

ON THE ORIGIN OF THE COHESIVE AND NON-COHESIVE SEDIMENT BOUNDARY ON THE WESTERN SHELF OF INDIA

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ABSTRACT

The cohesive (recent mud) and non-cohesive (relict calcareous sand) sediment boundary occurs at about 60m on the Western continental shelf. A casual relationship exists between the depth at which the boundary occurs (60m), the long period waves (13/14 seconds) and the depth of effective sediment movement of these waves. The boundary is, therefore, attributed to the action of long period waves.

An attempt is also made to derive from theoretical considerations the magnitude of the speeds required to initiate the movement and transport of these sediments.

INTRODUCTION

Results of the grain size analyses of the surficial sediment on the western continental shelf has shown that they consist of two type of sediments (1) cohesive sediment - the recent, organic matter rich, terrigenous silt and clay found on the inner shelf to a depth of about 60m, (2) the non-cohesive sediment - coarse calcareous relict sands present on the outer shelf seaward of 60m. These two types of sediments have been shown in Fig.1. In other words these fine grained cohesive sediments represent a shoreward thickening wedge of modern, pro-delta sediments, contributed by the rivers Narmada and Tapti, overlying on a late Pleistocene carbonate surface. This generalisation of the sediment distribution is based on detailed sampling and various kinds of analyses¹. It is necessary however to point out here that the depth of the sediment boundary is not precisely at 60m. There exists a transition zone between 50 and 70m where the two sediment types intermingle resulting in textures such as sandy clays and sandy silts (Fig.2). The chemistry of the muds also reflects this zonation². Since alumina (Al_2O_3) is located mainly in the aluminosilicates (clays), the abundance of alumina may be used as an index of the argillaceous fraction in the sediments³. In the present context it can also be used

as an indicator of the terrigenous components in the shelf sediments. It can be seen from Fig. 3 that the <0.5 to $>0.5\%$ boundary of Al_2O_3 closely follows the 60m isobath indicating a decreasing amount of terrigenous material beyond that depth.

The purpose of the paper is to attempt an explanation of this cohesive - non cohesive sediment boundary.

Geomorphic setting of the western continental shelf

The western continental shelf is bordered by a narrow coastal plain and is backed by the Western Ghats. Because of the narrow coastal plain the rivers draining the coast are short, except the Narmada and the Tapti. Because of the strongly seasonal nature of the rainfall they show peak discharges during

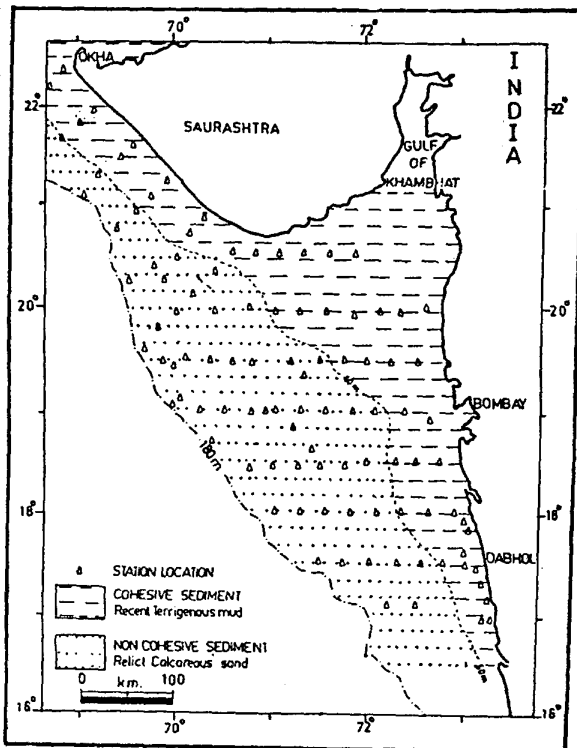


Fig.1. Distribution of samples on the basis of which the cohesive and non-cohesive sediment boundary has been demarcated.

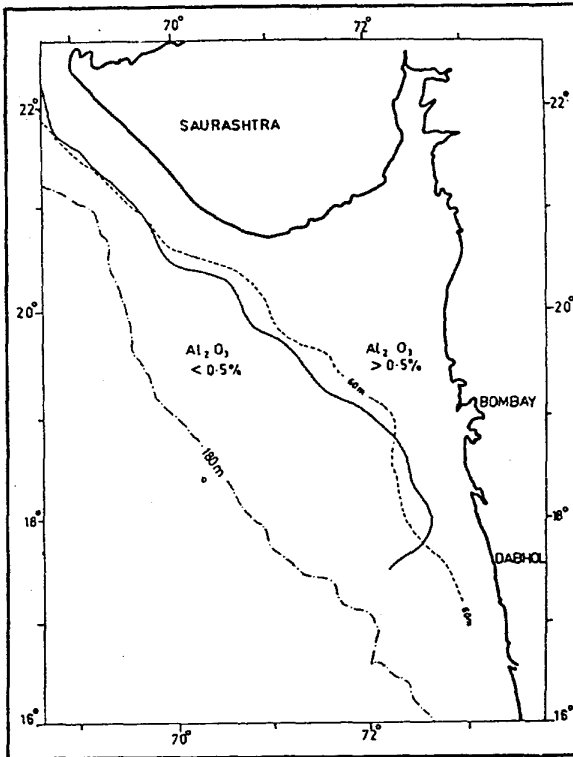


Fig.2. Clay percentage versus depth plot to show the change in feature from shallow water (inner Continental shelf, 0 to 50m) to deep water (outer Continental shelf, 50 to 100m). Note the zone of transition texture between 50 and 70m.

the monsoon months from June to September. The rivers drain a terrain which is highly lateritised and consequently the sediment load is largely silt and clay with little sand size material. Estuaries into which the rivers terminate act as sediment traps⁴. Sand size material is retained in the estuary, except probably during the peak discharges associated with the monsoon, when the silts and clays are discharged into the inner continental shelf. The continental shelf is about 100 km wide off Saurashtra, increases to 300 km off Bombay and decreases to 185 km off Dabhol in the south. The shelf edge is oriented in the northwest-southeast direction. This orientation is especially important because it results in the entire shelf being uniformly exposed to the incident wave direction. The pre-dominant wave approach directions are from the west and southwest. During the winter months a northwest direction is also observed (Table I).

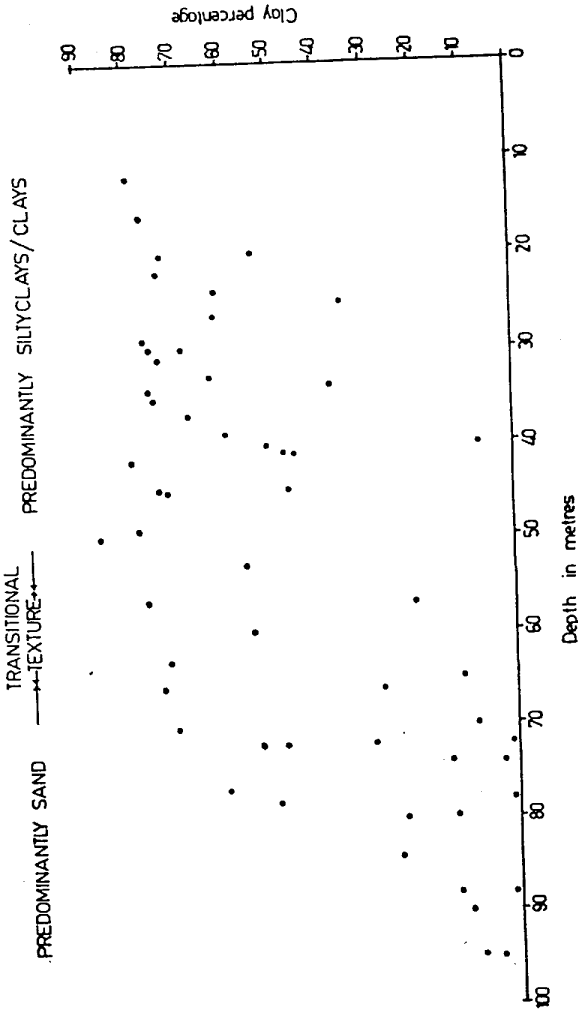


Fig. 3. Relationship of the 60m isobath and the Al_2O_3 percentage in the acid soluble fraction of the sediment.

Table II - Calculated values of wave lengths and orbital velocities at 60 m Depth for fair weather and monsoon waves.

Months	Wave Period (Sec.)	Wave Length (m)	Wave Height (m)	Orbital Velocity (cm/sec.)
March	6	56.16	2.5	0.3
	14	305.76	2.5	14.03
July	7	76.47	8.0	3.27
	13	263.64	8.0	48.4
Average fair weather	5.5	47.19	3.0	0.3347
	14	305.76	-	16.8364
Average Monsoon (June - Sept.)	7	76.47	7.5	2.6306
	14	305.76	-	42.0910

Sediment zonation and its cause

Shelf sediment zonation on a regional scale is usually the result of the following two primary controls. These controls may act separately or in unison, and may be either topographic or hydraulic. In the following section their effectiveness is evaluated.

Topographic Control: Echosounding in the area has shown that the inner shelf mud zone is smooth and featureless to a depth of about 60m. Beyond that depth however, the bottom topography becomes irregular. These irregularities or topographic prominences are small scale features of the order of 1m in relief at 60m and increase in relief to about 10m on the outer shelf. These features are composed of late Pleistocene algal and oolitic ridges⁵. Shallow penetration sub-bottom profiles and sub-bottom reflections on echograms indicate that these relict features extend under the shoreward thickening wedge of muds⁶. Localised damming or ponding of sediment may take place, for example, on the outer shelf where the relief is greater. However, when considered over a length of 400 km where the boundary is noticed, the possibility of such small scale features acting as sediment dams becomes rather remote. Topographic control as the cause of the sediment boundary is, therefore, unlikely to be an important factor.

Hydraulic Controls Hydraulic controls on sediment distribution on the continental shelf may take two forms.

(i) Tidal currents, especially if differences in flood and ebb velocities are large, may at times result in textural zonation. Such tidal effects will be more pronounced in gulfs and embayments rather than on the open continental shelf. (ii) Processes other than tidal which bring about sediment displacement are wave induced bottom currents. Such currents result in net transport in the direction of wave propagation⁷. Theoretically a given wave would interact with the bottom at about one-half the wave length and, therefore, significant particle motion will take place at this depth.

The wave climate⁸ on the shelf waters of the west coast shows strong seasonality and consists of a combination of long period swells and short period waves during the monsoon and predominantly short period waves during the non-monsoon or fair weather months (Table I). We assume that even though the period of three months of the monsoon is considerably shorter than the total fair weather period of nine months, the total energy (in qualitative forms) expended on the sea floor and resulting in sediment redistribution will be greater during the monsoon months than that expended during the fair weather months. Assuming the above reasoning to be correct we must now look for an aspect of the waves and the specific depth of about 60m

where the sedimentary boundary occurs. Since the water depth under consideration is 60m, it follows that a wave length of about 300m will interact with the sea floor at about one half the wave length (150m) and be most effective in moving the sediment at one fifth of the wave length for deep water waves⁹, which is about 60m. From the relationship $Ld = 1.56 T^2$ (in metres) one obtains a period of 14 seconds for a 300m deep-water wave length. Wave statistics (Table I) obtained by meteorological analysis indicate that the maximum wave period in the area under discussion is 13/14 seconds. These long period swells constitute about 8% of the total swell. Between November and February, 5 to 7 second wave occur for about 60% of the time⁸. Thus there is a close correspondence between the depth of zonation, the long period wave and the depth of effective sediment movement which to a first approximation is significant and suggests a causal relationship. It is, therefore, reasonable to assume that the long period waves even though they occur for a limited period of time are responsible for the sediment boundary at 60m.

The orbital velocities associated with the waves during the fair weather and the monsoon season computed according to the method of Zenkovich¹⁰ is shown in Table II. The orbital velocities associated with the 6 and 7 second waves during the fair weather and the monsoon are of the order of 0.3 to 2.6 cm/sec and coupled with the fact that their wave length is 47 and 76m respectively leads us to conclude that no significant movement of the sediment can be caused by them at 60m depth. In the absence of sediment movement no sediment zonation is possible.

On the other hand the 13/14 second swells with the wave heights of 7 to 8m result in orbital velocities of about 42 cm/sec. Despite the high orbital velocities, however, by themselves they are incapable of transporting sediments because of their oscillatory nature. Their main effect will be to impart the necessary motion to the sediment particles and once put into motion the forces required to transport them becomes much less. Such forces are the various currents found in the shelf waters. Swift¹¹ has classified these currents into four major categories. They are, in order of importance, meteorological currents (barometric storm surge, wave surge, direct wind currents), tidal currents and density currents (landward bottom currents, internal waves). Out of these four categories Swift¹¹ concludes that the wind-drift velocity components are the most significant factor in sediment dispersal. Unfortunately, it is difficult to evaluate the importance of the above mentioned four categories of currents because of the lack of data. One is, therefore, left with the speculation that in keeping with the processes on other continental shelves of the world, a combination of wind-drift (currents associated with the strong onshore winds during the southwest monsoon)

and wave-drift currents will yield the required velocities to transport the sediments once they have been set into motion by the oscillatory motion of the waves.

The transition region between 50 and 70m (Fig.2) consists of silts and clays with varying proportion of sand. The speeds required to initiate the movement of such a range of sizes varies from 20 cm/sec to 100cm/sec¹². In the normal course of events it is highly unlikely that such near bottom speeds are encountered on the western shelf, and even if they do occur would perhaps be limited to events such as cyclones which are rather rare in the Arabian Sea as compared, for example, to the Bay of Bengal. However, the possibility exists that such high speeds may not be required under actual field conditions. It was mentioned earlier that seaward of 60m the sea bottom consists of small scale topographic irregularities. Flow over such irregular or rough bed forms usually results in turbulence as a consequence of which speeds lesser than the ideal would suffice for sediment movement.

Mechanics of sediment transport

In this section we attempt to derive from theoretical consideration the magnitude of the speeds required to initiate the movement of the sediments found on the transition zone on the continental shelf. The general principles governing sediment transport mechanics are found in many publications. The application of these principles and their critical evaluation to field conditions, especially shelf sediment movement, is to be found in Swift et al¹³, Stanely and Swift¹⁴.

The sediments of the transition zone are polymodal sediments with mean diameters ranging from 3 to 60. The resulting textures are sandy silts and silty clays and more importantly have varying proportions of carbonate material in the form of shells of many kinds of organisms like molluscs, foraminifera, coralline algae. The mineralogy of the clays in this region consists of in order of abundance montmorillonite, kaolinite, illite, and trace quantities of chlorite¹⁵. The hydraulic behaviour of such sediments is difficult to understand because much of the laboratory studies have been carried out on quartz sands. Field studies are more informative and the competency curves obtained by Sundborg¹² though derived from river flows, have been found with certain limitations, to be applicable to conditions in the marine environment.

The critical shear velocity of fine sands may be obtained from the formula given by Smith and Hopkins¹⁶.

$$(U_{*c}) = [0.1 \left(\frac{\rho_s - \rho}{\rho} \right) g d]^{1/3}$$

where $(U_*)_c$ is the critical shear velocity, ρ_s and ρ the sediment and water densities respectively, g the acceleration due to gravity and ν the kinematic viscosity.

Taking the average temperature¹⁷ of the shelf waters as 26°C, the kinematic viscosity of water at 26°C as 0.8×10^{-2} cm²/sec, and a sediment density of 2.65 g/cm³, gives a critical shear velocity $(U_*)_c$ of 1.1 cm/sec. These values of shear velocities, as emphasised by Smith and Hopkins¹⁶ are local values of skin friction and are not to be confused with the total boundary shear stress which is what is commonly measured in the field. These field measurements are usually carried out at some distance above the bed and in practice the velocities reported are those prevailing at 100 cms above the bed. There are two possible ways of obtaining the value. One is to obtain it directly from the competency curves of Sundborg¹² and the other is to compute according to the method of Smith and Hopkins¹⁶. The former method gives a value of 36 cm/sec while the latter method using the relationship

$$\frac{u_c}{(u_*)_c} = 5.75 \log \left[\frac{(u_*)_c Z_1}{\nu} \right] + 5.5$$

where \bar{u}_c is the velocity at a height of 100 cms (Z_{100}) above the bed, gives a value of 32 cm/sec. Therefore, where field measurements yield a velocity of the order of 32 to 36 cm/sec one metre above the bed, the possibility of the erosion of fine sand is indicated.

The above reasonings and the values of critical shear velocities derived therefrom apply only to sand sized material. Because of the cohesive nature due to their small grain size and organic matter content of the muds, critical shear velocities are not a function of size alone. Bulk sediment characteristics have to be considered and Migniot (in McCave¹⁸) relates the critical shear velocity $(U_*)_c$ to the yield strength τ_y as follows:

$$(u_*)_c = 0.5 \tau_y^{1/2} \text{ for } \tau_y > 20 \text{ dynes/cm}^2$$

$$(u_*)_c = \tau_y^{1/2} \text{ for } \tau_y < 10 \text{ dynes/cm}^2$$

Since no data are available for the yield strength of the shelf muds, it is not possible at present to arrive at a value of the required critical erosion velocities. It is, however, of interest to note that Migniot's calculations indicates that a critical velocity of 0.77 cm/sec will erode mud with a yield strength of 0.4 dynes/cm², corresponding to his concentration of 125 to 300 gms/litre and water content of 89 to 95%.

CONCLUSION

From the data in Table II, it will be observed that for the long period waves the orbital velocities exceed the critical shear velocities for fine sands and probably for the muds as well. Transient velocities even higher than those found during the normal conditions may take place during cyclones such as the one that occurred during June 1976 in the Arabian Sea during which wave heights of as much as 15m were reported¹⁹. Storms and cyclones are however, of short duration and are associated with rapid changes in direction and magnitude. Under these conditions wave action may be felt to depths greater than normal and temporary or local increase of sediment dispersal may result. For example, the curves provided by Komar and Miller²⁰ indicates that a 15 second wave with a height of 5m is capable of causing movement of fine sand in a water depth of 130m. Zonation of the shelf sediments on the other hand is the response of the substrate to long term influence such as those taking place over geological time during which short term variations tend to be smoothed out. The regional nature of the zonation and the long time periods that are presumably involved implies that short term local near bottom current measurements will be of limited relevance to this particular problem. A combination of long term current measurements and information from sea bed drifters will be required for further meaningful interpretation.

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