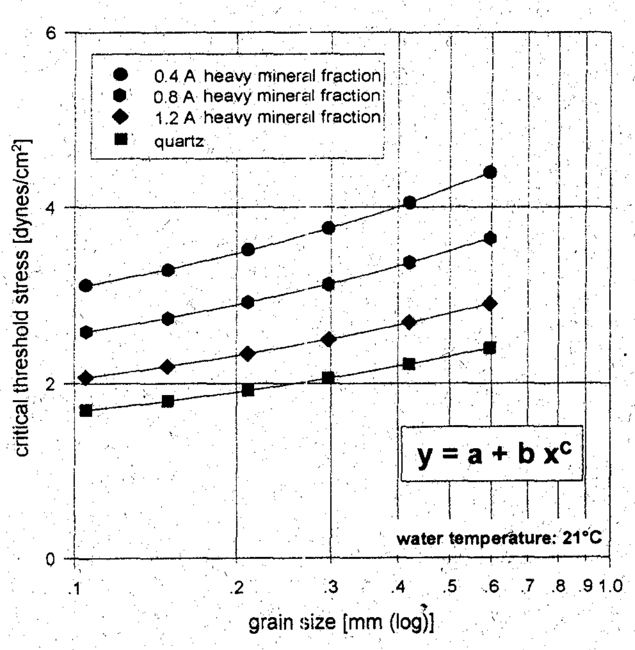

Fig. 11. Critical threshold stress of heavy and light minerals according to different grain size calculated by equations (3) and (4). — Norderney Island, southern North Sea.

are equivalent to ½-phi coarser quartz grains (1.5 times grain diameter), minerals of the 0.8 A fraction correspond to ¼-phi coarser quartz grains (1.25 times diameter) and the minerals of the 1.2 A fraction correspond to quartz grains of the same diameter. By contrast, the settling results of the material from Norderney show that all heavy mineral fractions have higher settling velocities than the quartz grains in the same size fractions (Tab. 2; Fig. 10).

The calculation demonstrates that the critical threshold stress increases with grain size and density, whereby the increase of density influences the critical threshold stress to a much larger degree than does the grain size (Tab. 3; Fig. 11). The critical threshold stress of the 0.4 A-heavy mineral fraction is 1.8 times larger than the critical threshold stress of quartz grains with an identical grain size; the threshold stress of the 0.8 A-fraction is 1.5 times and that of the 1.2 A-fraction is 1.2 times larger. The good correlation between mean threshold stress and mean settling velocity of different sediment particles is demonstrated in Fig. 12 (cf. Tab. 6). The settling velocity of particles increases proportionally with grain size, but there is no correlation between settling velocity and threshold stress independently of the density of the sediment particle. Thus, quartz grains and heavy mineral grains of the same settling velocity invariably have different threshold stresses. The critical threshold stress of a heavy mineral or quartz grain can be calculated by a given settling velocity using one of the equations given in Tab. 6. These equations were determined by non-linear fitting after the Levenberg-Marquardt method. They show a logarithmic gradient up to a settling velocity of about 3 cm/s followed by a linear gradient.

Discussion and Conclusions

The results would suggest that the enrichment of heavy minerals is mainly due to the high critical threshold stresses. Generally speaking, the heavy mineral content increases with decreasing grain size. The relative proportions of individual Ampere-fractions shift in favour of the fractions with heavy minerals of lower density. The 1.2 A-fraction is largely concentrated in the 0.18–0.25 mm size fraction in almost all heavy minerals layers. The density of heavy minerals in the size fractions decreases with decreasing grain size. The very fine sand fractions, which contain high percentages of heavy minerals, do not themselves form a high percentage of the grain size distribution. The same applies to coarser quartz grains that have a higher critical threshold stress.

The genesis of the heavy mineral layers, as they are revealed in the box core, may be summarized as follows: (1) The upper beach sections are flooded by higher tides connected with stronger energy inputs. Aquatic sorting and redeposition processes develop laminated sediment layers. (2) Heavy minerals and quartz grains enrich in 1–2 mm thick layers according to their critical threshold stresses, heavy minerals mainly concentrating in the fine-grained size fractions and quartz grains in the medium-grained size fractions. (3) Because of the given grain size spectrum on the beach, sorting and selection processes produce proportional changes in individual grain size fractions, i.e. finer particles (fine sands) are winnowed out, whereas heavier minerals are left behind. Coarser particles too (medium sand) are enriched. A concommitant concentration of coarse sand and heavy minerals of medium grain size is not observed because the latter are largely missing in the grain size spectrum of the local beach sand.

The results of this study have shown that the grain size and the heavy mineral content on the upper beach increases with a stronger hydrodynamic energy input on the beach. The selection and sorting processes, which lead to an enrichment of coarser and heavier sediment particles, can be described by two parameters: (1) settling velocity, and (2) critical threshold stress.

The settling velocity reflects the depositional behaviour of sediment particles as a function of grain size, density and shape and is therefore a depositional parameter.

The critical threshold stress, on the other hand, represents the force required to transpose a sediment particle of a given settling velocity from a state of rest into motion. This parameter depends mainly on density and to a lesser extent on particle size. The threshold stress may thus be interpreted as an erosional parameter.

The good correlations between settling velocity and grain size, critical threshold stress and grain size, as well as settling velocity and critical threshold sterss of mineral associations with different mean densities (Figs. 10–12) allow the calculation of each parameter from the other by means of the equations given in Tabs. 4–6. These equations give a first approximation only because the settling velocities and the critical threshold stresses have not been determined for specific grain sizes but rather for discrete grain size intervals.

The differences to the results of VEENSTRA & WINKELMOLEN (1978) may be due to different water temperatures during their measurements of settling velocities.

Heavy minerals are dominantly enriched due to their higher threshold stresses. Erosional processes can thus lead to a selective enrichment of heavy minerals as a function of relative energy levels. Depositional processes, on the other hand, result in the deposition of sediment particles

Table 4. Correlation between settling velocity and grain size of magnetic heavy mineral associations and quartz as expressed by linear curve fitting of the form $y = a + bx$ (cf. Fig. 10). — Norderney Island, southern North Sea.

Sediment Component	Equation
0.4 A heavy mineral fraction	$y = 0.550 + 18.500x$
0.8 A heavy mineral fraction	$y = 0.445 + 17.962x$
1.2 A heavy mineral fraction	$y = 0.551 + 16.661x$
Quartz	$y = -0.557 + 15.217x$

Table 5. Correlation between critical threshold stress and grain size of magnetic mineral associations as expressed by power curve fitting of the type $y = a + bx^c$ (cf. Fig. 11). — Norderney Island, southern North Sea.

Sediment Component	Equation
0.4 A heavy mineral fraction	$y = 2.009 + 2.995x^{0.442}$
0.8 A heavy mineral fraction	$y = 1.541 + 2.605x^{0.405}$
1.2 A heavy mineral fraction	$y = 1.203 + 2.097x^{0.393}$
Quartz	$y = 1.014 + 1.714x^{0.408}$

Table 6. Correlation of settling velocity and critical threshold stress of magnetic heavy mineral associations and quartz (nonlinear fitting after the Levenberg-Marquardt method). — Norderney Island, southern North Sea.

Sediment Component	Equation
0.4 A heavy mineral fraction	$y = 0.149364x + 2.80949\ (1-e^{-1.63911x})$
0.8 A heavy mineral fraction	$y = 0.102724x + 2.52748\ (1-e^{-1.11334x})$
1.2 A heavy mineral fraction	$y = 0.0931809x + 1.9646\ (1-e^{-1.37797x})$
Quartz	$y = 0.0764312x + 1.75521\ (1-e^{-1.90565x})$

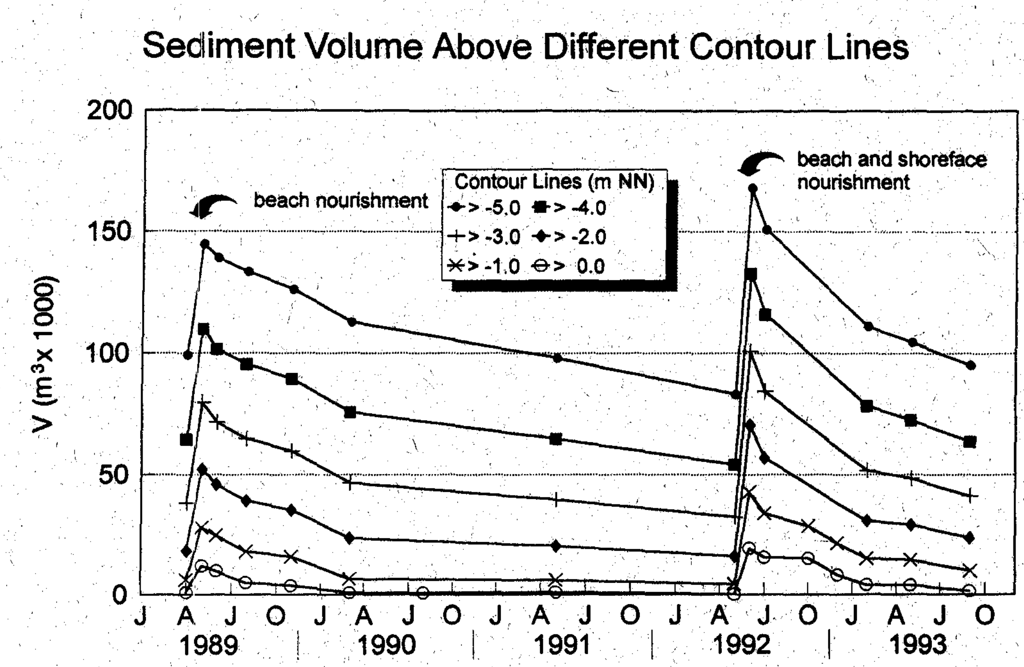

Fig. 13. Temporal development of sediment volumes within the groyne field D_1-E_1 after beach nourishment in April 1989 and May 1992. — Norderney Island, southern North Sea.

with similar settling velocities and therefore produce mixtures of quartz and heavy minerals. Depositional processes alone are thus unable to produce heavy mineral placer deposits!

Heavy mineral concentrations and, to a lesser extent also grain size coarsening, commonly observed in the wake of storm surges on eroding beaches, can therefore be interpreted as indicators of erosional processes. Heavy mineral concentrations are thus typical lag deposits.

Moreover, temporal changes in sediment distribution patterns on beaches simply reflect spatial redistributions within the given grain size spectrum. In any particular situation sediment coarsening is only possible up to the coarsest grain size within the available grain size spectrum. The same applies to the finest grain size and other sediment particles. This is the main reason why quartz grains that have equivalent critical threshold stresses as the heavy minerals, are not enriched in the beach sediments of Norderney. Such quartz grains would have to be larger than 1 mm, grain sizes that are not present in the size spectrum of local beach sands.

These results have an important technical implication for artificial beach nourishment programmes. In the literature the opinion is still widespread that grain size plays the overriding role in the longevity of beach fill material (KRUMBEIN & JAMES 1965; JAMES 1974, 1975; DEAN 1974; SWART 1991). It is claimed that losses of the refilled material cannot exceed the quantity of the finer-grained sands that are winnowed out. This purely theoretical consideration has never been proven. In the case of Norderney a continuous removal of the total fill sand can be observed (Fig. 13), i.e. finer as well as coarser particles are removed from the filled beach section. Of course, the finer particles are invariably winnowed out quicker than the coarser grains, but the temporal differences are very small because of the minimal variations in critical threshold stresses. This is particularly evident after storm surges which lead to strong sand losses. The hydrodynamic energy input is so great that both finer and coarser sediment particles are eroded and transported in a seaward direction.

Artificial beach fills are commonly eroded because they are not in equilibrium with the external boundary conditions. Such erosion leads to the selective enrichment of those sediment particles that have higher critical threshold stresses than the bulk fill material, i.e. the heavy minerals. A number of studies have demonstrated the close association between shoreline erosion and placer formation (e.g. RAO 1957; KOMAR & WANG 1983; KOMAR 1989; FRIHY & KOMAR 1991). The beach counteracts erosion with this passive enrichment process of heavy mineral grains without the ability to stop it because there is usually not enough material available. This effect is particularly prominent on artificially nourished beaches (EITNER 1993).

Heavy mineral sands thus appear to be well-suited for extending the longevity of beach fills (EITNER 1995). Heavy minerals have the required higher critical threshold stresses without changing structural beach properties as would be the case, for example, when using gravel. Unfortunately, natural heavy mineral sands are not available in sufficient volumes to form a viable alternative for currently used beach fill material.

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