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Mudbanks of the Southwest Coast of India III: Role of Non-Newtonian Flow Properties in the Generation and Maintenance of Mudbanks

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ABSTRACT

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A study of the Alleppey mudbank, one of many which occur annually with the onset of the southwest monsoon season in southern India, indicates that differences in stress-rate of strain relationships exist between the semi-consolidated bottom muds (suggested to be the source of the mudbank material) and dense suspensions (fluid mud) generated from the natural bottom. These differences appear to provide plausible explanations for: (1) generation and accumulation of the mud deposit during the monsoon, (2) preservation of the shorefast mudbank during the high energy event, and (3) disappearance and seaward dissipation of the mudbank after the cessation of the monsoon. These deposits cause seaward accretion of the coastline fronted by the mudbank while erosion occurs in inter-mudbank areas. Post-monsoonal conditions involve change of wave character and direction, the suspended mud settles to the bottom and flows down the shelf gradient to accumulate below wave base and consolidate for approximately nine months, until the next monsoon season.

ADDITIONAL INDEX WORDS: *Consolidation, erosion, fluid mud, rheology, viscosity.*

INTRODUCTION

Mudbanks, defined as accumulations of dense fine-sediment suspensions which form sub-circular/elliptical deposits having dimensions from 2–5 km alongshore and 1.5 to 4 km offshore, occur yearly along the west coast of southern India (Kerala State). Mudbanks nearly always occur shortly after the arrival of the southwest monsoon in late May/early June; however, instances of earlier formation (and sometimes of no formation) have been noted. They usually form in the same place each year and often show a downcoast migration during their brief existence (generally 1.5 months). While active they are noted for their wave damping effects (MATHEW *et al.*, 1994). BABA *et al.* (1992) present data off Alleppey showing that a 1.8 m high wave outside the mudbank is reduced to 0.5 m high within the mudbank, a distance of 1.1 km, Figure 1a. They state (p. 61) that in a fully developed mudbank almost 100% dissipation of wave height occurs within a distance of a few wave lengths over the mudbank zone. The mudbank also provides protection to the coastal zone, allowing a net seaward accretion to occur behind it. Downcoast, the areas between mudbanks are actively eroding during the monsoon. Because of the effectiveness of wave damping, the mudbank provides an environment pleasing to the local fishermen—an environment within which they can continue fishing while the 2–3 m high monsoon waves make fishing outside the mudbank impossible. There appears to be a biological richness to the mudbank, perhaps due to the abundance of organic matter (≥5%) attached to the sediment particles or perhaps due to the reduced turbulence and the enhanced turbidity, which seem to attract the juvenile fishes and the larger fishes which feed upon them (GOPINATHAN and QASIM, 1974).

Numerous hypotheses have been advanced to account for the existence of the mudbanks, most of which have been considered as being too speculative and lacking hard evidence to support conclusions. These hypotheses are referenced but will not be discussed. The latest hypothesis (MATHEW

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and BABA, 1994) suggests that the muds are derived from an inner shelf mud deposit located in about 20 m depth, which becomes fluidized through various mechanisms, works its way en masse upslope due to wave orbital forces, and becomes resuspended in the nearshore waters to form a sub-circular/elliptical deposit, some 5–7 km in diameter, which is fast to the shore on one end, and remains in contact with the bottom at about 9–10 m depth at the offshore end (Figure 1b).

STATEMENT OF THE PROBLEM

Several earlier workers (DAMODARAN and HRIDAYANATHAN, 1966; DORA *et al.*, 1968, 1984; SHENOI and MURTY, 1986; NAIR, 1988; MURTY and MUNI, 1987; MALLIK *et al.*, 1988) have attributed the wave damping phenomenon to the high viscosity of the suspended sediment of the mudbanks. While appearing to provide a reasonable explanation, they provided no physical measurements to support their suggestions. In fact, no actual measurements of these properties were attempted until BABA *et al.* (1992), who observed that Bingham plastic flow behavior was characteristic of the comparatively high density suspensions. A similar view was taken by KURUP (1977) and MACPHERSON and KURUP (1981), who suggested that wave damping is due to energy absorption in the near-bottom viscoelastic bed. This interpretation is supported by KURIAN and BABA (1987), who found it necessary to utilize a higher friction factor (at least 1.5 × the rigid bed value) to account for wave energy loss and the observed wave attenuation at the Alleppey site.

In an attempt to clarify the possible role of mud rheology in the mudbank-forming process, the viscous properties of the seabed at Alleppey and the suspensions generated from it have been analyzed and interpreted on a preliminary basis with respect to their importance in mudbank dynamics.

OBSERVATIONS

The samples consisted of the material retained in two Van Veen grab samples taken from the pier at Alleppey (Figure 1a), just prior to the onset of the 1992 monsoon. Thus, the samples represent material from the clayey unit which forms the innershelf clay deposit from which the mudbank sediments are presumably generated. The pier extends 300 m seaward, perpendicular to the shoreline and ends in water depth of 5.2 m. Alleppey #1 was taken from the end of the pier, and a second sample (Alleppey #2) was taken some 100 m landward, in 4.6 m depth. Both samples are classified as 'silty clays' (SHEPARD, 1954), with Alleppey #1 possessing up to 9% of sand, while Alleppey #2 possessed no sand-sized (>63μm) material. Size analysis was performed with the ASTM 152H hydrometer (BOWLES, 1970), organic matter content (average 5%) was determined with the strong oxidizing agent (hydrogen peroxide) treatment, and the stress-rate of strain behavior was analyzed in a Brookfield RVT 8-speed rotational viscometer, equipped with a set of coaxial spindles capable of generating reproducible values of shear rates and shear stresses over a wide range of shear rate (FAAS, 1990). No pretreatment (*e.g.*, removal of carbonates, oxidation of organic matter) was done prior to the viscometric studies. Analysis was done within three days of sampling

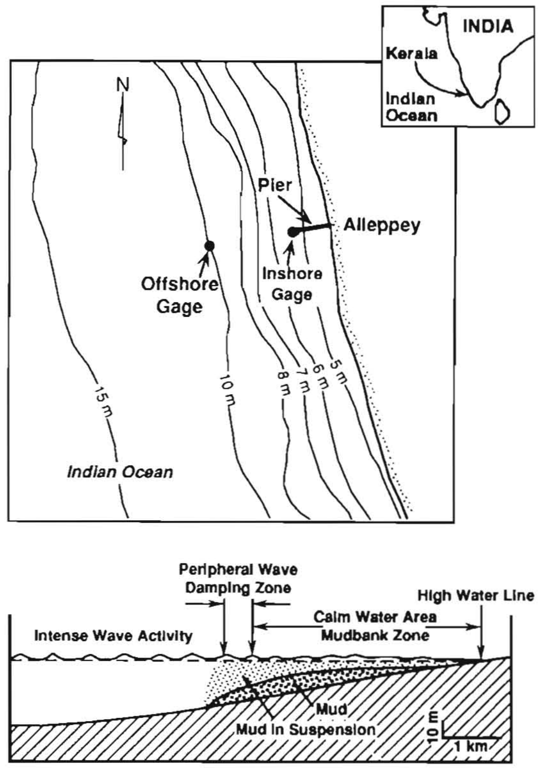

Figure 1. a. Position of pier and nature of bottom topography off Alleppey, Kerala, India. The distance between the offshore wave gage and the inshore wave gage is 1.1 km. b. Schematic profile of a mudbank region (after NAIR, 1988).

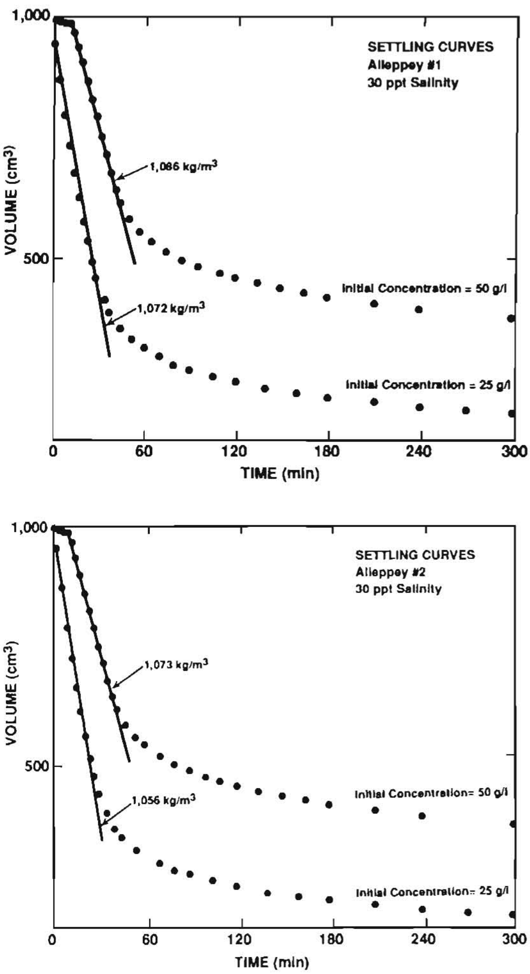

Figure 2. Hindered settling curves for the two Alleppey samples, settled at 25 and 50 g/l in water of 30 ppt salinity. Linear settling changes at suspension density of 1,073 kg/m³ in all samples, indicating structural formation associated with hindered settling occurs at that density: (a) Settling of Alleppey #1, (b) Settling of Alleppey #2.

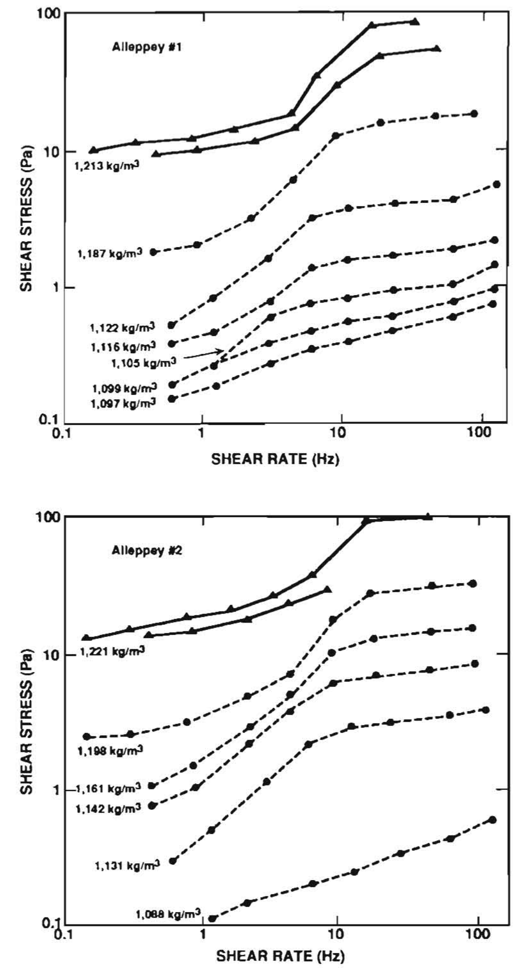

Figure 3. Flow diagrams for the two Alleppey samples, each showing the flow behavior of the undisturbed sediment bed (solid lines) and the resuspended sediment at different sample densities (broken lines): (a) Flow behavior of Alleppey #1, (b) Flow behavior of Alleppey #2.

so as to ensure as near natural conditions as possible. Mineralogically, the Alleppey mud is dominated by montmorillonite (50–60%), followed by kaolinite (30–40%) with minor amounts of illite (5–7%) and gibbsite (1–2%) (BABA *et al.*, 1992). Atterberg limit tests of Alleppey samples classify them as 'inorganic clays of high plasticity'. Liquid limit ranged between 151–157, plastic limit between 60–61, and plasticity index between 91–97.

Hindered Settling

Sub-samples of 50 and 25 g dry weight of both samples were resuspended in a liter sedimentation tube in natural sea water at 30 ppt salinity and allowed to settle in the hindered settling mode (TEETER, 1985; FAAS, 1991). The column was 35 cm high and hindered settling proceeded for 24 hours. Final densities achieved for Alleppey #1 were 1,138 kg/m³ (50 g) and 1,144 kg/m³ (25 g) (Figure 2a). Density for Alleppey #2 samples was slightly less, 1,137 kg/m³ (50 g) and 1,133 kg/m³

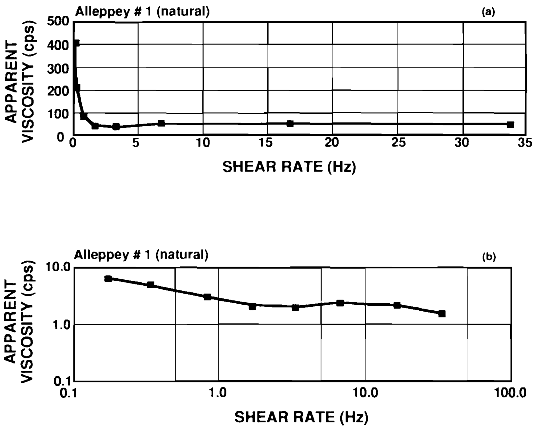

Figure 4. Rheogram of the natural bed sediment at Alleppey #1. The sample demonstrates a continuous reduction in 'apparent' viscosity to a shear rate of approximately 5 Hz. Shear thickening occurs between 5 and 7 Hz and is followed by shear thinning to 34 Hz (a). This behavior is also shown on a log-log scale in (b).

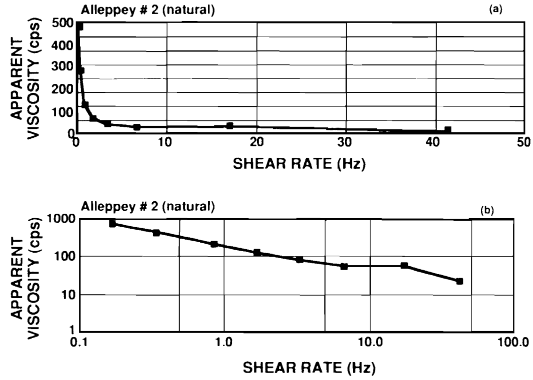

Figure 5. Rheogram of the natural bed sediment at Alleppey #2. The sample shows a nearly continuous reduction in 'apparent' viscosity. An indication of Newtonian flow occurs at about 18 Hz and is followed by shear thinning to 42 Hz (a). This behavior is also shown on a log-log scale in (b).

(25 g) (Figure 2b). Both 50 g samples began with a significant (>10 minutes) interval of nearly complete hinderance, with the sediment-water interface falling only about 3 mm during the delay period. However, once occurring, settling of the interface continued very rapidly for the first 40–60 minutes. A change in slope of the 50 g samples occurred at densities of 1,086 kg/m^3 (#1) and 1,073 kg/m^3 (#2). This transition possibly correlates with the moment at which the suspension changes from fluid-supported to partially grain-supported, with an increase in pore pressure (FAAS, 1991, SILLS and ELDER, 1985). These experiments suggest that fluid mud evolves very rapidly from the suspended material in the water column. Settling thereafter is rather slow and density increase is likewise slow. Thus the period of existence of fluid mud, *i.e.*, before density >1,300 kg/m^3 is achieved, if ever under these conditions, extends beyond 36 hours.

Flow Behavior

Flow behavior of the seabed sample of Alleppey #1 (depositional density of 1,213 kg/m^3) showed an unusual pattern, beginning with an interval of shear thinning extending through initial shear stresses (9–14 Pa) (Figure 3a). Flow behavior changed from shear thinning to Newtonian at shear stresses between 14 to 29 Pa. The flow diagram for the seabed sample of Alleppey #2 (depositional density of 1,221 kg/m^3) exhibited near identical behavior, except decreased shear thinning occurred between shear stresses from 34 to 87 Pa (Figure 3b). Figures 4a,b and 5a,b are rheograms which show the nearly completed shear thinning flow behavior of the natural samples (Alleppey #1 and #2) in detail.

Sub-samples from each seabed sample (Alleppey #1 and #2) were successively diluted to pro-

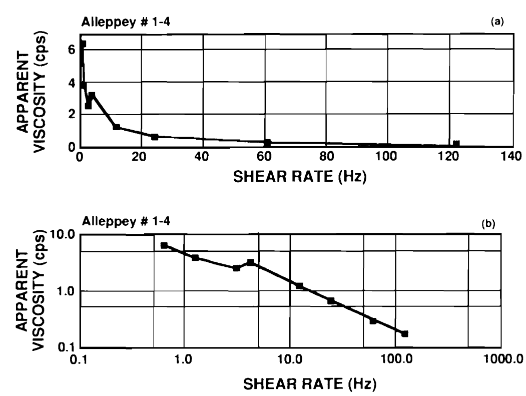

Figure 6. Rheograms of Alleppey #1–4 (density 1,118 kg/m^3), a suspension made from a bed sample from Alleppey #1. a) shows clearly the apparent viscosity increase (shear thickening) which occurs between 3 and 6 Hz. Apparent viscosity continues to decrease to the end of the run after 6 Hz. b) shows the same interval of apparent viscosity increase (shear thickening) on expanded logarithmic coordinates.

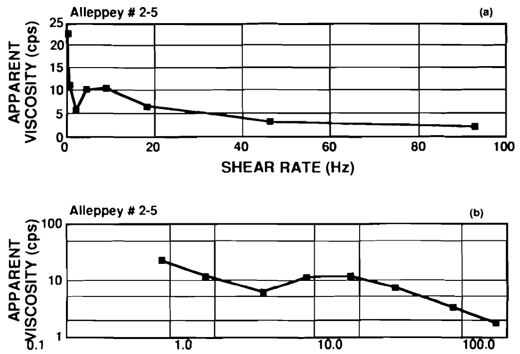

Figure 7. Rheograms of Alleppey #2–5 (density 1,161 kg/m³), a suspension made from a bed sample from Alleppey #2. a) shows clearly the apparent viscosity increase (shear thickening) which occurs between 2 and 5 Hz. This is followed by an interval of constant apparent viscosity (Newtonian flow) to 9 Hz. The remainder of the figure shows apparent viscosity decreasing (shear thinning) to the end of the shear rate scale. b) shows the same data on expanded logarithmic coordinates.

vide a series of mud samples of decreasing density. Their flow curves are presented for comparative purposes as a general overview in Figs. 3a and 3b. In both samples, shear thinning behavior characterized the lowest density samples, until their density exceeded about 1,100 kg/m³. Above this density, Newtonian and shear thickening flow occurred until a shear rate of 6 Hz was achieved. This behavior is analyzed in detail in the following: Fig. 6a is a rheogram of diluted sample Alleppey #1–4 (density 1,118 kg/m³) which shows a change in behavior, from extreme shear thinning (pseudoplastic) flow to shear thickening (dilatant) flow between shear rates of 3 to 6 Hz, then shear thinning to the end of the run. Figure 6b is a log-log plot of the same data and shows the increase in apparent viscosity through this interval. Figure 7a is a rheogram from Alleppey #2–5 (density 1,161 kg/m³) and the corresponding log-log plot of the data is shown in Fig. 7b. Shear thickening behavior occurs between 3 and 12 Hz, after which shear thinning flow is characteristic. This change in behavior was observed in nearly all but the most diluted suspensions. Thus, the stress-rate of strain behavior of suspensions derived from the seabed appears to be quite different from that of the seabed itself.

The flow diagrams were constructed from analyses made in both accelerating and decelerating

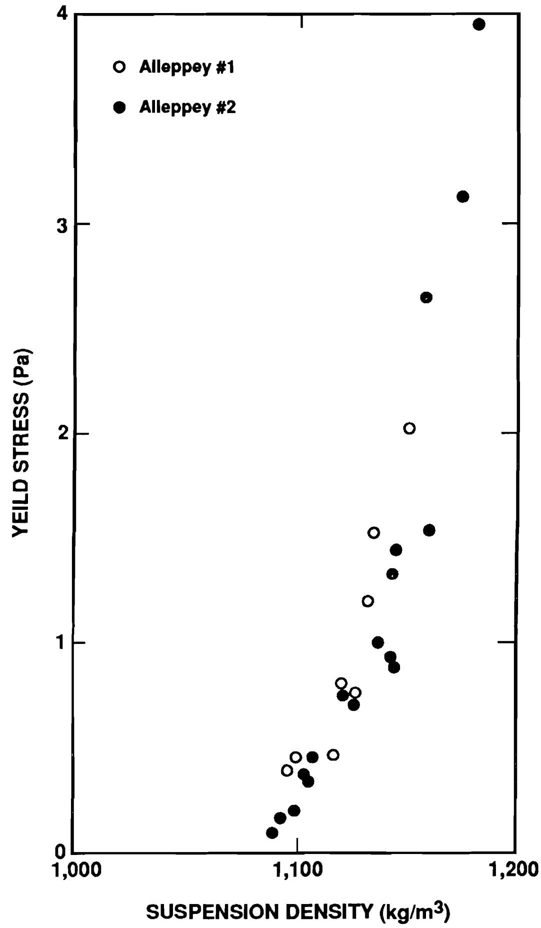

Figure 8. Plot of yield stress (measured at lowest possible shear rate) versus suspension density for both Alleppey #1 and Alleppey #2 samples.

shear rate modes to determine the presence of thixotropy. In addition, several samples were held at constant shear rate and measured each minute for five minutes to determine thixotropy (as seen by a decrease in shear stress). None of the samples showed evidence of thixotropic behavior.

Yield Stress

Upper Bingham yield stress measurements indicate that the typical non-linear relationship between yield stress and density exists for the Alleppey muds (Fig. 8). The greatest increase in yield stress occurs between 1,100 and 1,200 kg/m³. The figure suggests that the yield stress intercepts the X-axis at a density of about 1,080 kg/

m^3. Not surprisingly, this corresponds to the density that is attained by the hindered settling samples when they change from fluid-supported to grain-supported settling (Figures 2a and 2b). Consequently, no measurable yield stress can be expected to occur for at least 40 minutes of settling after a resuspension event. Extrapolation of the yield stress curve to the depositional density of the bed sample results in values between 4 to 5 Pa. No *in situ* bed shear strength measurements are available for comparison.

DISCUSSION

It is believed that the existence of mudbanks along the southwest coast of India is enhanced through the rheological behavior of the fluid mud suspensions comprising the mudbank. Contrasting behavior patterns are expressed between the soft bottom muds and suspensions generated from the bottom muds.

Specifically, fluid mud suspensions generated from the natural bottom mud tend to exhibit Newtonian and non-Newtonian (shear thickening) flow behaviors when densities become greater than 1,100 kg/m^3. This occurs early in the shearing cycle, generally between 2.5 to 10 RPM in the viscometer, and accompanied by low shear rates (1 to 6 Hz). Under these conditions, resuspension and transport are diminished and mud tends to remain in place. These conditions have been observed to occur in the Amazon coastal mud stream (KINEKE and STERNBERG, 1994), and the phenomenon appears linked to a continuous supply of suspended sediment so that the appropriate density can be achieved (FAAS, 1985; 1987).

The behavior of the natural Alleppey bottom, *i.e.*, the initial shear thinning interval indicates that, following the overcoming of sediment bottom yield strength by the hydrodynamic stress, resuspension and generation of near-bottom suspensions occurs easily and within a narrow range of shear stresses. Shear thickening of these muds will occur only following a significant loss of sediment, perhaps from the removal of a low-density flocculated layer overlying a more well-developed higher density layer. Organic effects, *e.g.*, bacterial and algal mucal secretions, may also play a role in this unusual sediment bed behavior since they should be expected to be present in significant quantities in the bed sediment (analysis of bed sediment indicates organic matter contents of 5%), but not in the suspensions.

Thus, a critical mechanism for creating the mudbank appears to be one which will generate a sufficient supply of sediment to achieve and maintain a density greater than 1,100 kg/m^3 before maximum shear stresses occur in order not to have the mud behave in a shear thinning fashion and be advected away. Mudbank occurrences on the west Indian coast are discontinuous, suggesting that the non-mudbank areas simply do not receive a sufficient amount of sediment to allow a shear thickening rheological response to applied shear stresses—rather, their behavior must follow that of lesser concentrated suspension, *i.e.*, shear thinning with consequent resuspension and transport from the environment.

It is recognized that critical elements in this process, *i.e.*, the nature, properties and processes which influence the rheological behavior of the natural sediment bed, has not been thoroughly studied and the conclusions of this paper are based on minimal data, *i.e.*, two analyses of only two samples from the sediment bed—a rather unstable foundation! Slurry samples pose no problem—they are naturally disturbed but still characteristic of the resuspended mudbank material. Since this paper suggests that rheological differences exist between the undisturbed sediment bed and the suspensions, it is imperative that research be focused on the natural, undisturbed sediment bed in order to adequately demonstrate these differences. Only then will it be possible to make unequivocal comparisons.

CONCLUSIONS

It seems reasonable to suggest that the mudbank exists, in part, because of the rheological behavior of the bottom sediment from which the suspended sedimentary material is derived. Release of material from the bottom during shear thinning behavior provides the dense suspension which comprises the mudbank. Once formed, the Newtonian and shear thickening behavior of the suspension under low shear stresses may be responsible for maintaining it as a discrete unit.

Once established, the mudbank becomes a stable entity within the high energy environment and creates conditions, through shear thickening, which reduce wave energy to a minimum through wave damping (MCPHERSON and KURUP, 1981). Hindered settling will occur within the low energy region, allowing for rapid accumulation of a deposit of fluid mud, possessing densities in excess of 1,100 kg/m^3. MATHEW *et al.* (1994) show suspended solids concentration profiles taken through the Alleppey mudbank, where nearbed concentrations exceed 174,000 mg/l (density 1,130 kg/m^3) and extend upward from the bottom for several meters, achieving concentrations of 200–400 mg/l two meters above the bottom and continuing to the surface.

During the waning phase of mudbank, the waves change their periodicity and energy, no longer supplying sufficient sediment to maintain the mudbank. This would allow greater turbulence to occur and would cause suspensions of lesser density to develop which would flow in a shear thinning fashion down the shelf gradient and accumulate on the bottom below the active wave base. There they would undergo self-weight consolidation, and form a semi-consolidated deposit which will become available for mudbank development in the following monsoon season. Thus, the cycle repeats itself and a new, longer term cycle of sedimentation is recognized, one which is annual in duration and perhaps capable of producing deposits which can be recognized in the geologic record.

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