

CHANGING DEPOSITIONAL ENVIRONMENTS DURING THE LATE QUATERNARY ALONG THE WESTERN CONTINENTAL MARGIN OF INDIA*

M. THAMBAN

*Geological Oceanography Division, National Institute of Oceanography,
Dona Paula-403 004, Goa*

Abstract

Sedimentological and palaeoceanographic studies were carried out on two sediment cores collected within the Oxygen Minimum Zone (OMZ - between 150 to 1200 m water depth) along the western continental margin of India. The glacial to interglacial variations on a shallow core off Cochin, suggests that the average sedimentation rates were very high (~13.2 cm/kyr) and varied widely during the Holocene and the late Pleistocene. Grain size measurements reveal that the clay content varied with the Late Quaternary climatic changes, as inferred from the stable isotope studies. The boundary between the Stage 2 and 1 is marked by a pronounced increase in the flux of terrigenous clays and a fall in organic carbon (C_{org}) and carbonate ($CaCO_3$) content. The rapid sea level fluctuations during the deglaciation and the proximity of the core site to the continent during the lowered sea level, lead to a relatively high average sedimentation rate. Contrastingly, a core from the isolated topographic high off Goa showed relatively lower average sedimentation rates (~ 5.2 cm/kyr) during the Holocene and the late Pleistocene. The contrasting sedimentation features observed at two different locations within the same oceanographic regime underlines the fact that topographic features and proximity of the core site to the continent controls the sedimentation rates during the late Quaternary.

Introduction

Recent palaeoclimatic investigations using a variety of geological proxies have suggested that the intensity of Indian monsoon had fluctuated greatly during the Late Quaternary (Prell *et al.*, 1980; Duplessy, 1982; van Campo, 1986; Fontugne and Duplessy, 1986; Clemens and Prell, 1990; Sarkar *et al.*, 1990; Shimmield *et al.*, 1990; Sirocko *et al.*, 1991, 1993). Both geological and modelling studies have shown that the Arabian Sea summer monsoon responded in a strong, coherent fashion to changes in the distribution of solar radiation as determined by cyclical variability in the obliquity and precession of Earth's orbit (Kutzbach and Guetter, 1986; Prell and Kutzbach, 1987; Clemens *et al.*, 1991). It has been revealed that the climate of Asia was affected by severe changes including an intensification of southwest monsoon around 9 kyr B.P. and a respective weakening at 18 kyr B.P.

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Studies on sediment accumulation rates along the southwestern continental margin of India revealed contrasting sedimentation patterns with occurrences of patchy sediment lobes representing high accumulation rates compared to rest of the Arabian Sea (Sirocko *et al.*, 1991). These unique features have been attributed to the local topographic depressions of the Chagos-Laccadive Ridge (Kolla *et al.*, 1981; Naidu *et al.*, 1985). Compared to the upwelling area of Oman margin, the depositional history and palaeoceanography of the western continental margin of India is less understood. Present study makes an attempt to delineate the pattern and rate of sedimentation during the last glacial and interglacial period along the western continental margin of India.

Physiography and Oceanographic Setting

The continental shelf off western India is relatively smooth and featureless and varies in width between 60 km off Cochin to about 300 km off Bombay and the shelf break generally occurs at around 130 m (Nair and Hashimi, 1980). The Western Ghat mountain ranges are the major hinterland physiographic features situated parallel to the coast with elevations up to 1000 m above sea level. The rivers draining the Western Ghats are relatively small and run for short distances through the coastal plains, carry less sediment load and are fed by the heavy summer monsoon rains (Vaithyanathan *et al.*, 1988).

Circulation in the Arabian Sea is featured by a unique, seasonally reversing monsoonal circulation system which brings heavy rains to the Indian subcontinent during summer (southwest) monsoon and less rainfall during winter (northeast) monsoon (Wyrcki, 1973). The modern summer monsoon is driven by two primary mechanisms: differential (land-ocean) sensible heating and tropospheric latent heating (Clemens *et al.*, 1991). Off India, monsoon winds induce upwelling of cool, nutrient-rich subsurface water to the surface, leading to an enhanced productivity during summer (up to 1.0 gm C/m²/day; Qasim, 1977). An exceptionally broad and stable Oxygen Minimum Zone (OMZ) characterises the intermediate water depths of eastern Arabian Sea between 150 and 1200 m (dissolved O₂ < 0.5 ml/litre) (Wyrcki, 1971).

Materials and Methods

The two gravity cores (GC-5 and GC-3) used for the present study were collected during the 6th cruise of M/V *A. A. Sidernko* in 1994. GC-5 is from the upper continental slope off Cochin (280 m water depth) and GC-3 is from the isolated topographic high off Goa (335 m water depth) (Fig. 1). Hence both the cores fall within the modern OMZ. The total length of core GC-5 is 333 cm and that of GC-3 is 445 cm. Shortly after the core recovery onboard, variations in colour and lithology were noted. Subsampling of the cores were done onboard at 2 cm intervals for the top 20 cm and 5 cm intervals for the rest of the length (Thamban *et al.*, 1997). Grain size analyses were carried out on representative sediment intervals in both the cores following standard procedures.

Stratigraphy for the cores were realised by stable isotope measurements on surface dwelling planktic foraminiferas *Globigerinoides ruber* (white variety) and *Globigerinoides sacculifer* (without the sac-like chamber). Detailed preparation procedures and stable isotope results will be reported elsewhere (Thamban *et al.*, manuscript in prep.). The oxygen

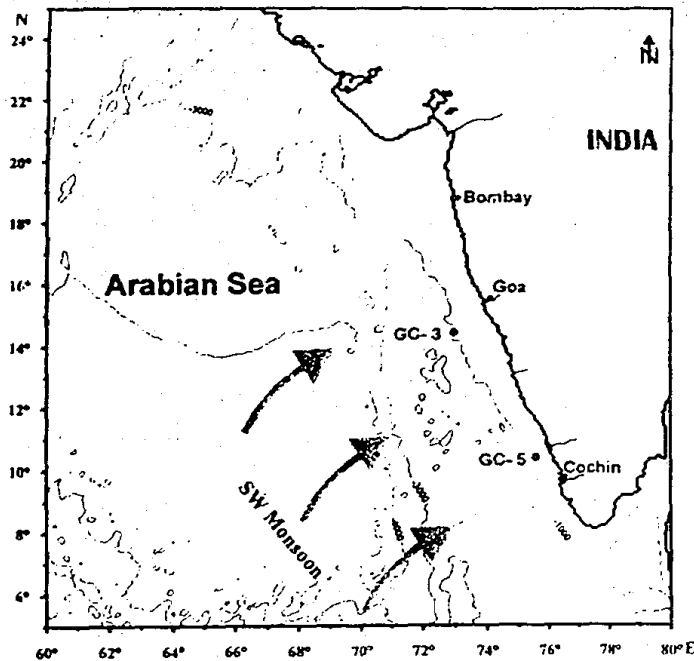


Fig. 1. Map Showing the Core Locations and a Generalised Atmospheric Circulation during the Summer Monsoon Months (June to August)

isotope records obtained were subsequently correlated with the stacked SPECMAP record of Imbrie *et al.* (1984) to obtain an age model for the cores. GC-5 represents a high resolution record of isotope events 2 and 1 (i.e., the last glacial and deglacial period). In GC-3, stratigraphy has been realised only for the top ~200 cm of the core, representing isotope stages 1, 2 and part of stage 3. Hence the present sedimentological interpretation focuses only the last glacial and deglacial period spanning ~24 kyr B.P.

Results

Stratigraphy and Sedimentation Rates

The isotopic stage boundaries as inferred from the oxygen isotope variations of *G. ruber*, allows us to estimate the average sedimentation rate during the last glacial and interglacial period. In the core from the upper continental slope off Cochin (GC-5), the Stage 2/1 boundary is accordingly placed at ~150 cm and the Last Glacial Maximum (LGM ~18 kyr B.P.) at around 240 cm (Fig. 2). The average sedimentation rate delineated from this isotope age model using the criteria of van Campo (1986), are given in Table 1. From the base of Stage 2 (~310 cm) to about 160 cm depth interval (~24-12.5 kyr B.P.), the average sedimentation rate was about 13 cm/kyr. The bulk sedimentation rate was relatively high (~16 cm/kyr) for the interval between 160-80 cm and was low (~10.7 cm/kyr) between 80 cm and core top (Table 1). The average sedimentation rate reported here is lower than the previously reported rate for a nearby site (~27 cm/kyr: Sirocko *et al.*, 1991), but is much higher than that reported from the deeper region (2.2 cm/kyr: Sarkar *et al.*, 1993).

TABLE 1: AVERAGE SEDIMENTATION RATES CALCULATED FOR THE TWO CORES BASED ON INTERPOLATED ISOTOPE CHRONOLOGY

Core GC - 5 (off Cochin)			Core GC - 3 (off Goa)		
Depth (cm)	Estimated Age (Kyr)	Sedimentation rates	Depth (cm)	Estimated Age (Kyr)	Sedimentation rates (cm/kyr)
0-80	0-7.5	10.7	0-50	0-12	4.2
80-160	7.5-12.5	16.0	50-125	12-24	6.3
160-310	13-24	13.0			

The sedimentation rate in a core from the topographic high off Goa (GC-3) was relatively lower than that obtained for the ones off Cochin. Stage 2/1 boundary is placed at about 50

TABLE 2: GRAIN SIZE PARAMETERS MEASURED FOR SEDIMENT CORES GC-5 AND GC-3

Core GC - 5 (off Cochin)				Core GC - 3 (off Goa)			
Depth (cm)	Texture (wt. %)			Depth (cm)	Texture (wt. %)		
	Sand	Silt	Clay		Sand	Silt	Clay
2	12.9	54.8	32.2	2	3.1	58.6	38.4
10	21.9	47.5	30.6	10	7.9	57.5	34.6
16	12.8	55.2	32.0	18	22.6	48.4	29.0
22	9.62	52.58	37.8	37	48.8	30.4	20.8
42	13.1	55.4	31.5	52	38.2	29.8	32.0
62	11.1	48.3	40.6	72	43.8	29.8	26.4
82	3.8	34.3	61.9	92	44.4	28.3	27.3
102	1.0	28.9	70.1	112	26.0	36.2	37.8
122	2.0	27.2	70.8	127	6.5	33.3	60.2
142	4.2	26.8	69.0	152	8.5	32.5	59.0
167	21.3	35.2	43.5	172	20.7	32.3	47.0
177	20.6	40.3	39.1	202	5.0	41.8	53.2
202	22.2	39.5	38.3	222	1.0	43.3	56.3
222	13.6	44.6	41.8	242	5.4	42.3	52.3
242	10.8	45.0	44.2				
262	11.3	44.0	44.7				
282	16.5	47.7	36.3				
302	7.0	53.8	39.2				
322	5.5	49.9	44.6				

cm and 2/3 at 125 cm interval, giving an average sedimentation rate of ~ 4.2 cm/kyr and 6.3 cm/kyr for Stages 1 and 2, respectively (Table 1: Fig. 3). Sedimentation rate was not calculated below Stage 2 as the chronology is incomplete for Stage 3.

Sedimentological Parameters

The core from the upper slope off Cochin revealed that silt and clay dominates throughout the core (Table 2: Fig. 2). The clay content varies between ~31 and 71 weight percentage (wt.%) with lowest values at the core top and relatively higher values below. Maximum clay content was registered between 80-140 cm intervals (up to 71 wt.% clay), which correspond to an age interval of 11-7.5 kyr B.P. (Fig. 2). The carbonate content (measured as wt. %

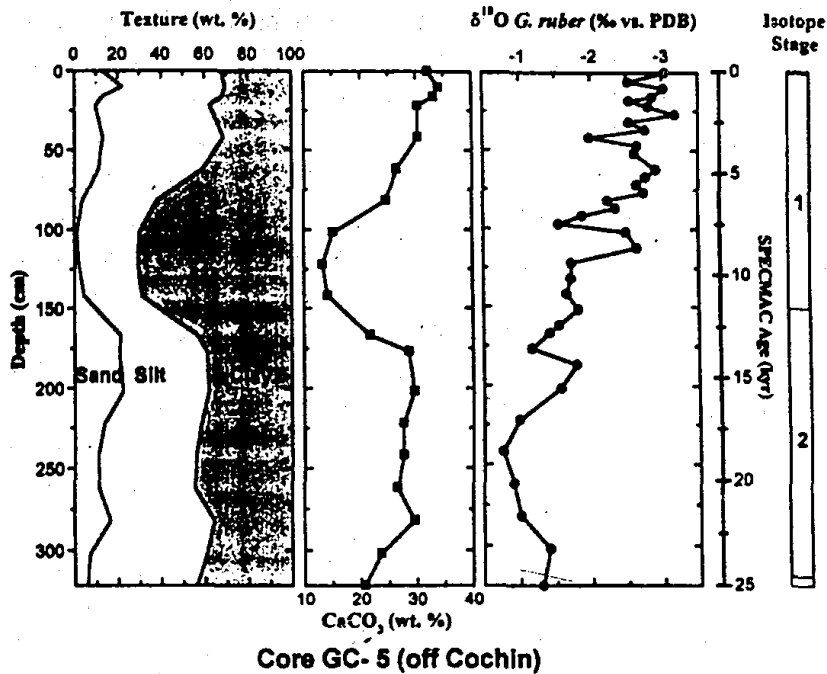


Fig. 2. Down Core Variations in Texture and Carbonate Content in Core GC-5. Also Inserted is the Isotope Curve of *G. ruber* for Age Reference. The isotope stages are defined based on the SPECMAP records of Imbrie *et al.* (1984)

CaCO_3) closely follows the textural parameters with lower (upto 15 percent) values around the same interval. Organic carbon (C_{org}) content is relatively low and exhibits a more or less uniform trend in Stage 2 (av 1.5 percent). There after the values increase very rapidly during Stage 1, culminating at the core top with a value of 3.8 percent (Thamban *et al.*, 1997).

Although silt and clay represents the main textural constituents in the core from the topographic high off Goa, their distribution is nevertheless complex. Higher content of silt and clay is found in Stage 1 and Stage 3 (varies between 74 and 97 wt.%), and high sand content in Stage 2 sediments (upto 49 wt.%) (Table 2: Fig. 3). Carbonate content closely correlates with the sand fraction, with lower values on top and higher values in Stage 2. The C_{org} content exhibits a positive correlation with clay content with higher values (up to 8.6 percent) in the Holocene (Stage 1) and lower values (av 1.6 percent) in Stage 2 sediments (Thamban *et al.*, 1997).

Discussion

Glacial to Interglacial Variation in Lithogenic Input

The lithogenic sedimentation along the western continental margin of India is mainly attributed to the river runoff and eolian input is either absent or insignificant (Sirocko *et al.*, 1991). The clay fraction which consists mainly of terrigenous material may represent the past climate on land. The clay content is generally low during the last glacial period (Stage 2) and increases dramatically around ~11 kyr B.P. (Fig. 2). The relatively high sedimentation rates at this core site allows us to interpret the detailed history of lithogenic sedimentation during the past ~24 kyr B.P.

Several studies have suggested that the southwest monsoon was very weak during the LGM due to the decreased solar insolation and increased land albedo and the monsoon intensity was maximum at about ~9 kyr B.P., when the Northern Hemisphere insolation was at its maximum (Prell *et al.*, 1980; van Campo *et al.*, 1982; Kutzbach and Street-Perrot, 1985; Sirocko *et al.*, 1993, 1996). Glacio-eustatic sea level was at about ~120 m below the present sea level during LGM (Fairbanks, 1989) when the global ice cover was maximum. The widespread glaciation in the vicinity of Himalayas and Tibetan Plateau during this time must have led to maximum snow and/or ice cover, and therefore maximum albedo. The enhanced albedo reduced the land to ocean sensible heating, resulting in a weakened monsoon circulation (Prell, 1984). The fact that the core site is presently at 280 m water and shelf width off Cochin is only about 60 km, would mean that during LGM, even though the south west monsoon was less intense and resultant sediment load was very less, the proximity of the core site to the land may have led to the bulk transport of sediments directly to the core site.

The highest clay content observed (up to 71 wt.% clay; Fig. 2) around 80-140 cm depth interval of the core GC-5 (an estimated age of 7.5-11 kyr B.P.), corresponds with the period of intensified southwest monsoon in the Arabian Sea and Indian subcontinent. This period has been described as a very humid period with greatest abundance of monsoonal rains (van Campo, 1986). Interestingly, this period also marks the period of the greatest global transgression of the recent geologic past known as the global melt water peak 1a, during which the great ice sheets of the Northern Hemisphere started melting and the sea level was constantly rising (Fairbanks, 1989; Fairbanks *et al.*, 1992). The Northern Hemisphere summer insolation was maximum during this time leading to the melting of ice sheets. It is well established that the Asian monsoon exhibits a direct, but nonlinear response to the maximum solar radiation (Prell, 1984; Kutzbach and Street-Perrot, 1985; Clemens *et al.*, 1991). As both the monsoonal intensification and melting of ice sheets are forced by the same external mechanism (i.e., insolation), it has been suggested that the period of global melt water peak is characterised by an enhanced fluvial discharge from the melt water and more importantly an increased precipitation on land (Kutzbach and Street-Perrot, 1985; Sirocko *et al.*, 1996). Model simulation studies showed that at ~9 kyr B.P., the precipitation around the Indian subcontinent was about ~0.75 cm/day compared to the modern value of ~0.5 cm/day (during summer), i.e., an increase of 50 percent (Kutzbach, 1981). Hydrological and energy balance studies of enlarged palaeolakes of Africa and India yield estimates of increased precipitation of 20 to 100 percent during ~9 kyr B.P. than the modern values (Kutzbach, 1981). The intense monsoonal precipitation and the fact that sea level was still at around 60 m below the present level experiencing large fluctuations (Fairbanks, 1989), should have led to the enhanced transport of fine terrigenous clays to the core site. So the high accumulation of clay sediments during the period of ~7.5-11 kyr B.P., is the sedimentological response to an enhanced summer monsoon. van Campo (1986), based on pollen studies in a core from the southwestern margin of India, concluded that climate change was the single largest factor that controlled the enhanced mangrove vegetation during ~11-10 kyr B.P. Present sedimentological investigations support the above findings.

A critical evaluation reveals that clay content in the core top is slightly less than that during LGM (Fig. 2). Sea level was already at its present position by ~6 kyr B.P. and stayed there since then without experiencing major fluctuations (Fairbanks, 1989; Bard *et al.*, 1989).

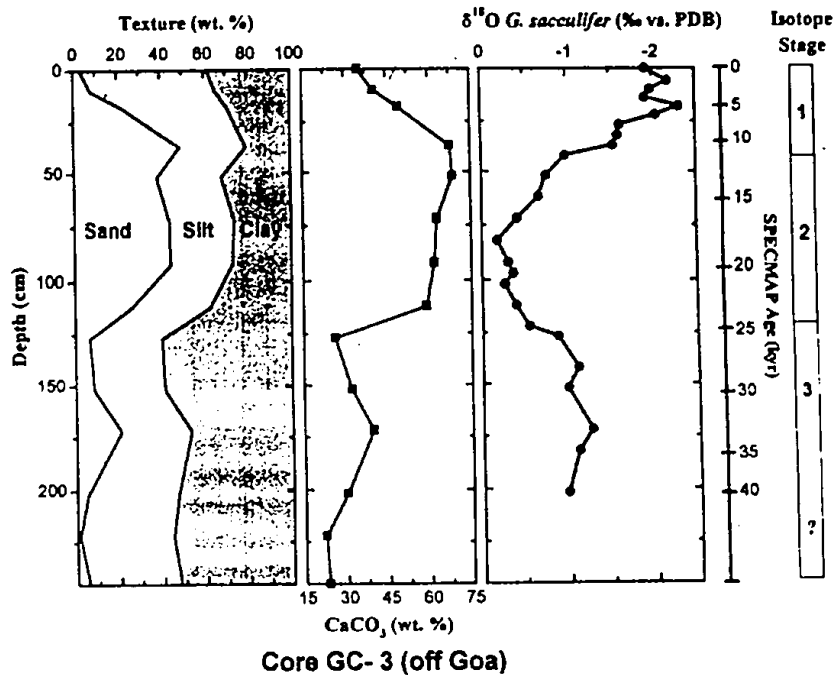


Fig. 3. Down Core Variations of Texture and Carbonate Content in Core GC-3. Note the isotope records span only up to about 200 cm depth interval

Monsoonal proxies and climate experiments have revealed that the intensity of the monsoon started declining since ~5 kyr B.P., after peaking at ~9 kyr B.P. (Kutzbach, 1981; Sirocko *et al.*, 1993). Continental climate records of the Indian subcontinent also revealed increased aridification during ~4 kyr B.P. (Singh *et al.*, 1972). Because of elevated sea level position and weaker monsoon, a major portion of fine clays brought by the Western Ghat rivers must have settled on the shelf and only a small fraction transported to the downslope. Clay mineral studies from the western Indian margin of surficial sediments indicated that the terrigenous clays brought by the rivers largely settle in the inner shelf region (Rao and Rao, 1995).

The topographic high is an isolated feature on the upper continental slope off Goa and rise from about 1200 m depth at the base to 330 m depth on the summit (Thamban *et al.*, 1997). The sedimentological features are also totally different from the one discussed above. The relatively higher sand content during isotope Stage 2 is mainly due to the high amount of carbonate shells during this period. This is also evident from the carbonate distribution, which correlates well with the sand content throughout the core (Fig. 3). Even though the sand fraction is very low at the core top and in the Holocene sediments, carbonate content is about 35 wt.%, and is comparable with that of the core from the upper slope off Cochin. Hence one cannot invoke the decrease in carbonate and related sand content as a response to the monsoon related productivity changes. From the distribution of skeletal components, it is revealed that the Stage 2 sediments generally represents open ocean environments. The dramatic variations in the distribution of textural and CaCO_3 content around early Holocene in this core (Fig. 3) has been attributed to the possibility of subsidence of topographic high

during this period (Thamban *et al.*, 1997). Compared to the sediments in the core off Cochin, the complete deglacial monsoonal climatic sequences in the textural parameters are not recognisable due to the low sedimentation rates. Hence the sedimentological variations in this core may primarily indicate a change in depositional environment and to a lesser extent, climate.

It is evident from the above that the down core variations in the sedimentological parameters are indeed suggestive of the past climatic and sea level changes along the western continental margin of India. Local oceanographic and geological features also contribute for their variations.

Factors Controlling the Sediment Accumulation Rates

Glacial to interglacial variations in the sedimentation rates along the western margin of India fluctuated widely in time and space. Although both the cores were raised from the modern Oxygen Minimum Zone (OMZ), they showed varying sedimentation rates suggesting changes in depositional environments at each site. The sedimentological parameters in the sediment core off Cochin closely follow the past climatic fluctuations in the Arabian Sea and Indian subcontinent. Palaeo-monsoonal variations (Kutzbach, 1981; van Campo, 1986) appear to be the most important factor in controlling the lithogenic clay input and rate of sedimentation along the upper slopes of the western Indian margin. The relatively high sedimentation rate during the last glacial period, even when the monsoonal wind was weak, is mainly attributed to the lowered sea level (see above) and resultant proximity of the land and the favourable local topographic features. The maximum sedimentation rate (~16 cm/kyr) observed during ~12.5-7.5 kyr B.P., is attributed to high accumulation of clays when the monsoon was at its peak. The sedimentation rate fell shortly after this period mainly due to the fact that sea level has already reached its present level and the terrigenous clays were largely deposited on the inner shelf.

The relatively low sedimentation rates in the core off Goa are attributed to the unique topographic feature of this core site (isolated high) and the absence of any direct influence from the land. The relatively higher sedimentation rate during the last glaciation and subsequent low values during Holocene may be indicative of influence from the past sea level fluctuations.

Summary and Conclusions

Downcore study of grain size parameters and sedimentation rates along the western continental margin of India, serve to identify the late Quaternary climatic and sea level changes. The lithogenic clay input to the core site off Cochin was maximum between ~11-7.5 kyr B.P., when the intensity of southwest monsoon was at its peak, leading to maximum sedimentation rate during this period. During LGM, the lowered sea level provided a favourable depositional environment for the direct deposition of clayey sediments at the core site, even though the monsoon was less intense. The reduced sedimentation rate during the late Holocene is attributed to high sea level position, confinement of deposition of the clays to the shelf region and also due to the reduced monsoon intensity. Sedimentation rates are relatively low at the topographic high off Goa, mainly because of isolation of the core site from the land and the prevalence of an open ocean environment.

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