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Mudbanks of the Southwest Coast of India. II: Wave-Mud Interactions

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ABSTRACT

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In order to explain the various sedimentary characteristics and processes involved in the formation, sustenance and dissipation of monsoonal mudbanks off the southwest coast of India, an *in situ* examination of wave-mud interactions was carried out. It is concluded that fine sediment in comparatively shallow waters is fluidized by waves and subsequently transported shoreward by the combined action of waves and currents. Due to the convergence of wave energy, fluid mud is deposited at specific nearshore sites resulting in the occurrence of localized mudbanks. As wave action subsides at the end of the monsoon, the nearshore fluid mud slides back offshore due to gravity. Hence the duration of the mudbank depends on the ability of waves and currents in sustaining mud in the fluidized state and in overcoming its downslope offshore movement. A six-stage conceptual model of mudbank evolution is proposed.

ADDITIONAL INDEX WORDS: *Energy dissipation, fluid mud, viscosity, wave energy.*

INTRODUCTION

Part I (MATHEW *et al.*, this volume) dealt with the wave characteristics at the mudbanks off Alleppey, Kerala, along the southwest coast of India. It is shown that in the context of mudbank generation, the associated wave energy dissipation leading to the calmness within the mudbank zone and other related processes, the wave characteristics and their interaction with the bottom mud are of crucial importance. The generation, sustenance, spreading, dissipation, localization and migration of the mudbank are discussed in this paper with respect to the sediment characteristics and wave-mud interaction processes. Most of the earlier studies on mudbanks have focussed attention primarily on the upper water column and the suspended sediment. On the other hand, the significance of near-bed sedimentary processes has been brought out only in some recent studies (*e.g.*, NAIR, 1985; MALLIK *et al.*, 1988; MATHEW, 1992; RAMACHANDRAN, 1993). An examination of the mudbank sediments, both suspended and fluidized, was a part of the study described here.

FIELD MEASUREMENTS AND LABORATORY ANALYSES

Water and sediment sampling and field measurements of currents, salinity and temperature were carried out in the Alleppey mudbank area (MATHEW, 1992). The sampling stations are shown in Figure 1. To facilitate the measurements and collection of samples from within the mudbank area, a 3 m long, self-supporting platform was erected at the pier end. Collection of water and sediment samples and measurement of current was carried out from this station during different stages of mudbank evolution. Wave measurements are explained in MATHEW *et al.* (this volume).

In addition to daily measurements from the platform, all the measurements described above were made once at different stations inside and outside the mudbank area. Suspended sediment load was determined from samples following the gravimetric method. Salinity was determined from the filtrate of each water sample by Mohr's volumetric method. The viscosity of the fluid mud samples was measured using a Brookfield HBT viscometer. Particle size of the bed surficial samples was determined by the standard pipette analysis method. Mineralogical assemblages of surfi-

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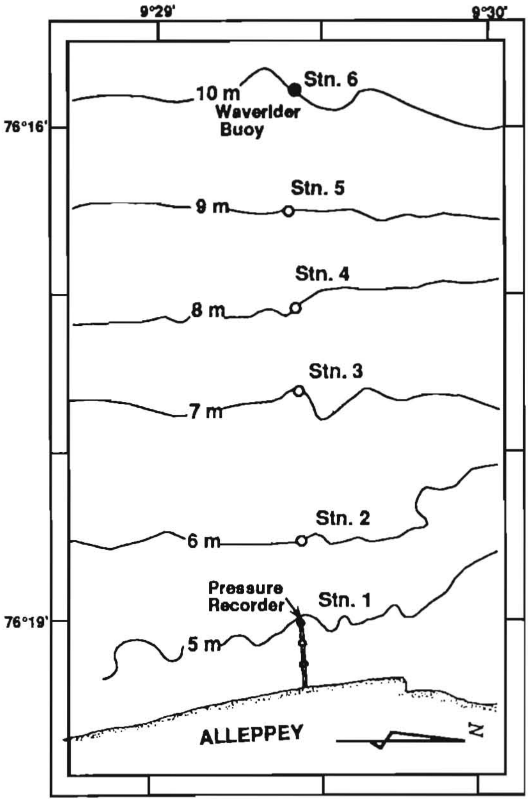

Figure 1. Study site showing the pier used for measurements and sampling stations.

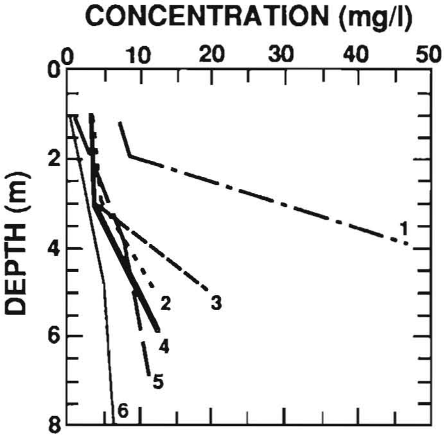

Figure 2. Vertical variation of SSC during a non-mudbank period (July, 1987); nos. 1, 2, 3, 4, 5 and 6 indicate stations, which correspond to depths of 5, 6, 7, 8, 9 and 10 m, respectively.

cial and fluid mud samples were examined by the X-ray diffraction method. Details of field data collection and analyses can be found in MATHEW (1992).

SUSPENDED SEDIMENT

The availability of fine-grained sediment in the locality or its transport to the site or both are prerequisites for the formation of a mudbank. The suspended sediment concentration (SSC) in the nearshore zones of Alleppey coast is generally very low, below 5 mg/l in the upper water column during most part of the year. On the other hand, during rough, monsoonal sea conditions sediment concentration increases up to 1,000 mg/l.

Figure 2 illustrates the vertical variation of SSC in the study area during a non-mudbank period (July, 1987). The surface SSC value at different locations towards offshore is observed to be less than 7 mg/l. Bottom SSC values reached a maximum of 46 mg/l in the nearshore; in the offshore locations, the bottom SSC ranged between 7 and 19 mg/l.

The vertical distribution of suspended sediment during different stages of mudbank evolution is illustrated in Figure 3. In the pre-mudbank condition, the surface water had SSC in the range of 600–900 mg/l, marking the onset of the mudbank. This condition coincided with the maximum nearshore significant wave height during this period (1.2 m) and frequent spilling breakers observed in the offshore indicating turbulent sea. A moderately high, quasi-steady current (~66 cm/sec) also contributed to turbulence in the nearshore. About two days later, the SSC values in the upper water column showed a drastic decrease (to less than 100 mg/l), whereas the near-bed layer concentration increased to 12,500 mg/l. This change could have been due to the settling of the suspension resulting from a decrease in the wave height and the current velocity.

SSC further decreased after two days in the upper water column in response to a considerable decrease in the dynamic forces. The observed concentration was <30 mg/l in the upper water column with a corresponding near-bed concentration of about 174,000 mg/l. This high near-bed SSC is generally defined as "fluid mud" (MATHEW, 1992). The thickness of this fluid mud layer was about 2 m.

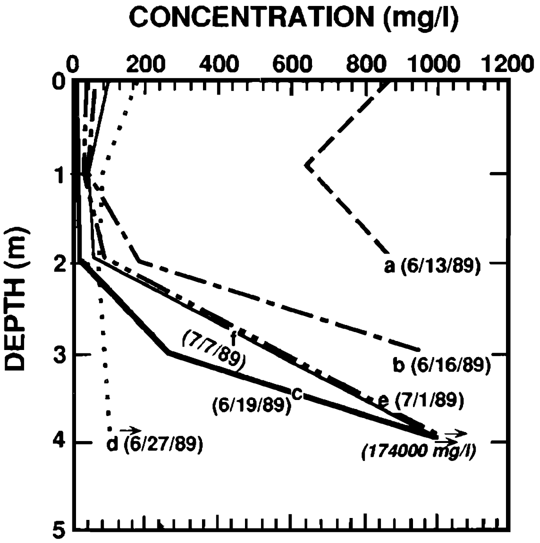

Figure 3. Vertical variation of SSC before and during mudbank formation: a) Before mudbank formation (nearshore wave height, H_s = 1.23 m). b) During mudbank formation (H_s = 0.77 m; suspended sediment concentration at the bottom, SSC_{bottom} = 12,500 mg/l). c) When the mudbank was formed (H_s = 0.31 m; SSC_{bottom} = 174,000 mg/l). d) When the mud was settling and spreading laterally (H_s = 0.10 m; SSC_{bottom} = 94,000 mg/l). e) When the offshore wave activity increased and currents became noticeable in the mudbank area (H_s = 0.50 m; SSC_{bottom} = 161,000 mg/l). f) When settling recommenced in the mudbank area (H_s = 0.45 m; SSC_{bottom} = 81,000 mg/l).

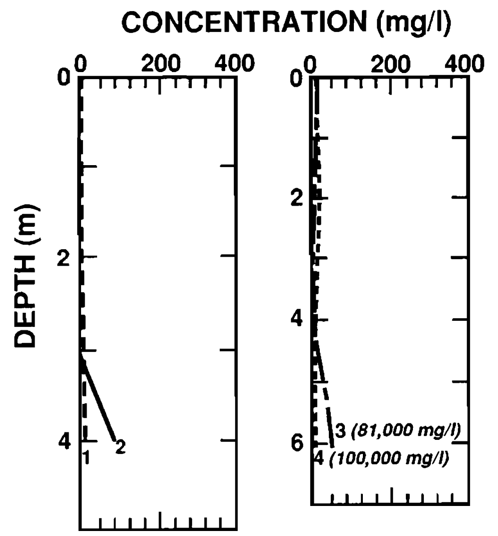

Figure 4. Vertical distribution of SSC at different stations (1, 2, 3 and 4) in the later stage of mudbank evolution. Maximum concentrations obtained at the bottom are marked in 3 and 4.

Redispersal of sediments from the upper part of fluid mud to the overlying water column was observed subsequently due to increased current velocity (~55 cm/sec), while a calm condition prevailed in the mudbank area. The vertical profile above the fluid mud layer showed a homogeneous concentration of the suspension during this phase. The thickness of the fluid mud layer decreased to about 1 m with a lateral spreading of the mud to either side. Previous observations report similar phenomena (Kurup, 1977).

An increase in the wave height (Mathew *et al.*, this volume), coupled with an increase in the thickness of the fluid mud layer was observed after a few days. As explained earlier, the wave height outside the mudbank zone was large (~2 m). However, the wave height was less than 50 cm in the nearshore area during this period. Thus, the concentration in the upper water column became very low as a result of a rapid settling of sediment. The vertical distribution of SSC at four stations in the mudbank area during this period is shown in Figure 4. Note that the upper water column shows a very low concentration. It is also interesting to note that the concentration and thickness of fluid mud at the seaward periphery of the mudbank were higher than further inside the mudbank. Data beyond the peripheral zone could not be collected due to high wave activity.

Surficial salinity values observed during the monsoonal non-mudbank period ranged between 30.5 and 33.6‰. Salinity variation during different stages of the mudbank evolution was from 34.5 to 29.1‰. The maximum salinity value coincided with the pre-mudbank period, followed by a slight decrease and a subsequent increase to the earlier higher value. This slight decrease could have been due to precipitation. Since salinity above 10‰ has a negligible effect on particulate deflocculation, salinity values observed in the present case could not have accelerated the deflocculation of particles. Hence, the deflocculation hypothesis for bottom sediment redispersal in the mudbank area, as suggested by earlier researchers (Varma and Kurup, 1969; Kurup, 1977; Murty *et al.*, 1984) as the reason for the high viscosity of the turbid mudbank waters does not appear to hold.

As noted, a comparison of SSC in the upper water column during different stages of mudbank

Table 1. *Viscosity and concentration of fluid mud during different stage of mudbank evolution.*

Station Depth (m)	Viscosity (Pa·sec)	Concentration (mg/l)	Remarks
5.5	4.76	174,000	Fully developed mudbank.
5.5	3.04	161,000	Increased wave activity offshore and along adjoining coasts.
5.5	0.22	94,000	Reduced wave activity in the offshore area. Dissipation commenced.
6.5	0.16	81,000	Dissipation stage. Lower concentration in the nearshore area.
7.0	0.84	100,000	Dissipation stage. Higher concentration in the offshore area.

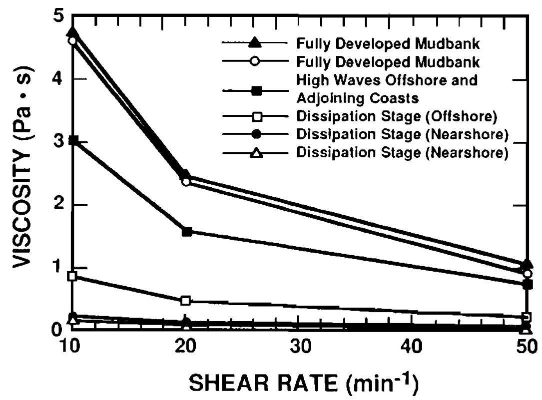

Figure 5. Viscosity of Alleppey mud for different shear rates during different stages of mudbank evolution.

evolution (Figure 3) reveals that the highest SSC values were encountered during the pre-mudbank period. Mudbank formation creates a low stress environment which helps in the rapid settling of suspended sediment from the upper water column. This observation is contrary to some earlier reports (KURUP, 1977; MURTY *et al.*, 1984; MALLIK *et al.*, 1988) of the occurrence of highly turbid surface water throughout the period of existence of the mudbank. Local fishermen use the mudbank area as a fishing ground and temporary harbor during the rough season. The operation of hundreds of these country crafts with fishing gear creates turbulence in the water column, which in turn may hinder the settling of the fine sediment. This could be one of the reasons for the reports of high sediment concentration in the upper layers in the earlier studies.

FLUID MUD

Characteristics of the fluid mud in the mudbank zone were examined. In the initial stages, the fluid mud had a thickness of about 2 m and a concentration of 174,000 mg/l in the superficial layers with a density of 1,270 kg/m^3. Samples from deeper layers of fluid mud could not be collected because the sampler did not penetrate these layers due to the very high sediment concentration. The dry density of sediment samples obtained was 2,270 kg/m^3, which is close to values reported by JAMES *et al.* (1987) for certain marine sediments.

Flow Behavior

To study the flow characteristics of fluid mud, viscosity measurements were carried out. No previous treatment (removal of carbonates or organic matter) was done prior to testing. The viscosity and concentration of fluid mud obtained during different stages of the mudbank evolution are given in Table 1. All measurements were made at room temperature. The viscous response of fluid mud depends on its mineralogy, concentration, pore fluid composition and temperature; changes in these factors during different periods of sample collection presumably also affect the viscosity. The viscosity of fluid mud obtained in the initial stage of mudbank formation was 4.76 Pa·sec, about 4,000 times greater than the viscosity of sea water. This value represents only the upper fluid mud layer sampled; no data are available on the density distribution of the *in situ* fluid mud. Due to differential settling of sediments, a less concentrated layer may overlie a high concentration layer. Hence the deeper layers may possess a higher viscosity. It should be noted that there was an increase in the viscosity for samples associated with high current velocities and offshore waves during the presence of mudbank. On the other hand, the lowest viscosity was obtained for the offshore fluid mud during the dissipative stage of the mudbank, 0.16 Pa·sec, which is about 200 times that of sea water.

Viscosity variation with shear rate (≥ 10 min^{-1}) for mud collected during different stages of mudbank evolution is shown in Figure 5. For each curve, the trend of decreasing viscosity with increasing shear rate indicates that the mud is pseudoplastic. At a given shear rate, increasing viscosity correlates with increasing mud concentration depend-

Table 2. *Mineralogical composition of surficial sediment and fluid mud during different stages of mudbank evolution.*

Sample	Montmorillonite (%)	Kaolinite (%)	Illite (%)	Gibbsite (%)	Remarks
Surficial sediment	34.2	56.3	6.9	2.6	Pre-mudbank.
Fluid mud	62.4	28.4	7.3	1.9	Fully developed mudbank.
Fluid mud	54.0	36.6	7.7	1.7	Dissipation stage—nearshore fluid mud.
Fluid mud	56.3	39.2	3.3	1.2	Dissipation stage—offshore fluid mud.
Surficial sediment	34.9	56.4	5.4	3.3	Increased wave activity in the offshore and adjoining coasts.
Surficial sediment	42.3	48.3	7.0	2.4	Reduced wave activity in the offshore. Dissipation commenced.
Surficial sediment	58.6	30.8	8.8	1.8	Dissipation stage—nearshore sample.
Surficial sediment	39.8	52.3	6.6	1.3	Dissipation stage—offshore sample.

ing on the stage of mudbank evolution (MATHEW, 1992).

Mineralogy

Relative proportions of clay minerals in the surficial sediment and fluid mud were examined by X-ray diffraction. Major clay minerals identified were montmorillonite, kaolinite, illite and gibbsite. The percentages of these four minerals are given in Table 2. Pre-mudbank surficial sediments from the nearshore showed a high percentage of kaolinite (56%) followed by montmorillonite. Illite and gibbsite in all the samples were found to be very low. Fluid mud samples showed an enrichment of montmorillonite with a corresponding decrease in kaolinite. These samples were collected from the upper layers of the fluid mud. It appears that finer-sized montmorillonite naturally formed the main clay mineral in fluid mud samples compared to the coarser kaolinite particles, possibly due to differential settling effects.

Textural Characteristics

Grain size distributions of the surficial sediment during different stages of mudbank evolution are given in Table 3. In the pre-mudbank condition the location registered a higher percentage of sand (34%), probably because the fines were brought into suspension by waves and currents. Sediment samples during mudbank formation showed an enrichment of clay particles. Since the sampler had to penetrate the near-bed fluid mud, samples obtained in the presence of mudbank represent an admixture of material in suspension and in the bed.

FLUID MUD DYNAMICS

Bed Erosion

Bed erodibility depends on the stress history of the suspension in addition to the instantaneous value of the bed shear stress. There is a critical shear stress below which practically no erosion takes place. This stress is mainly dependent on the density of the settled mud of given composition. Erosion of mud takes place as a consequence of the penetration of wave-induced motion within mud. Since the wave height during the pre-monsoon period is typically low (~0.5 m) (MATHEW, 1992), these waves do not adequately penetrate the bed to cause significant erosion. On the other hand, deep water wave statistics show that 2–3 m high waves predominate during monsoon period (MATHEW *et al.*, this volume). Continuous wave loading weakens the bed, resulting in mass erosion or bed fluidization. Low upward entrainment but high longitudinal dispersion of

Table 3. *Grain size distributions of surficial sediments during different stages of mudbank evolution.*

Station Depth	Sand (%)	Silt (%)	Clay (%)	Remarks
5.5	34.0	27.3	38.7	Pre-mudbank.
5.5	2.7	27.4	69.9	Fully developed mudbank.
5.5	11.8	36.4	51.8	High waves in the offshore and adjoining coasts.
5.5	10.3	38.6	51.1	Reduced wave activity in the offshore. Dissipation commenced.
5.5	10.2	35.4	54.4	Dissipation stage.
5.5	8.0	43.8	48.2	Dissipation stage.

this fluidized mud results in the spreading of mud in the near-bed boundary layer.

An examination of the likelihood of wave-induced suspension in the nearshore region was carried when the predominant wave period was 9 sec and the height was 2 m in the offshore region. A characteristic critical value of 18 cm/sec for initiating erosion of unconsolidated cohesive sediments reported by PARTHENIADES (1971), was selected in this study. It can be shown that such a wave can initiate sediment suspension at a water depth of 40 m (MATHEW, 1992). Previous observations by RAO *et al.* (1983) and RAMACHANDRAN (1993) have confirmed the availability of fine sediments in the inner continental shelf of this coast. Hence, it is reasonable to presume that the inner-shelf setting and wave conditions are conducive for the erosion and subsequent fluidization of mud.

RAO *et al.* (1983) reported that there is a substantial increase in the amount of montmorillonite towards offshore along the shelf regions of the southwest coast of India. RAMACHANDRAN (1993) observed that an offshore increase in montmorillonite is complementary to an offshore decrease in kaolinite. Though there are differences of opinion on the source of montmorillonite in the inner-shelf region, it is agreed that offshore sediments are richer in montmorillonite than those nearshore. Thus, the observation in the present study concerning an enriched montmorillonite composition in fluid mud suggests that wave-eroded offshore mud plays a significant role in mudbank formation in the nearshore. Moreover, a high rate of deposition of fine sediment within a short span of time cannot be attributed to a land source especially along this coast, which is devoid of any fluvitile source of sediment for a continuous stretch of 85 km.

Even during the mudbank phase, days of higher wave/current activity coincide with the higher occurrence of coarser surficial sediments. Thus, an increase in the silt content in the nearshore surficial sediment was observed during the dissipation stage of the mudbank. An increase in the clay content towards the offshore during this period was also observed. These trends could be due to the removal of finer sediment from the nearshore region due to a decrease in the hydrodynamic forcing. Thus, the textural characteristics of the surficial sediment seemingly reflect different stages of hydrodynamic forcing, implying a correlation between surface waves and the underlying sediment.

Fluid Mud Transport

The fluid mud layer formed tends to flow shoreward by the combined action of waves and currents, against the down-slope direction. In areas of low current speeds and when the flow regime is wave-dominated, a significant portion of sediment transport is confined to the near-bed region. Hence along this coast during the monsoon season, even when the currents are weak, persistent high waves alone can transport fluid mud shoreward *en masse*. The aberrant appearance of a mudbank during the December storm of 1965 (VARADACHARI and MURTY, 1966) is an example.

The fluid mud thus transported to the nearshore zone reaches only up to a certain depth, and movement further towards the shallower areas is restricted due to the decreased energy content of the waves. Further, the transport can cause a winnowing of the coarser fractions, ultimately resulting in a finer-grained particulate population in the fluid mud layer in the nearshore region.

During the mudbank dissipation stage, an increase in fluid mud density was observed in the offshore direction indicating sediment removal from the nearshore and its transport into deeper waters. A few days after its formation the fluid mud spread laterally as noted, extending the mudbank area in the alongshore direction. For instance, simultaneous extensions of the Alleppey mudbank about 4 km towards the south and about 2 km to the north were observed during the study period. The more southerly extension could be due to the effect of prevailing wave direction and southerly current. This spreading reduced the overall thickness of the fluid mud layer, with an attendant decrease in its density.

LOCALIZATION OF MUDBANK

The wave refraction pattern along this coast was studied to examine the cause of the localized occurrence of mudbanks along this coast. A deep water wave height of 2 m was considered in all refraction computations, since this height represents an average deep water significant wave height for this coast during monsoon per Indian Daily Weather Reports. An example of the wave refraction pattern thus obtained is shown in Figure 6. It was noted that in all the cases convergence of wave energy occurs at about the same locations, irrespective of the directions and periods examined (MATHEW, 1992). These convergence zones coincide with the zones of occurrence of the mudbanks (marked C in Figure 6). According to VARMA and KURUP (1969), REDDY and VARADACHARI (1973) and MURTY *et al.* (1980), the zones of occurrence of mudbanks are zones of offshore flow resulting from the convergence of littoral currents. However, convergence of littoral currents normally occurs in-between the zones of convergence of wave energy. The present observations suggest that offshore flow resulting from such convergence of littoral currents do not generate mudbanks.

Due to the convergence of wave energy, shoreward moving sediment accumulates in certain specific sites, resulting in the localized formation of the mudbank. Wave refraction also leads to year-to-year migration of mudbanks. Such a migration occurs due to the variation in bathymetric conditions, which in turn influences wave refraction. It is also surmised that the alongshore and offshore dimensions of the mudbank (MATHEW *et al.*, 1995) are determined by the intensity of energy convergence and the availability of sediment.

MUDBANK DISSIPATION

Following the active mudbank period, RAMACHANDRAN and SAMSUDDIN (1991) observed that excess sediment associated with the mudbank disappears, bringing the nearshore topography back to the pre-mudbank condition, with a predominantly sand bottom. Down-slope movement of bed material load due to gravity probably plays a noteworthy role in mudbank dissipation. It seems likely that such a gravity-driven transport may be much more significant where the sediment is fine enough to remain in suspension near the bottom. As and when the wave height decreases below a certain threshold value, the comparatively high bulk density of the fluid mud together with the down-slope component of gravity produces offshore transport of the fluid mud as it overcomes bottom frictional resistance. The rate of down-slope movement depends on the wave and also current conditions. The persistence of the mudbank is determined by the ability of the waves and current in sustaining mud in the fluidized state and in overcoming its tendency towards down-slope movement.

A CONCEPTUAL MODEL

A conceptual, six-stage model for wave-mud interaction processes in the mudbank area is developed based on the field observations. At low sediment concentration, hydrodynamic parameters significantly control the sediment transport; when concentration increases, lithodynamic features in turn begin to control the hydrodynamic parameters. Furthermore, the presence of a dense suspension in the lower layers leads to the suppression of turbulence and drag reduction.

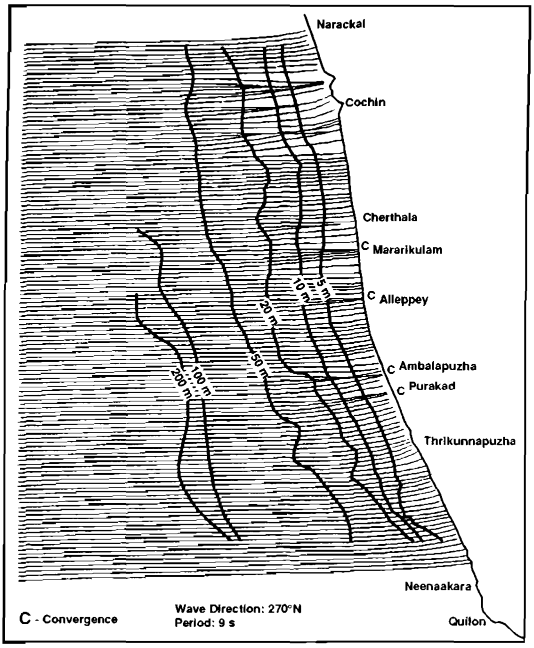

Figure 6. Typical wave refraction pattern in the vicinity of Alleppey (with westerly deep water waves).

Figure 7 conceptually shows the wave conditions and associated changes in the oscillatory water velocity and sediment concentration during different stages of mudbank evolution. Pre-monsoon conditions (stage 1) indicate a homogeneous water column with negligible SSC and low wave activity ($H_s < 50$ cm). As a result of the initiation of storm waves with the onset of monsoon (stage 2; $H_s > 100$ cm), the bottom sediment becomes entrained. Convergence of wave energy occurs due to wave refraction at specific locations depending on the bathymetry. This concentration of energy locally contributes sediment, leading to an increase in the sediment concentration over much of the water column. At the same time in the offshore region, the stress applied by the high waves over the muddy bottom weakens and erodes the bed, and its fluidization occurs. The mud con-

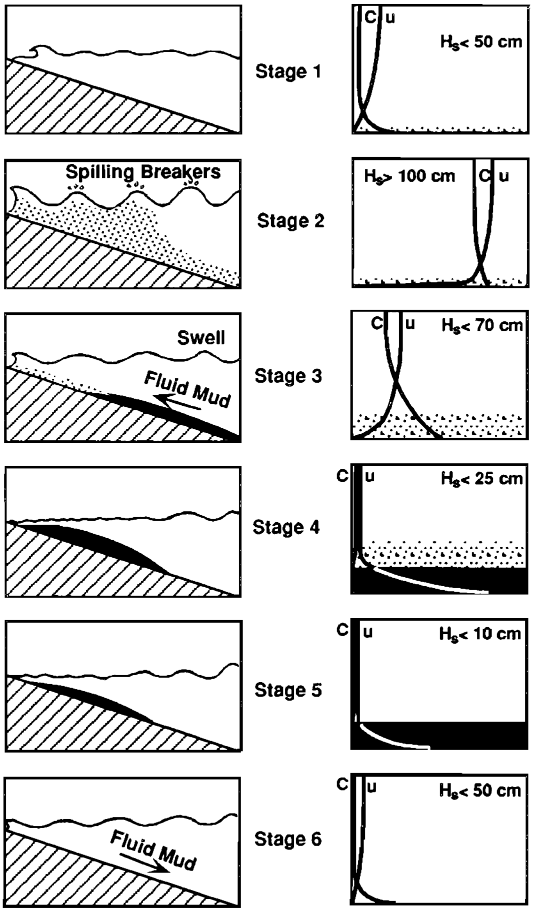

Figure 7. A conceptual model of mudbank evolution (C—concentration, u—orbital velocity).

centration in the boundary layer increases until it reaches ~20,000 mg/l. The formation of nearshore pools of fluid mud is accompanied by a reduction in the wave activity, as the wave energy is used for eroding and fluidizing bottom mud, transporting it to the nearshore and sustaining mud in the fluid state there (stages 3, 4, 5). This energy reduction in turn leads to the settling of sediment causing a measurable decrease in the sediment concentration in the upper water column.

As the wave height eventually decreases, gravity-driven, down-slope transport of fluid mud leads to the dissipation of the mudbank (stage 6). The persistence of the mudbank conditions thus depends on the wave and current conditions, which can maintain mud in the fluidized state and prevent the movement of fluid mud to the offshore.

The mudbanks off the southwest coast of India have been previously defined based on suspended sediment load and the prevailing calmness (MATHEW, 1992). In the light of the present investigation, which considers wave-mud interaction as the major factor in mudbank evolution, mudbank may be defined as a calm nearshore zone created by near-complete wave attenuation caused by a fluid mud bottom.

CONCLUSIONS

Application of a periodic stress due to water waves over a muddy bottom has a number of consequences, of which the important ones are bed erosion, generation of fluid mud and wave attenuation. Availability of fine sediment is a prerequisite for the formation of the mudbank. The described *in situ* study of the nearshore SSC reveals that sediment required for mudbank generation is transported from offshore regions.

A study of the wave-induced erosion process reveals that waves during monsoon are capable of causing erosion from intermediate water depths. Fluid mud generated by waves is transported to the nearshore *en masse* by the combined action of waves and currents. An investigation of the wave refraction pattern indicates that localization of mudbanks is due to wave energy convergence. Year-to-year migration of mudbanks is attributed to the variation in bathymetric conditions, which is one of the deciding factors for the energy convergence.

Alongshore extension of a mudbank a few days after its formation, as observed sometimes, is due to wave forcing outside the mudbank area and the prevailing coastal currents. Finally, down-slope movement of fluid mud is believed to play a major role in mudbank dissipation.

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