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# Currents related to sediment transport at the Ibero-Moroccan continental shelf*

by

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With 9 figures and 4 tables

## Strömungen und Sedimenttransport auf dem Ibero-Marokkanischen Schelf

*Zusammenfassung*

Auf dem portugiesischen und marokkanischen Schelf wurden Strömungsmessungen durchgeführt und Bodenproben genommen, um die Wirkung von Wasserbewegungen auf den Sedimenttransport zu untersuchen. Ergänzt wurden diese Arbeiten durch Unterwasser-Fernsehaufnahmen. Einige statistische Eigenschaften der beobachteten Strömungen werden dargestellt, und es wird diskutiert, wie weit die Daten als repräsentativ für bodennahe Strömungen in diesem Gebiet anzusehen sind. Es zeigt sich, daß die in diesem Experiment gemessenen Strömungen zu schwach waren, um einen Sedimenttransport in Gang zu setzen.

Um zu prüfen, ob schnell veränderliche Strömungen dafür stark genug sein können, wurde die Wahrscheinlichkeit für das Auftreten großer Bodenstromgeschwindigkeiten als Folge von Oberflächenwellen in diesem Seegebiet aus Seegangsstatistiken abgeschätzt. Man findet, daß solche periodischen Strömungen, vor allem als Folge langer Dünung, in der Lage sind, zu bestimmten Zeiten Sedimentbewegung in Gang zu setzen.

Der Nettotransport wird verursacht durch langsam veränderliche Strömungen, deren mittlere und maximale Geschwindigkeiten und Richtungen nicht aus den kurzen Zeitserien dieses Experiments bestimmt werden können. Dagegen liefern die geologischen Daten Informationen über die mittleren Richtungen. Aus der regionalen Korngrößenverteilung auf dem portugiesischen Schelf ergibt sich ein Sedimenttransport zum oberen Kontinentalhang hin. Im Mittel werden die mittleren Bodenströmungen diese Vorzugsrichtung dann nehmen, wenn die Summe aus oberflächenwellenerzeugten und langsam veränderlichen Strömungen ausreichend groß ist, um einen Sedimenttransport einzuleiten.

*Summary*

For a study of water motions related to sediment transport, current data and bottom samples were taken in two areas on the Portuguese and Moroccan shelf near the shelfbreak and supplemented by underwater television observations. Some statistical properties of the observed currents are presented, and their representativeness for the water movement very close to the bottom is discussed. It appears that the slowly varying currents observed in this experiment were too weak to start sediment transport. To check whether rapidly changing currents may be strong enough, the probability of occurrence of large surface-wave-induced components of bottom currents in this area is estimated from wave statistics. It turns out that such oscillatory currents, especially from swell, will be able to set up sediment motion during certain periods.

The net transport is caused by slowly varying currents whose average and maximum magnitudes and directions cannot be obtained from the short time series of this experiment. The geological data, however, supply some information about the average directions. A sediment transport towards the upper slope is indicated by the regional grain

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size distribution at the Portuguese shelf. On the average the bottom currents will therefore have preferred directions of the mean velocity when the sum of surface-wave-induced currents and slowly varying currents is sufficiently large to set up sediment motion.

## 1 Introduction

Bottom current data obtained by direct measurements near the sea floor on the continental shelf can provide information about the current variability pertinent to sediment transport processes. On the other hand, estimates of the rate and direction of the sediment transport from geological investigations may possibly indicate the frequency of occurrence of strong variable currents and the size of the mean currents. Because of the scarcity of available data from simultaneous work in these fields, it was decided to add an exploratory short-term current meter experiment to the geological and geophysical investigation of the Ibero-Moroccan shelf carried out during Meteor Cruise 8 in 1967 (CLOSS et al. 1969). The probable relevance of such currents and of surface wave induced currents for the sediment transport in this area will be discussed in the following paragraphs. Similar studies for other areas were reported by HADLEY (1964), DRAPER (1967), HOPKINS (1971), STERNBERG & MCMANUS (1972) and MCCLEMMEN (1973).

Sediment transport can be started by slowly varying currents as well as by the orbital motions of surface waves. By the term "slowly varying currents" all currents with time scales above those of wind-driven surface waves are summarized here. At the characteristic dimensions and densities of the sediment encountered here, slowly varying (quasi-steady) currents can be expected to start bed-load transport at a critical velocity 1 m above the bottom of approximately 35—40 cm sec$^{-1}$ (SUNDBORG 1967). With stronger currents, an increasing part of the sediment transport will be suspended load transport. Bed-load transport continues to exist down to approximately two thirds of the critical velocity when the current velocity decreases after the transport had been started.

The critical velocity for the onset of sediment motion by an oscillatory current is smaller than the value given above and can be described by a critical "setting off" Reynolds number (VINCENT 1958):

$$\text{(1)} \qquad \mathrm{Re_s} = \frac{\omega\, d_0\, \varepsilon}{\nu}$$

where $\mathrm{Re_s}$ = critical "setting off" Reynolds number

$\omega = \frac{2\pi}{\tau}$ = radian frequency

$\tau$ = period

$d_0$ = maximum total displacement of a water particle just above the oscillatory boundary layer

$\varepsilon$ = characteristic dimension of the sediment particles

$\nu$ = kinematic viscosity $\approx 10^{-2}$ cm$^2$ sec$^{-1}$

For characteristic sediment dimensions similar to the dimensions found in our bottom samples, VINCENT obtained the following results:

$$\mathrm{Re_s} = 70 \text{ for } \varepsilon = 0.023 \text{ cm} \approx 0.02 \text{ cm}$$

$$\mathrm{Re_s} = 165 \text{ for } \varepsilon = 0.046 \text{ cm} \approx 0.05 \text{ cm}.$$

These two conditions can be combined approximately by:

$$\text{(2)} \qquad \left(\frac{\omega\, d_0}{\nu}\right)_s \approx 3300 \text{ cm}^{-1}.$$

To obtain the amplitude of wave induced currents and resulting water particle displacements near the bottom, it seems reasonable to apply the solution of the linearised problem of surface waves (e. g. KINSMAN 1965). The horizontal velocity $u$ of a plane wave travelling in x-direction is given by:

$$\text{(3)} \qquad u = \frac{H}{2}\omega \frac{\cosh k(z+h)}{\sinh kh} \cos(kx - \omega t) = u_0 \cos(kx - \omega t)$$

with $u_0 = \frac{H}{2}\omega \frac{\cosh k(z+h)}{\sinh kh}$

where $H$ = wave height

$k = \frac{2\pi}{\lambda}$ = radian wave number

$\lambda$ = wave length

$h$ = bottom depth

$z$ = upward co-ordinate with zero at the surface.

The maximum total displacement $d_0$ of a water particle is then given by:

$$\text{(4)} \qquad d_0 = u_0 \frac{2}{\omega}$$

Inserting (4) into (2), we obtain the critical velocity $u_{0s}$ needed to start sediment transport:

$$\text{(5)} \qquad u_{0s} \approx 17 \text{ cm sec}^{-1}.$$

It should be kept in mind during the later discussions that (5) provides only an approximate number due to the simplifications necessary for the linear theory. It will be noted that the oscillatory current required to set sediment in motion is only about one-half of the critical value for a steady or slowly varying current 1 m above the bottom.

## 2 Current meter observations

Two moorings, each with one current meter, were set, mooring no. 1 off the Moroccan coast and mooring no. 2 off the Portuguese coast, both near the shelf break. The observation periods of the two moorings did not overlap. The station data are given in Table 1.

Because of the restrictions imposed by the mooring techniques, the instruments could not be placed closer than 5 m to the bottom. Sub-surface moorings with additional surface marker buoys and current meters of the type „Hydrowerkstätten Tiefenstrommesser“ (see CHEKOTILLO et al. 1969) were used. The mooring configuration is given in fig. 1.

At both positions underwater television camera observations showed a fairly smooth bottom without any ripples. The characteristic dimension of the sediment in bottom samples was 0.02 cm near mooring no. 1 (off Morocco) and 0.05 cm near mooring no. 2 (off Portugal). The mean sediment densities were 2.8 and 2.65 $gcm^{-3}$, respectively (see Table 4).

The results of the moored current meter data are presented by figs. 2 to 6 and table 2. We will first discuss some average properties of the observed currents and then study their time dependence. The sampling interval of the actual measurement was 5 minutes. All results given are based on data points separated by 10 minutes which were generated by vector-averaging.

The vector distribution plots in fig. 2 and the histograms of speed and direction in fig. 4 show that there existed a preferred direction along a line NNW to SSE at mooring no. 1 (off Morocco) with a peak in the direction histogram at approximately 320°. This is more or less perpendicular to the orientation of the shelf break. Although there is also a peak in the direction histogram of mooring no. 2 (off Portugal) at approximately the same direction (see figs. 3 and 4), the vectors are much more uniformly scattered over all directions in this case. (The accumulation of vectors at a circle corresponding to a speed of 1 m $sec^{-1}$ is caused by a linear calibration curve for the current meter's propeller with a non-zero speed indication at zero revolutions per time unit.)

Speeds range up to 29 cm $sec^{-1}$ at mooring no. 1 and up to 36 cm $sec^{-1}$ at mooring no. 2. The mean speeds are just below 10 cm $sec^{-1}$ and the most frequent speeds somewhat above 10 cm $sec^{-1}$ at

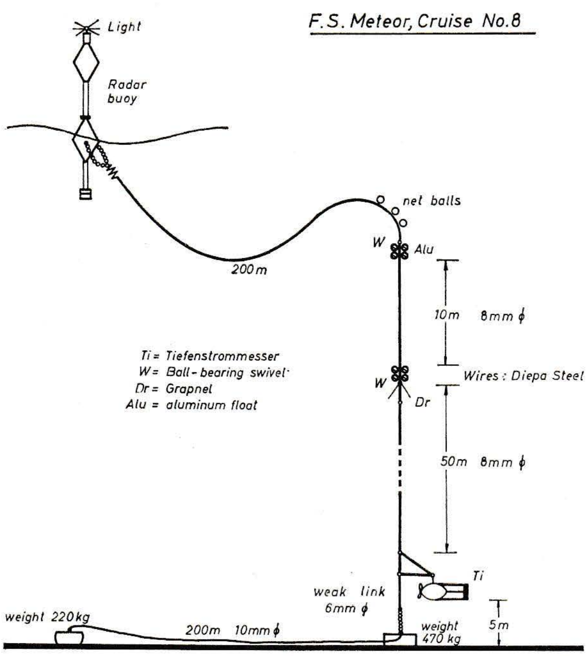


Fig. 1. Configuration of moorings no. 1 and 2.
Abb. 1. Aufbau der Verankerungen Nr. 1 und 2.

Table 1 Station record of current meter moorings.
Tabelle 1 Stationsliste der Strommesser-Verankerungen.

| Data | Mooring No. 1 (Morocco) | Mooring No. 2 (Portugal) |
|---|---|---|
| Latitude | 33° 19.0′ N | 37° 49.9′ N |
| Longitude | 9° 00.0′ W | 9° 02.0′ W |
| Distance form coast | 40 km | 20 km |
| Width of shelf | 40 km | 20 km |
| Mean gradient of shelf | 4 ‰ | 8 ‰ |
| Width of continental slope | 65 km | 140 km |
| Mean gradient of continental slope | 62 ‰ | 34 ‰ |
| Water depth | 180 m | 175 m |
| Depth of meter | 175 m | 170 m |
| Record start | 23—1—1967, 10.29 | 06—2—1967, 08.20 |
| Record end | 30—1—1967, 18.19 | 12—2—1967, 14.50 |
| Seabottom television | 23—1—1967, 09—10 | 06—2—1967, 06—07 |

Table 2 Statistical properties of observed currents (10 min. averages).
Tabelle 2 Statistische Eigenschaften der beobachteten Strömungen (10-min. Mittel).

| Property (cm $sec^{-1}$) | Mooring No. 1 | Mooring No. 2 |
|---|---|---|
| East component | | |
| Mean | −3.2 | −4.6 |
| Standard deviation | 4.5 | 6.5 |
| North component | | |
| Mean | 1.6 | −1.2 |
| Standard deviation | 8.5 | 9.0 |
| Speed | | |
| Mean | 9.0 | 9.8 |
| Standard deviation | 4.9 | 7.0 |

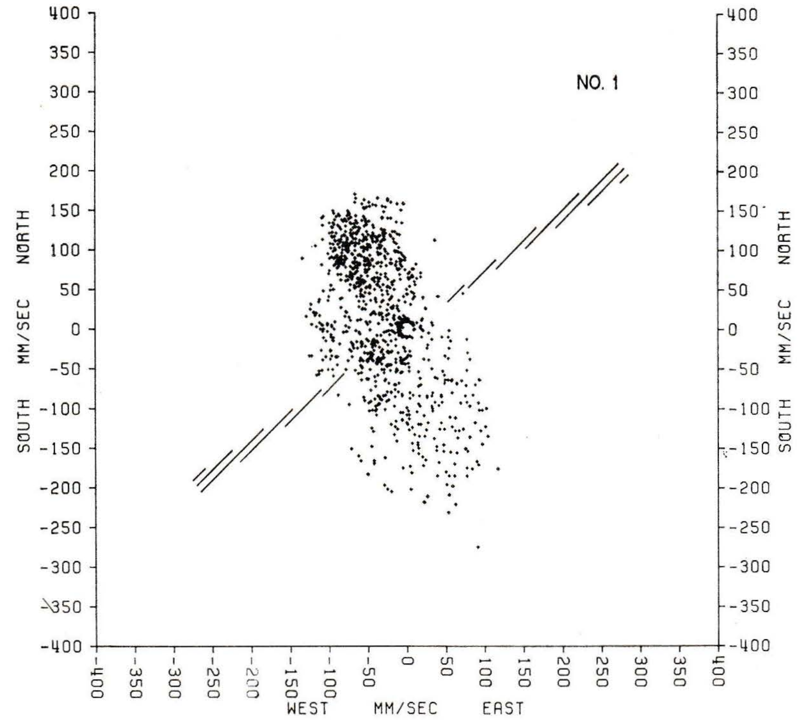


Fig. 2. Vector distribution plot for mooring no. 1 (Morocco). Hatching indicates general orientation of the shelf break.

Abb. 2. Vektorverteilung für Verankerung Nr. 1 (Marokko). Der gestrichelte Bereich zeigt die allgemeine Orientierung der Schelfkante an.

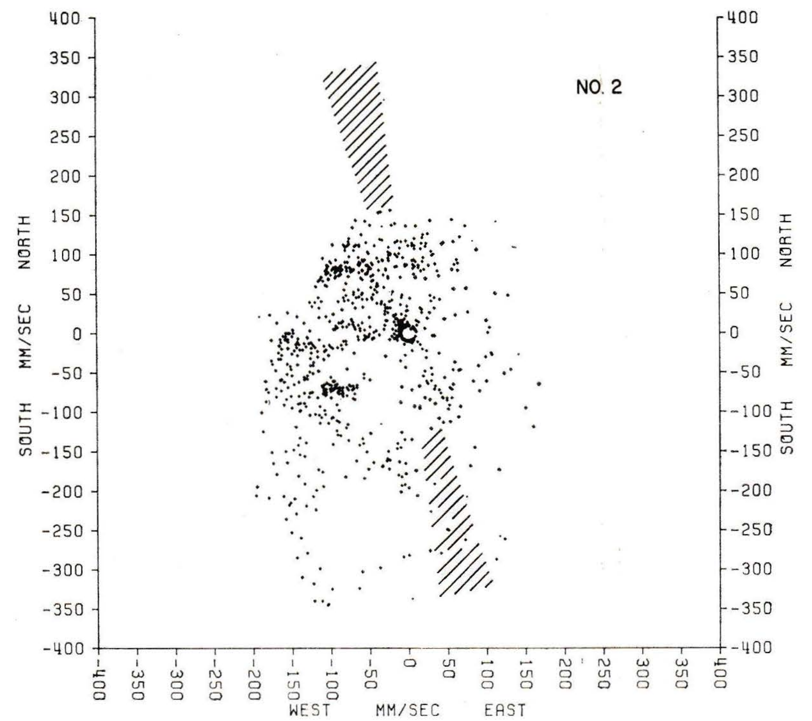


Fig. 3. Vector distribution plot for mooring no. 2 (Portugal). Hatching indicates general orientation of the shelf break.

Abb. 3. Vektorverteilung für Verankerung Nr. 2 (Portugal). Der gestrichelte Bereich zeigt die allgemeine Orientierung der Schelfkante an.

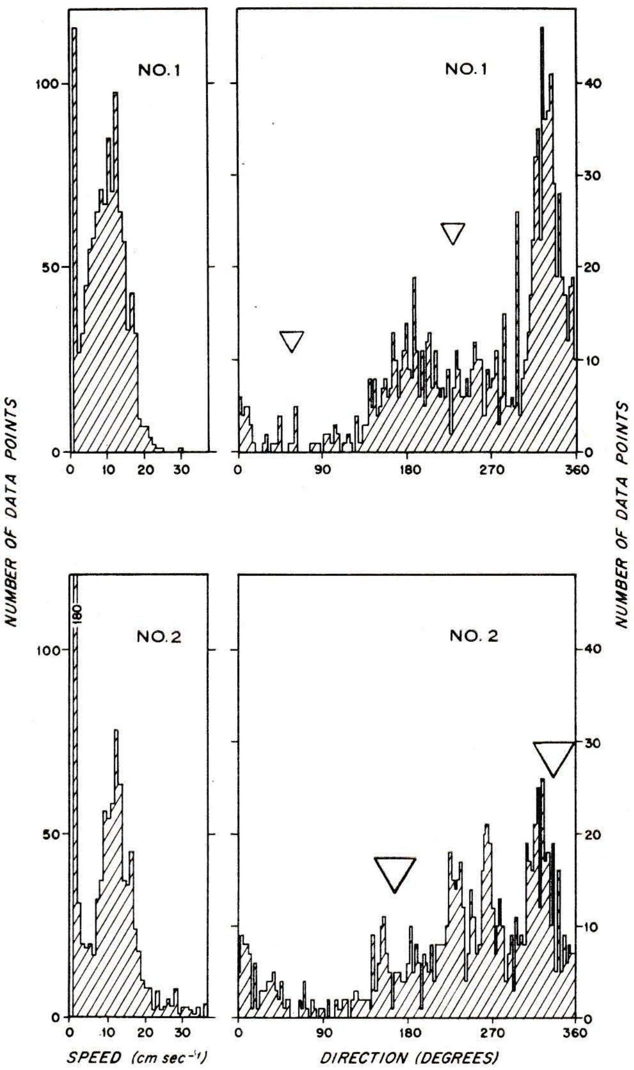


Fig. 4. Histograms of speed and direction for moorings no. 1 and 2. Marks indicate general orientation of the shelf break.

Abb. 4. Häufigkeitsverteilung der Geschwindigkeit und Richtung für die Verankerungen Nr. 1 und 2. Die Markierungen zeigen die allgemeine Orientierung der Schelfkante an.

both positions. Some statistical properties of both records are given in Table 2. The standard deviations of the velocity components are in both records larger than the mean values, and the opposite is true for the speeds. This indicates that most of the variability in time is due to directional changes.

The current variations as a function of time are plotted in figs. 5 and 6. The component records are dominated by a semi-diurnal tidal signal with amplitudes of approximately 10 cm sec$^{-1}$ in both cases. However, a much more slowly varying component of comparable size is present at mooring no. 2. The spectra of energy density $E(f)$ as function of frequency $f$ are given in fig. 7. A presentation of $f \cdot E(f)$ as a function of $\log f$ was chosen to obtain an area below the curve which is proportional to the energy. Both spectra are very similar, with a predominant peak at the semi-diurnal tidal frequency and a smaller peak at its first harmonic. The current amplitude corresponding to the main peak in the spectrum at 12 hours is in both cases $\sqrt{U^2 + V^2} \approx$ 14 cm sec$^{-1}$ with the Cartesian velocity components $U$ and $V$. To obtain some information about long-term changes, the progressive vector diagrams are given in fig. 8. The net virtual displacements per total recording time are similar, and both records have marked changes in the direction of the mean flow in the middle of the observation periods. The displacement per day almost doubles after this change in direction at mooring no. 1, and drops to about one half its former value at mooring no. 2. Thus the progressive vector diagrams simply show that no statement about mean displacements can be given from records of such a short duration.

For a comparison of the observed velocities with the critical velocity necessary for a start of sediment transport it is necessary to estimate the resulting speeds at 1 m above the bottom. Observations in areas on the continental shelf with predominantly tidal currents have shown that the logarithmic law for the current profile usually is valid within 2 to 3 m above the bottom (Bowden 1962):

$$\overline{U}(\zeta) = \frac{u_*}{\varkappa} \ln\left(\frac{\zeta}{\zeta_0}\right) \qquad (6)$$

where $\overline{U}(\zeta)$ = slowly varying velocity in $x$-direction at level $\zeta$
$u_*$ = friction velocity
$\varkappa$ = Kármán's constant
$\zeta$ = upward co-ordinate with zero at the bottom
$\zeta_0$ = roughness length

A typical value of $\zeta_0$ estimated from measurements in tidal flow over a sand bottom on the continental shelf (Charnock 1959, Bowden et al. 1959) is given by:

$$\zeta_0 = 0.2 \text{ cm}.$$

The roughness length $\zeta_0$ depends on the bottom configuration of the specific area. For a guess of the approximate variation of the velocity with decreasing bottom separation $\zeta$ we will assume that the above $\zeta_0$ can be used here and that $\zeta = 5$ m is within the logarithmic layer. We then obtain the following ratios:

$$\frac{\overline{U}(1\text{ m})}{\overline{U}(5\text{ m})} \approx 0.8 \qquad \frac{\overline{U}(1\text{ cm})}{\overline{U}(5\text{ m})} \approx 0.2\,.$$

The velocity $\overline{U}$ at $\zeta = 1$ m is approximately 80% of the velocity measured at $\zeta = 5$ m. For $\zeta = 1$ cm we

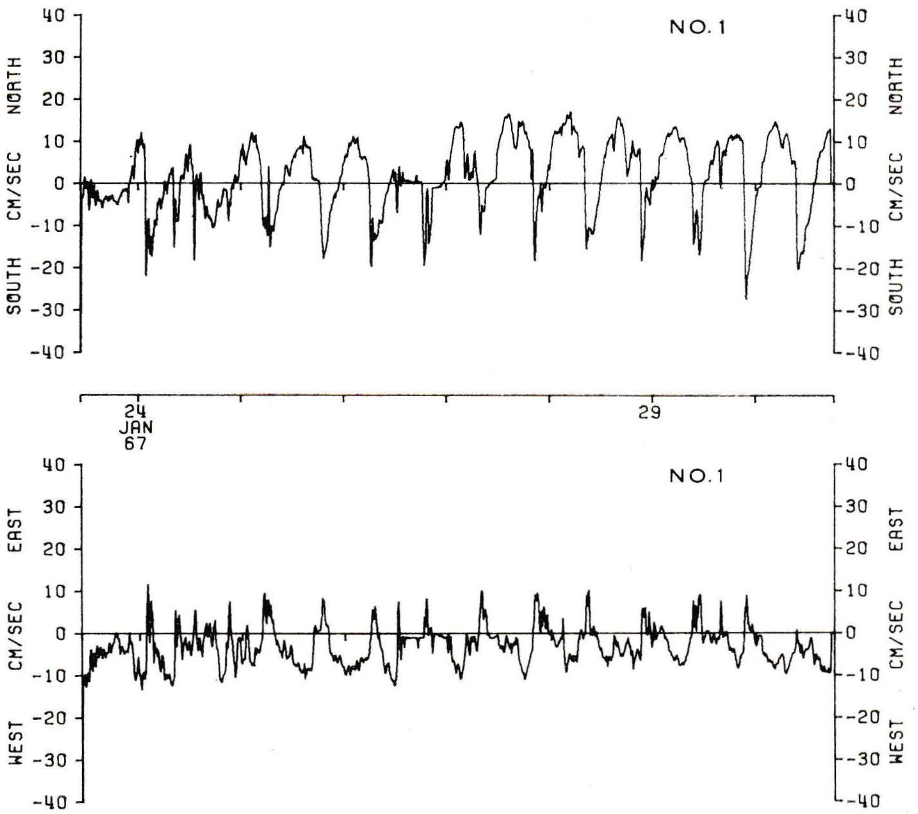


Fig. 5. Time series of north-south and east-west velocity components at mooring no. 1 (Morocco).

Abb. 5. Zeitserien der Nord-Süd- und Ost-West-Komponenten der Geschwindigkeit bei Verankerung Nr. 1 (Marokko).

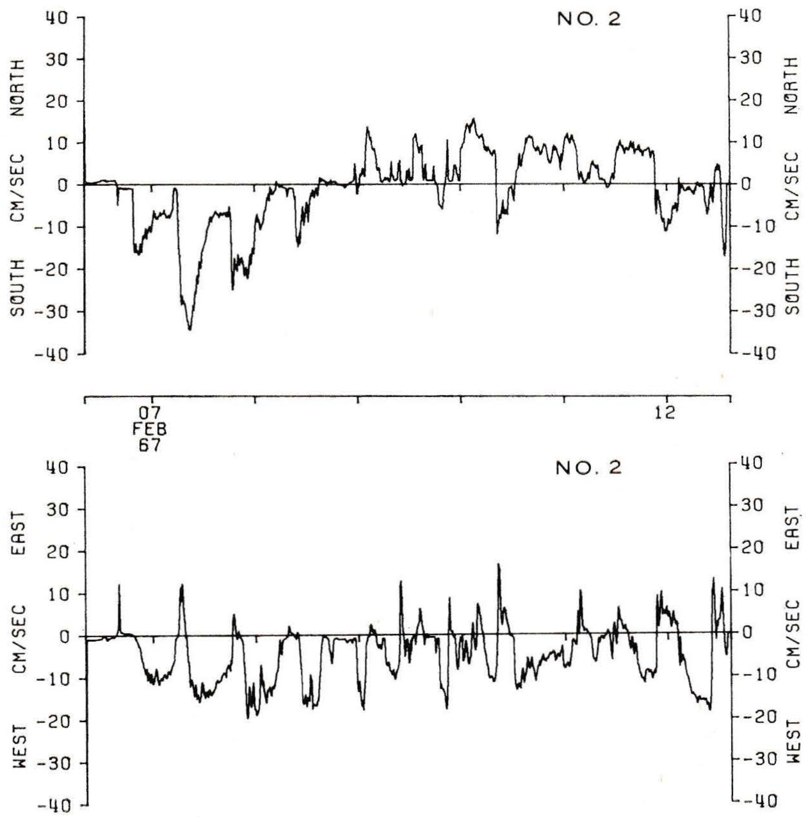


Fig. 6. Time series of north-south and east-west velocity components at mooring no. 2 (Portugal).

Abb. 6. Zeitserien der Nord-Süd- und Ost-West-Komponenten der Geschwindigkeit bei Verankerung Nr. 2 (Portugal).

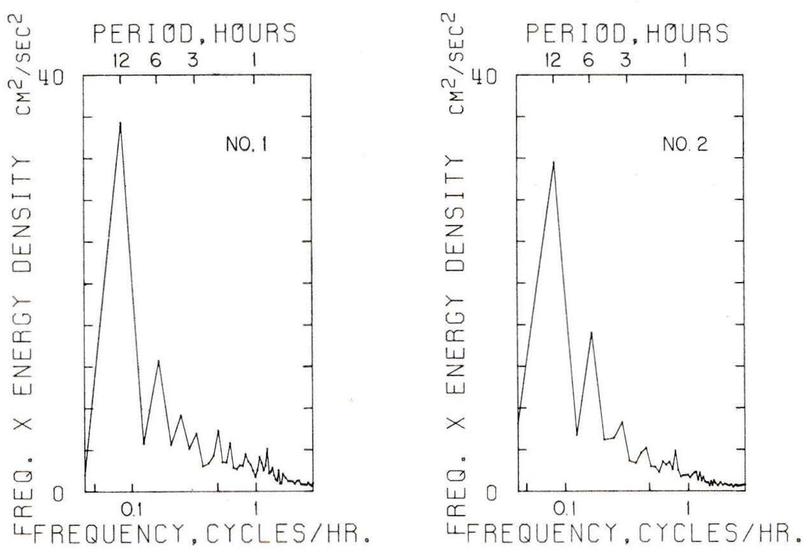


Fig. 7. Spectra of energy density for moorings no. 1 and 2.

Abb. 7. Energiedichtespektren für die Verankerungen Nr. 1 und 2.

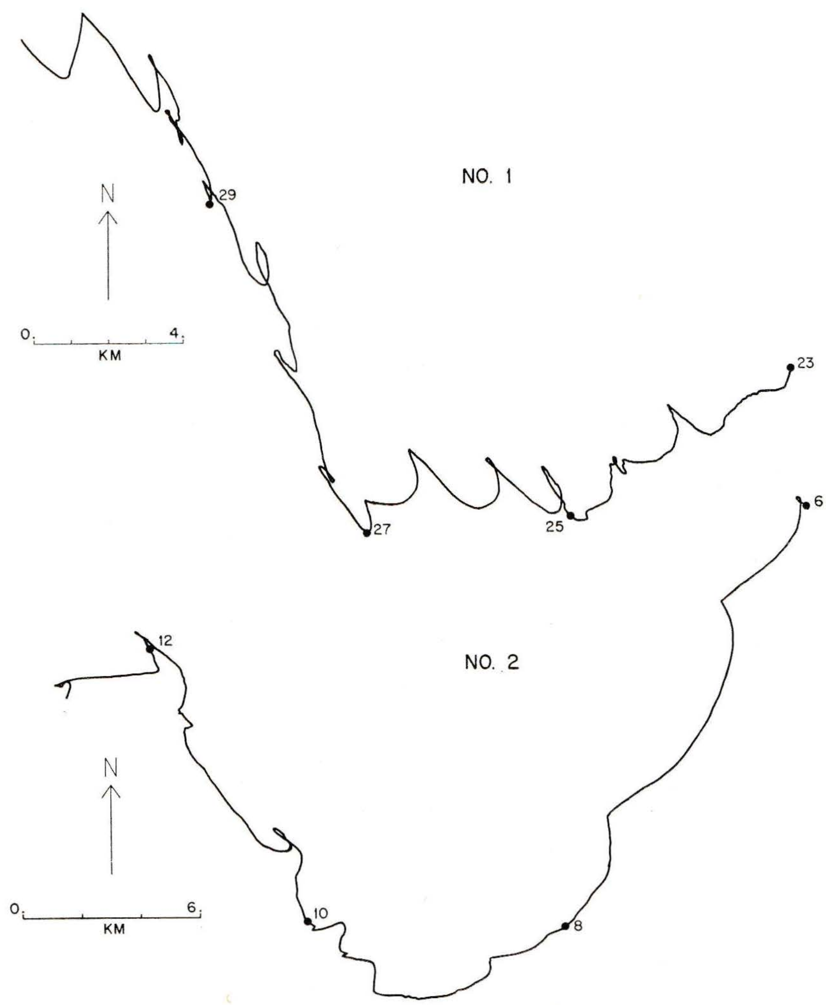


Fig. 8. Progressive vector diagrams for moorings no. 1 and 2. The numbers at the curves indicate the date at time 00.00; the somewhat different scales and the directions are indicated to the left of the virtual displacement curves.

Abb. 8. Progressive Vektor-Diagramme für die Verankerungen Nr. 1 und 2. Die Zahlen an den Kurven geben das Datum zur Zeit 00.00; die etwas unterschiedlichen Maßstäbe und Richtungen sind links von den Kurven angegeben.

obtain 20%. These fractions may well be larger because it is uncertain that the logarithmic range extends up to 5 m and that $\zeta_0$ is as small as 0.2 cm. It appears that the slowly varying currents observed 1967 by the direct measurements were too low to start sediment transport.

## 3 Estimation of currents induced by surface waves

The results of the direct current measurements reveal information about the current variability down to periods of about one hour. These samples were taken during times of low or moderate surface wave activity. At other time periods there may, however, exist significant contributions of surface wave motion to the bottom currents relevant for sediment transport. The very long waves causing strong deep currents will mostly occur as almost single-period swell in the area. Therefore single small-amplitude plane waves as deduced from linear wave theory will be a sufficient approximation. For similar calculations where the wave spectrum is taken into account, see DRAPER (1957, 1965, 1967) and HADLEY (1964). To obtain an estimate of the wave induced currents at levels close to the bottom, observational data of wave height and period can be used. The wave number $k$ is obtained from the dispersion relation:

$$k \tanh kh = \frac{\omega^2}{g} = \frac{4\pi^2}{g\tau^2} \tag{7}$$

It follows from (3) that for a fixed depth $z$ the amplitude of velocity $u_0$ increases with increasing $H$ and decreasing $k$, and it results from (7) that $k$ decreases with increasing $\tau$. The maximum velocities of the wave induced currents will thus be obtained with the maximum wave heights at the long wave periods. The corresponding frequency distribution of observed large wave heights at large wave periods is given in table 3 for an area including the positions of both moorings (HOGBEN et al. 1967). Also given are the wave-numbers $k$ and the maximum velocities $u_0$. The group of maximum velocities exceeding 17 cm sec$^{-1}$ (eqn. 5) is indicated by a solid line. It appears that the critical velocity for a start of sediment transport is exceeded in 69 cases, corresponding to approximately 0.1% of the total number of observations.

Although the frequency of occurrence of sufficiently large currents is rather low, they may have a significant effect on the sediment transport averaged over long time periods. High velocities can mainly be expected in autumn and winter when large swell preferably from north-west and west is observed in this part of the ocean (HOGBEN et al. 1967, U. S. Naval Oceanographic Office 1963). The actual fraction of sufficiently strong wave-induced currents is probably larger because spectral properties of the wave fields were not considered in this discussion.

Table 3 Number of observed large waveheights and long periods (afte HOGBEN & LUMB 1967) and the computed corresponding maximum velocities [cm sec$^{-1}$] 5 m above the bottom for a depth of 175 m from a total of 73 133 observations.

Tabelle 3 Zahl der beobachteten großen Wellenhöhen und langen Perioden (nach HOGBEN & LUMB 1967) und der daraus berechneten Maximalgeschwindigkeiten [cm sec$^{-1}$] 5 m über dem Boden für 175 m Wassertiefe aus einer Gesamtzahl von 73 133 Beobachtungen.

| Wave height [m] | Wave period (sec) / Wave number [$10^{-4}$ cm$^{-1}$] | | | | | |
|---|---|---|---|---|---|---|
| | 12.5<br>2.58 | 14.5<br>1.92 | 16.5<br>1.49 | 18.5<br>1.21 | 20.5<br>1.01 | 21.5<br>0.94 |
| 1.5 | 236 | 86 | 29 | 8 | 1 | 7 |
| | 1 | 2 | 4 | 6 | 8 | 9 |
| 2.0 | 301 | 86 | 33 | 4 | 4 | 5 |
| | 1 | 3 | 6 | 8 | 11 | 12 |
| 2.5 | 375 | 142 | 43 | 7 | 1 | 2 |
| | 1 | 4 | 7 | 10 | 13 | 15 |
| 3.0 | 378 | 135 | 37 | 8 | 3 | 4 |
| | 2 | 5 | 8 | 13 | 16 | 18 |
| 3.5 | 356 | 132 | 47 | 9 | 1 | 1 |
| | 2 | 5 | 10 | 15 | 19 | 21 |
| 4.0 | 237 | 99 | 45 | 11 | | 1 |
| | 2 | 6 | 11 | 17 | | 24 |
| 4.5 | 199 | 118 | 42 | 12 | 3 | 4 |
| | 3 | 7 | 13 | 19 | 24 | 27 |
| 5.0 | 36 | 13 | 10 | 2 | | |
| | 3 | 8 | 14 | 21 | | |
| 5.5 | 43 | 18 | 15 | 3 | | |
| | 3 | 8 | 16 | 23 | | |
| 6.0 | 77 | 35 | 9 | 5 | | 2 |
| | 3 | 9 | 17 | 25 | | 35 |
| 6.5 | 46 | 21 | 6 | 1 | 1 | |
| | 4 | 10 | 18 | 27 | 35 | |
| 7.0 | 17 | 9 | 2 | | | 1 |
| | 4 | 11 | 20 | | | 41 |
| 7.5 | 29 | 12 | 1 | | | |
| | 4 | 11 | 21 | | | |
| 8.0 | 20 | 15 | 4 | 1 | | 1 |
| | 5 | 12 | 23 | 33 | | 47 |
| 8.5 | 10 | 10 | 2 | | | 2 |
| | 5 | 13 | 24 | | | 50 |
| 9.0 | 12 | 4 | 2 | | 1 | |
| | 5 | 14 | 25 | | 48 | |
| 9.5 | 14 | 11 | 4 | 1 | 1 | |
| | 5 | 14 | 27 | 40 | 51 | |
| 14.0 | 1 | | | | | |
| | 8 | | | | | |

In the presence of surface waves an additional wave-induced mean current, the "mass-transport current", occurs very close to the bottom which is caused by convection of vorticity from the boundary into the interior of the water (LONGUET-HIGGINS 1953). The "mass-transport current" near the bottom points into the direction of wave propagation, and the maximum speed $\hat{u}$ just outside the bottom sublayer is given by:

$$\hat{u} = 1.376 \frac{k}{\omega} \frac{\left(\frac{H}{2}\omega\right)^2}{\sinh^2 kh} \approx 1.376 \frac{k}{\omega} u_0^2 . \quad (8)$$

For the maximum of $\hat{u}$ according to table 3 we obtain:

$$\hat{u} \approx 1 \text{ cm sec}^{-1} .$$

The "mass-transport current" can therefore be expected to be usually smaller than the slowly varying currents according to the current meter observations.

## 4 Geological observations

At the positions of both current meters underwater television camera observations showed a fairly smooth bottom morphology without any ripples smaller than the observation width of about 3—4 m. Some sediment properties are given in Tab. 4.

Table 4 Surface sediment properties (after KUDRASS 1973)
Tabelle 4 Eigenschaften des Oberflächensediments (nach KUDRASS 1973).

| | Mooring 1 = "Meteor" Station 8013 Morocco | Mooring 2 = "Meteor" Station 8063 Portugal |
|---|---|---|
| *Total Sediment:* | | |
| Mean diameter (cm) | 0.02 | 0.05 |
| Sand (> 63 μ) (%) | 90.8 | 88.4 |
| Coarse Silt (40—63 μ) (%) | 2.2 | 3.5 |
| Fine material (<40 μ) (%) | 7.0 | 8.1 |
| Carbonate (%) | 69 | 32 |
| Mean density (gcm$^{-3}$) | 2.8 | 2.65 |
| *Sand Fraction:* | | |
| a) Content > 250 μ (%) | 25.5 | 75.4 |
| b) Some biogenic components (%) | | |
| Foraminifera | | |
| Calcareous | 14.5 | 11.0 |
| Arenaceous | 2.6 | 0.9 |
| Planktonic | 17.4 | 9.9 |
| Molluscs | | |
| Benthic | 3.7 | 5.4 |
| Planktonic | 3.2 | Tr. |
| Fossil biodetritus | 36.0 | 11.7 |
| Glauconite | 11.9 | 22.3 |
| Terrigenous minerals | 2.8 | 34.0 |

The *Moroccan* sample fits well into the general features of the outer shelf sediments there: Medium grained sands rich in foraminifera with glauconite and other characteristics of relict sediments. The content of fine material is very low (MATTHIEU 1968, MCMASTER & LACHANCE 1969, TOOMS et al. 1971, KUDRASS 1973).

Underwater television confirms the coarse sand cover. Benthic organisms are distributed in patches, holes from burrowing organisms rather densely. Therefore it seems that the sands were not moved too much. After "CARTE 6229, Croquis de pêche 1, Service Hydrogr. Marine, Paris 1963" the sediment cover is continuous only in water depths of more than 200 m. In shallower water it is patchy with rock outcrops.

The outer shelf off *Portugal* is covered by coarser sands with a higher content of terrigenous minerals, as illustrated in Table 4. The percentage of relict grains is again high (up to 60% of total sediment). Underwater television shows patchy benthos distribution. The benthos is rich in suspension feeders. Again many holes from burrowing organisms can be observed, some of them with indistinct appearance. Sometimes outcropping rocks form minicliffs (cm-scale) with epibenthos visible on the inner shelf. Sands are fine grained (MONTEIRO 1971), but there also rocky bottoms occur (Carta litologica submarine do Cabo de Sines ao Cabo de S. Vicente, Ministerio da Marinha, Lisbon 1927/1948). Nearshore sands appear about 4 km off-shore, in water depths of 40—50 m. The data in Table 4 and the above mentioned observations show that fine particles are winnowed out at the mooring position. Winnowing or reduced deposition is even more effective near and on morphological obstacles off Portugal:

1) About 25 km south of the mooring position a ridge crosses the shelf from NE to SW (GIESEL & SEIBOLD 1968, Fig. 2 and p. 58, profile XXV/1). At the base the width is about 5 km in 260 m water depth, the crest about 100 m higher. The northern base shows a moat due to reduced deposition. A thin sediment cover on the crest ("Meteor" Station 8005, KUDRASS 1973) consists of biogenic coarse sand with a high content of sessile benthos remains: Sessile Foraminifera, Bryozoans, Serpulids, partly subfossil.
2) Similar moats normally accompany the landward base (water depths 240—680 m) of a ridge crossing the slope SW of C. de Sines, about 10 km NW of the mooring position. Ridge width at the base is 1—10 km, height 10—150 m (GIESEL & SEIBOLD 1968, profiles XXIII, XXII, VI, IX). Sediments on top of feature IX will be discussed later.

Sedimentological results confirm a transport of finer material from the shelf to the upper slope, as discussed in KUDRASS (1973):

a) After Fig. 9 sand content is diminishing in this direction — silt, more or less, too. The ratio of coarse silt (40—63 μ) to sand (> 63 μ) (Fig. 9/2) reaches less than 0.04 on the shelf, a maximum of 0.2—0.6 in 400—600 m water depth and less than 0.2 in more than 600 m. This means a concentration of coarse silt compared to sand on the uppermost slope.

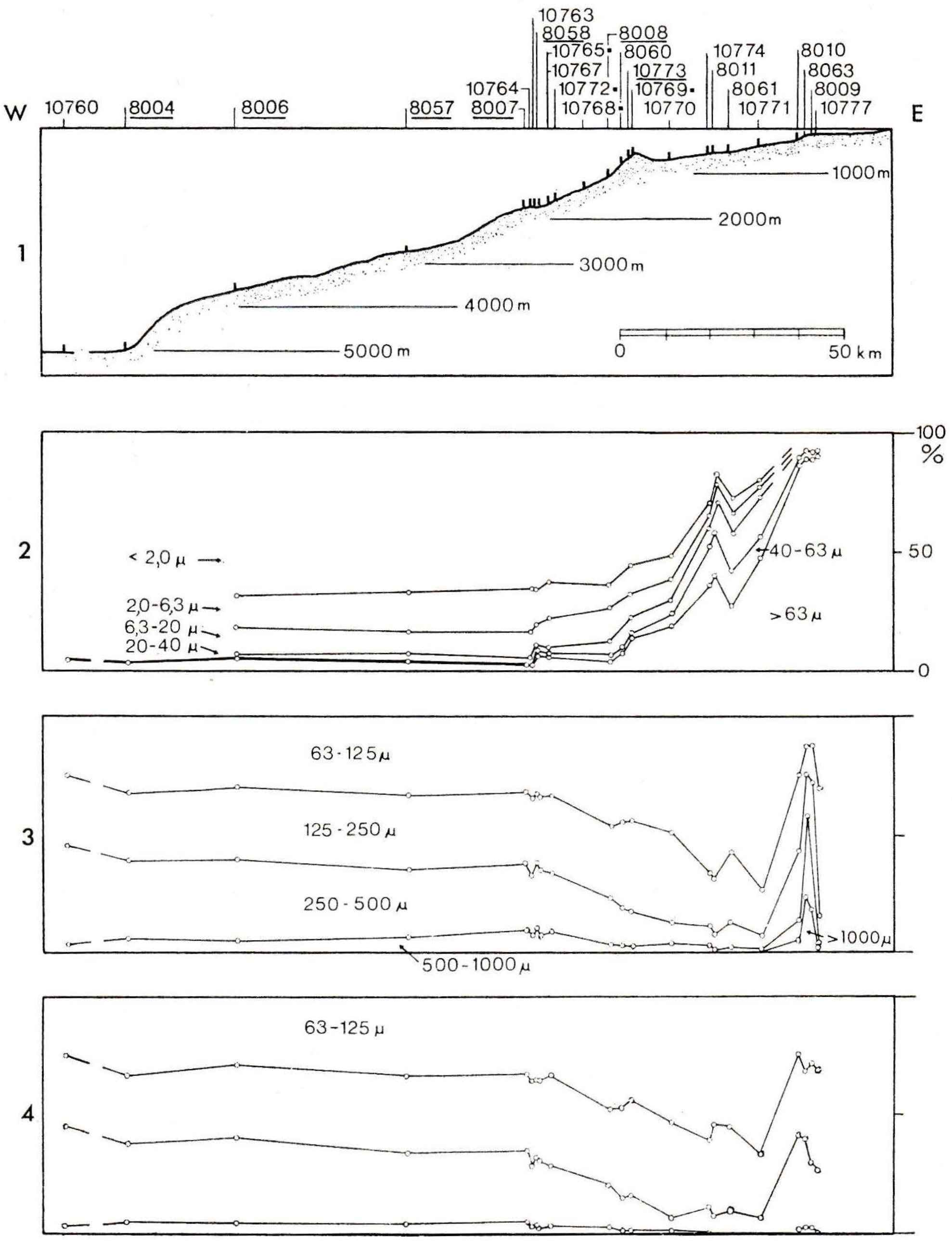


Fig. 9. Sediment properties of surface samples, continental margin off Cap de Sines, Portugal (1 = Morphology, sample location, 2 = Total sediment: grain size distribution, 3 = Sand fraction: grain size distribution, 4 = Planktonic foraminifera > 63 μ: grain size distribution, fractions as in 3).
Irregularities in the distribution of grain sizes may be due to morphological features on the slope and to the influence of the Mediterranean Outflow (between about 500 and 1400 m of water depth). Samples were obtained during "Meteor" Cruises 8—1967 and 19—1970 (Fig. 9 after KUDRASS 1973).

Abb. 9. Sedimenteigenschaften von Oberflächenproben am Kontinentalrand vor Cap de Sines, Portugal (1 = Morphologie, Ort der Probennahme, 2 = Gesamtsediment: Korngrößenverteilung, 3 = Sandanteil: Korngrößenverteilung, 4 = Planktonische Foraminiferen > 63 μ: Korngrößenverteilung, Fraktionen wie in 3).
Unregelmäßigkeiten in der Korngrößenverteilung können eine Folge morphologischer Strukturen und des Einflusses des Mittelmeerausstroms (zwischen etwa 500 und 1400 m Wassertiefe) sein. Die Proben wurden während der „Meteor"-Fahrt 8—1967 und 19—1970 gewonnen (Fig. 9 nach KUDRASS 1973).

b) Ratios of sand fractions (63—125 μ) to (125—250 μ) (Fig. 9/3) are less than 0.8 on the shelf, reach a maximum (of 2—4) in 400—600 m, and are less than 1.5 in deeper water, again showing a concentration of finer (63—125 μ) compared to coarser material (125—250 μ) on the uppermost slope.

c) In Portuguese shelf sands up to 1/7 of the particles are planktonic foraminifera shells, in sands between 200 and 600 m they reach 1/3—1/2, in deeper stations 2/3—9/10 (Kudrass 1973). Part of these ratios may be influenced by the effect that normally planktonic foraminifera are smaller in cooler, upwelling areas (Berger 1969) as discussed for Portugal by Thiede (1972). Nevertheless, we believe that the grain size distribution of the planktonic foraminifera as shown in Fig. 9/4 with a maximum of 63—125 μ-shells in sediments of about 500 m water depth shows a transport of these particles from the shelf towards the uppermost slope.

d) Further hints are the diminution of 1) the median diameters of all components of the sand fraction, 2) the Glauconite and fossil biodetritus content of the sand fraction, and 3) the content of terrigenous minerals of the sand fraction (shelf: 20—60%, 200—600 m: 20—35%, > 600 m: < 4%) (Kudrass 1973) with increasing water depth.

e) An interesting exception is the sediment on the above mentioned slope ridge (sample 10769, water depth 611 m, see Kudrass 1973): Again sessile benthos is present (Sponges, Corals, Bryozoans, Balanids). The coarse silt/sand-ratio of 0.02 and the 63—125 μ/125—250 μ-ratio of 0.32 are similar to those from the shelf. Sand content reaches 73%, 48.5% of which are planktonic foraminifera. Sand on the ridge contains about 0,7% terrigenous minerals, but in similar depths there between 4 and 30%. Only about 26% of the total sediments are finer than 40 μ. Samples in similar depths on the nearby slope contain 48—73%. Sediment supply from the shelf, therefore, is restricted and/or winnowed out on this ridge with an elevation of about 150 m above the surrounding area.

The sedimentological data from the Moroccan station are not detailed enough to allow similar conclusions.

## 5 Conclusions

It appears from the preceding discussion that orbital velocities of surface waves in these areas can be expected to start sediment transport during certain periods. It remains unknown whether slowly varying currents alone are sufficiently strong at some times to start erosion, but they will be sufficient during certain periods to maintain sediment transport once it was started by surface wave motion. Because of the possible superposition of slowly varying currents and orbital motions of similar directions, rather low surface wave currents may be able to start sand movement.

The transport rates and directions are determined by the "mass-transport current" and by other slowly varying currents. It is unknown whether our one-week records displayed velocities which are typical for these positions. As the velocities are dominated by tidal, probably largely barotropic signals, it may well be that the range of observed actual velocities is typical for these areas. The records are far too short to make a similar statement for the mean currents. If the observed tidal motion were mainly barotropic, there may exist a general preference of directions along a line NNW to SSE at mooring no. 1 off Morocco. The "mass-transport currents" will usually be small compared to other slowly varying currents in these areas, and it therefore seems unlikely that they will produce preferred directions of the net transport parallel to the direction of wave propagation.

A more conclusive result with respect to the mean currents can however be obtained from the geological data. They indicate a preferred sediment transport from the shelf to the upper slope off the Portuguese coast near mooring no. 2. This requires a net bottom water transport in similar directions during the time when sediment transport occurs. It can be concluded that on the average over long time periods the mean velocity of bottom water will have a considerable component towards the upper slope during periods of strong bottom currents on the Portuguese shelf.

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