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Rheological Control of Fine-Sediment Suspension, Cape Lookout Bight, North Carolina

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ABSTRACT

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Anoxic to hypoxic fluid muds are accumulating at average rates of 10 cm/yr in the central basin of Cape Lookout Bight, despite low suspended-sediment concentrations in the water column and periodically-energetic currents at the bed. Physical properties of the sediments, which are classified as "highly plastic inorganic clays" on the Casagrande Plasticity Chart, are remarkably uniform: median particle size ranges narrowly between 13 and 18 microns, organic contents between 9 and 15%, and silt/clay ratios between 3 and 6.

The rheological behavior of the muds, *i.e.*, low density yield stress development and, in particular, shear thickening (dilatant) behavior, act in such a way as to inhibit particle resuspension and retain sediment on the bed. XRD analysis of the clay-sized fraction indicates the presence of illite and kaolinite; however, SEM studies reveal that muds in the bight are not dominated by these clay minerals, but include significant quantities of silt-sized particles of quartz, feldspar, and mica with stepped surfaces and angular corners. A mechanically-interlocking fabric, together with an abundance of bacterial mucilage (which serves as a biological glue for macroaggregates in the water column), provide an explanation for the unusual rheological behavior and the retention of muds on the seabed.

ADDITIONAL INDEX WORDS: *Fluid muds, rheology, resuspension, retention.*

INTRODUCTION

Although sheltered from direct oceanic wave attack, estuarine, lagoonal, and backbarrier sediments often accumulate on seabeds that are neither below wave base during frequent winter storms nor subjected only to negligible fair-weather tidal currents. Much of the sediment that accumulates in these environments is mud and accumulation rates may be on the order of several centimeters per year with short-term deposition rates that are even higher (NICHOLS and BIGGS, 1985; NITTROUER and DeMASTER, 1986). The presence of fine-grained, cohesive sediments in energetic shallow-water environments has led to recognition of fundamental differences between cohesive and non-cohesive sediment properties and acceptance of the fact that cohesive sediments behave differently than non-cohesive sediments under the same conditions.

In this study we analyze the physical properties of fine-grained sediments accumulating in the periodically-energetic embayment of Cape Lookout Bight, North Carolina. Sediments in Cape Lookout Bight pose an interesting problem because they accumulate on the bottom at average rates of 10 cm/yr, despite the fact that particle concentrations in the overlying water column are typically less than about 30 mg/l and horizontal flux is believed to be low (WELLS, 1988). To achieve such rapid accumulation the vertical flux must be high (even though the sinking rate of individual silt- and clay-sized mineral grains is low), the bottom sediment must be resistant to resuspension, or both. Photographs of sediments in the water column show that large aggregates of "marine snow" are essentially always present and usually abundant in the bight, thus accelerating the vertical flux of sediment to the bottom (WELLS and SHANKS, 1987). Our present focus on the seabed suggests that the properties of the sediment substantially enhance its retention and that the sediment therefore exerts significant control over its ultimate fate.

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LOCATION AND ENVIRONMENT

Cape Lookout Bight is a shallow (7.5 m deep) embayed basin located at the southern end of the North Carolina Outer Banks island chain. Cape Lookout is the point of juncture between two barrier island limbs, oriented at right angles to each other and separated by a tidal inlet (Figure 1). Barden Inlet was opened by a hurricane in 1933, first dredged in 1938, and subsequently has widened at an average rate of 8.8 m/yr between 1940 and 1979 (DOLAN *et al.*, 1980).

Morphologic development of the bight through spit growth created the basin in which fine-grained sediments are rapidly accumulating. Approximately 1.6 km^2 of the bottom can be classified as anoxic to hypoxic fluid-like mud (WELLS, 1988; Figure 1). Methane generation, accompanied by bubble formation with upward migration, occurs from May to November (MARTENS *et al.*, 1986) and tends to inhibit normal compaction, thus keeping the sediment in a constantly remolded condition (FAAS and WARTEL, 1977). CHANTON *et al.* (1983) have shown that the upper meter of mud has accumulated at rates of 8.4 – 11.4 cm/yr and that thin well-sorted sand layers in the sediment column were deposited in association with known storm events. Box cores show that recent mixing of sediments by bioturbation is unimportant. Small polychaetes (<2cm), which col-

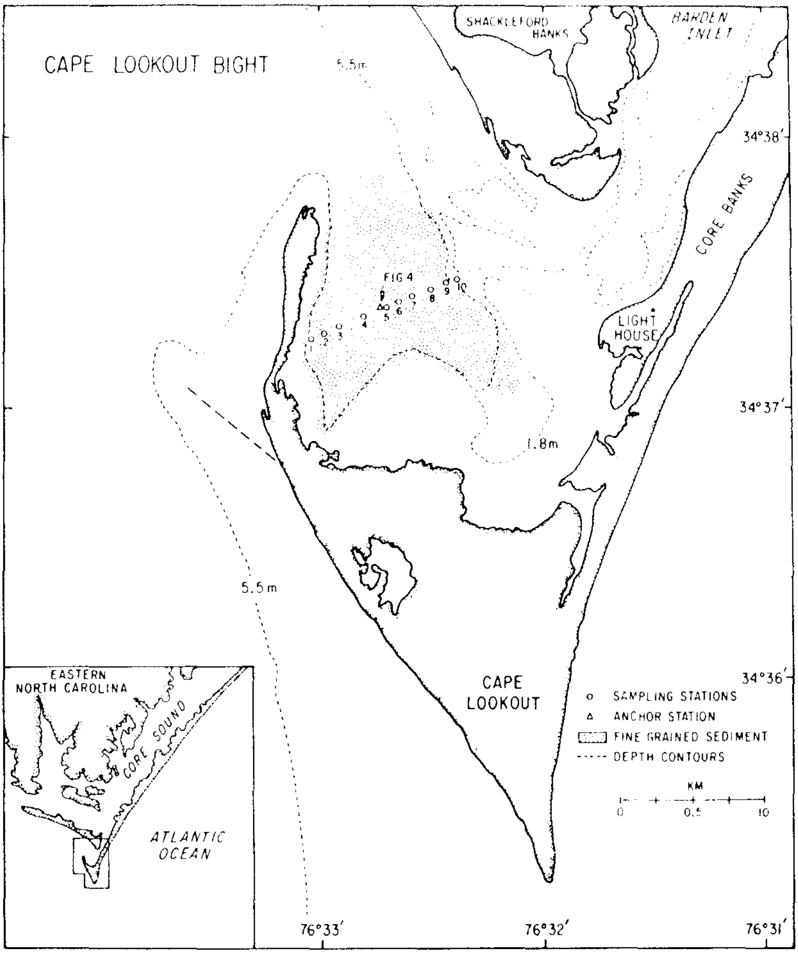

Figure 1. Cape Lookout Bight showing locations of sampling stations across fluid and deposit.

onize the upper few cm of the mud during February through May, are absent during the remainder of the year (BARTLETT, 1981) and do not significantly rework the sediments (MARTENS and KLUMP, 1984).

It appears that survival of mud in the central basin of Cape Lookout Bight can be attributed in part to the sheltering effect afforded by the geometry of the system. Enclosure of the bight from spit growth that began in the 1940s has provided a partial barrier to direct wave attack from the southwest. However, current meter records show that sheltering from wave attack has not led to a completely quiescent environment, but that intervals of relatively calm conditions are interrupted by strong tidal and wind-driven currents (WELLS, 1988). In fact, one of the most significant aspects of mud accumulation in Cape Lookout Bight is the relative energy level to which the surrounding barrier islands are exposed.

Statistical summaries show that winds of 15–20 m/s (30–40 kt) occur during every month of the year (AU, 1974), but that speeds are highest in fall and winter when "northeaster" storms dominate the regional weather patterns (PORTER, 1985). Mean annual wave height is 1.7 m on the inner shelf and wave heights of 2.0 m are exceeded 30% of the year (NUMMEDAL *et al.*, 1977). This section of the North Carolina coast experiences an average of 1.64 hurricanes per year (HERON *et al.*, 1984) and, overall, the Outer Banks experience one of the highest average levels of wave energy on the U.S. east coast (THOMPSON, 1977). Wave heights within the bight during northeaster storms and hurricanes are unknown.

Figure 2 is a plot of simultaneous observations of suspended sediment concentration and current speed taken 1 m above the bottom during four 25-hr anchor stations in the center of Cape Lookout Bight (Figure 1). Measurements were made using an InterOceans Systems, Inc. S4 electromagnetic current meter which recorded data every 0.5 s, then averaged over 1 min intervals every 5 min. The near-bottom currents, each represented in Figure 2 by a 15-min average computed once an hour from continuous 25-hr time series records, show no correlation with suspended-sediment concentration. Peak speeds are approximately 50 cm/s during spring tides and 25 cm/s during neap and intermediate phases of the tide. Variation in sediment concentration appears to be independent of current speed over the range of measurement from 5 cm/s to 50 cm/s. Either the soft muds in Cape Lookout Bight are resistant to resuspension over the observed range in near-bottom current speed, or the broad sampling interval of 1 hr failed to reveal subtle resuspension effects. It was the apparent lack of resuspension that provided us with the impetus to take a closer look at physical properties of the bed.

SEDIMENT CHARACTERISTICS

Character of the bottom sediment was determined by field and laboratory measurements from a southwest-northeast transect line across the center of the bight (Figure 1). Ten stations were established with an average spacing of 120 m between stations. Shear strength of the sediment at 15 cm and 30 cm depths was measured in situ with a hand-held, diver-operated shear vane that consisted of an 0.8-cm-diameter stainless steel shaft with two blades (2.54 × 2.54 cm) at right angles at the base of the shaft. The shear vane measures the torque which is exerted in the sediment as the sediment mass is sheared. Although the vane was calibrated before and after sampling, the values are relative rather than absolute since shear rate was uncontrolled.

Shallow cores (7.5 cm × 30 cm) were taken by a diver, capped, and returned to the surface for subsampling. Samples of the upper 10 cm were brought to the laboratory to determine sedimentological and rheological properties of the slurries. Particle size distribution was determined with a Bouyoucous 152H hydrometer (LAMBE, 1967), organic matter was computed through loss-on-ignition at 450° for 24 hr in a muffle furnace after salts were leached (DAVIES, 1974), and x-ray diffraction analysis was performed to determine clay mineralogy using a Phillips Norelco Diffractometer with Cu-alpha radiation (BISCAYE, 1965).

Bottom samples containing 50 g/l (initial density of 1.058 Mg/m^3) were thoroughly dispersed in a blender and allowed to flocculate and settle in one-liter graduated cylinders. Hindered settling of the flocculent interface occurred quite rapidly, with most samples achieving a density of 1.268 Mg/m^3 within one hour. Subsamples were taken from the settling tube at various

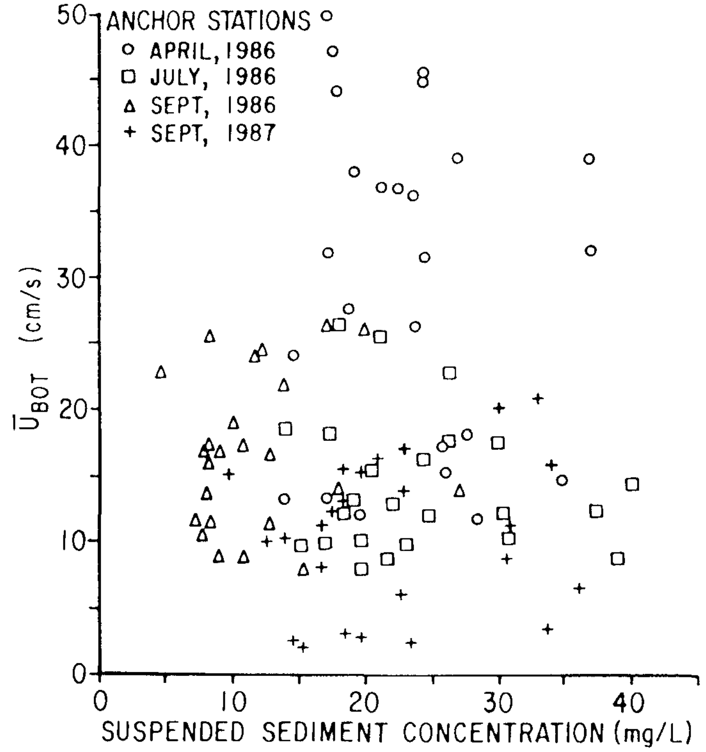

Figure 2. Simultaneous data on near-bottom current speed and suspended-sediment concentration. Measurement location shown in Figure 1.

intervals up to 2 hrs and analyzed in a Brookfield 8-speed rotational viscometer equipped with a special adaptor for low viscosity fluids. This adaptor is described in detail in the Technical Note which appears in this issue of this volume. Yield stress was determined directly by shearing the slurry at a low and constant rate (0.61 per s) to measure the stress-time response of the material. Under these controlled shear rate conditions, the shear stress will increase to a maximum value, to be followed by a decrease. This is considered to be the actual moment when flow begins and is recorded as the yield stress. Flow behavior was then determined by shearing the material at successively greater shear rates until the maximum was attained (122.36 per s). Torque values were recorded from which shear stress was calculated at each shear rate and flow diagrams were constructed. At the conclusion of the analysis, the slurry was poured from the adaptor cup into an aluminum moisture dish and placed in a drying oven at 105° C for 24 hr. After reweighing, the water content and the salt-corrected suspension density were determined.

Particle Size Distribution

Sediments accumulating inside Cape Lookout Bight are surprisingly uniform with respect to lithology and physical properties. Median diameters range narrowly between 13 and 18 microns, organic contents between 9 and 15%, and the silt/clay ratios between 3 and 6 (Figure 3). Samples can be classified as silt and clayey silt (SHEPARD, 1954) with the exception of sample #10, from the basin margin, which has a median diameter of 33 microns and contains 60% sand. Despite the uniform measures of central tendency, all samples are poorly sorted.

Cores show that the upper 80 cm of the sediment column contains approximately 90% mud

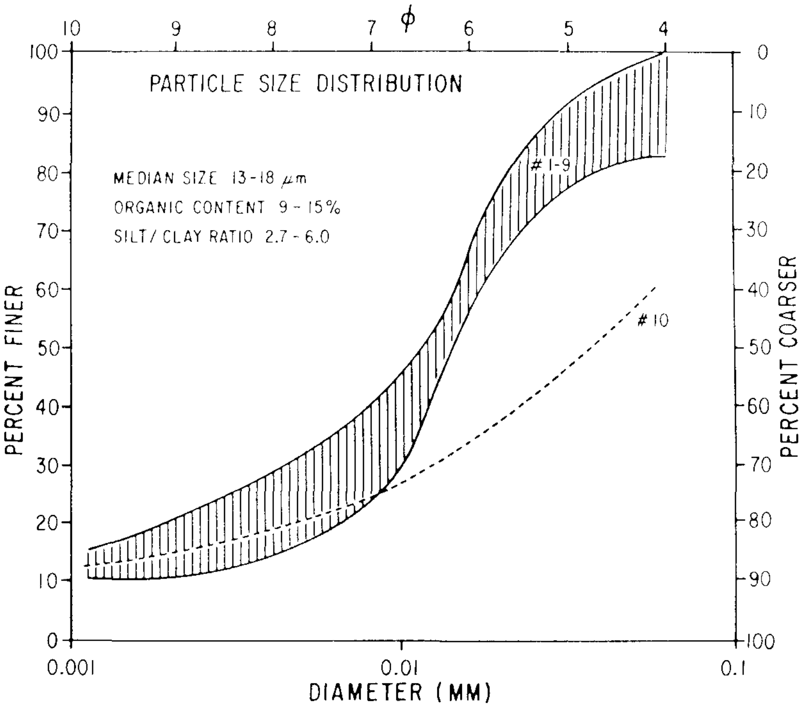

Figure 3. Particle size distributions of fluid mud deposit.

and 10% sand (WELLS, 1988). Sand content increases gradually from 1 m to a depth of 3 m where it reaches 90%. Numerous 1–3 cm thick, well-sorted sand layers are intercalated in the muds. CHANTON (1979) counted 13 sand layers in the upper 2.5 m of a core and, using ^{210}Pb geochronology, attributed them to instantaneous storm events, which had been previously documented. If accumulation rates of mud are on the order of 10 cm/yr, then an average of 1–2 storms every 2 years must be of sufficient intensity to transport significant quantities of sand to the center of the bight in order to form these laminations.

Water Content and Atterberg Limits

Figure 4A shows the values of the Atterberg Limits in surface samples. Liquid limit (w_L), the water content at which a sediment-water mixture ceases to behave as a liquid, is high at the seaward side of the bight, increases toward the basin center, then decreases abruptly toward the landward margin. In general, laboratory analyses of fine-grained sediment from different investigations indicate that soils possess shear strengths between 2.0 and 2.5 kPa at their liquid limit (MITCHELL, 1976).

Plastic limit (w_P), the water content at which the sediment-water mixture takes on characteristics of a brittle solid (no longer deformable), is nearly constant throughout the bight. Although variations in plastic limits are not easy to interpret, the well-defined lack of variation indicates a constant mineralogy of the fine fraction. The plasticity index (I_P), which parallels the liquid limit, is interesting because it shows that the sediments develop significant shear strength at water contents in excess of 150%, implying a resistance up to 2 kPa while in a very fluid state.

Figure 4B shows that sediments in Cape Lookout Bight may be classified as "highly plastic inorganic clays" on the Casagrande Plasticity Chart. Essentially no difference in plasticity is observed between samples, except sample #10 which exhibits surprisingly high plasticity inasmuch as it contains 60% sand.

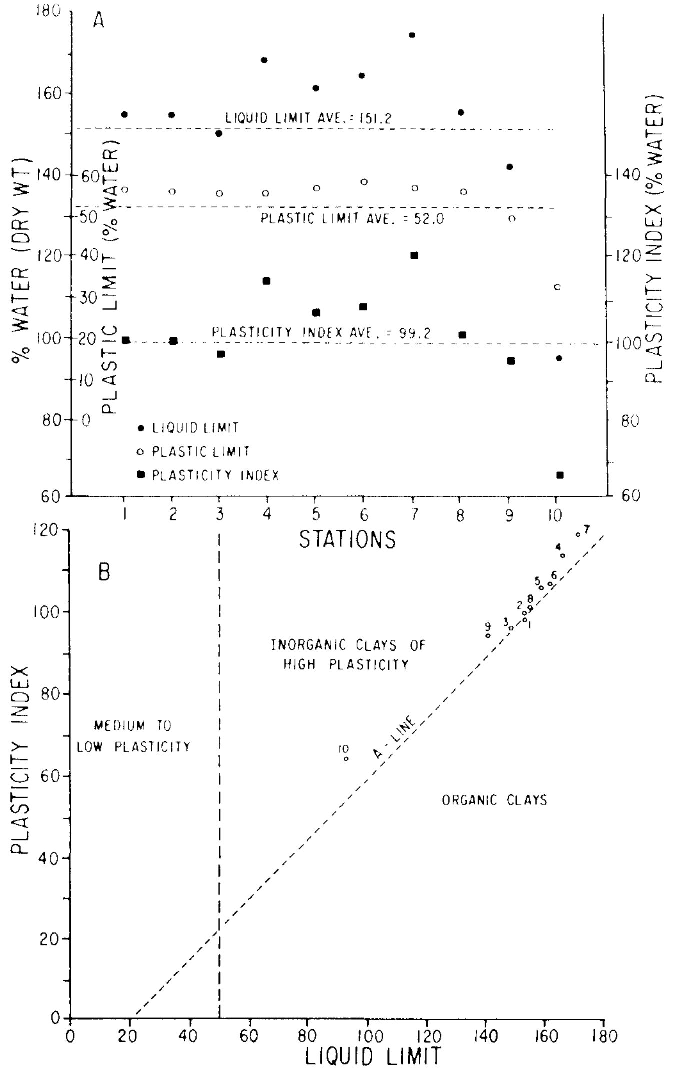

Figure 4. Profile of Atterberg limits across the basin (A); Casagrande Plasticity Chart (B).

Organic matter tends to increase the liquid limit of sediment (RASHID and BROWN, 1975; BUSCH and KELLER, 1981; BOOTH and DAHL, 1986) and the high liquid limits of samples from the bight (140%–180%) reflect this relationship; the liquid limit-organic content relationship compares favorably with lagoonal sediments from the Western Mediterranean and Brazil, and with sapropels from the Eastern Mediterranean (CHASSEFIERE, 1987). The fact that sediments are classified as "inorganic" appears to be a contradiction since they contain 9–15% organic material. The apparent contradiction stems from the fact that the plastic limit is low (average = 52%) and the plasticity index (range of water content through which the sediment exhibits plastic behavior) is quite large. SEED *et al.* (1964) have shown that increasing amounts of non-clay minerals in a soil tend to decrease the plastic limit whereas it is well known that organic matter increases the liquid limit and, to a much lesser extent, the plastic limit (ODELL *et al.*, 1960). Therefore, the classification "inorganic" should be considered a behavioral indicator which, in Cape Lookout Bight, reflects a high percentage of non-clay minerals (see SEM analyses in a later section).

In Situ Strength

In situ shear-vane profiles across the basin show nearly constant sediment strength of 2–3 kPa near the surface but greater and more variable strength at a depth of 30 cm (Figure 5). Whereas the upper 15 cm of sediment is very close to its liquid limit and can be considered to be in a fluid-like state, the greater values at depth (3–4 kPa) indicate greater strength (denser sediments due perhaps to an increase in sand content and greater consolidation near the basin margins).

Rheology and Yield Stress

Measurements of the yield stress and suspension density of Cape Lookout Bight slurries indicate that yield stress increases linearly with suspension density (Figure 6), reaching an extrapolated value of 0.14 kPa at 1.20 Mg/m^3. A composite flow diagram which shows the rheological behavior of 6 samples for one- and two-hour settling times, reveals several common patterns that characterize these samples (Figure 7). Each pattern exhibits non-Newtonian flow characteristics resulting from a lack of proportionality between the shear rate (rate of deformation of the material) and the shear stress (force applied to cause flowage). The steepened portion of the shear rate-shear stress curve shows shear-thickening (dilatant) behavior. Through this interval, the rate of shear increases less than in proportion to the shearing stress, the slurry becomes more viscous and flows less easily. The flatter portions of both ends of the curves indicate that the shear rate increases at a greater rate than the shear stress. The slurry is then offering only slight resistance to the shear stress, *i.e.*, becoming less viscous, in a form of behavior termed shear thinning (pseudoplastic).

IMPLICATIONS TO SEDIMENT RESUSPENSION

While recognizing the uncertainties involved in directly transferring behavior in the labo-

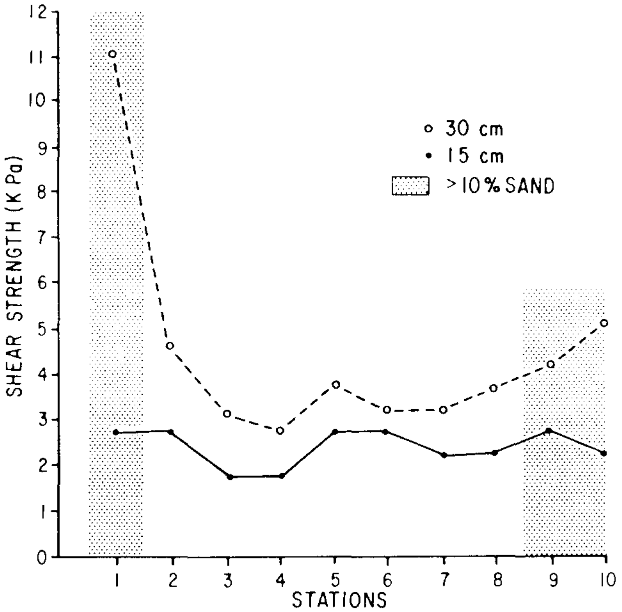

Figure 5. In situ shear-vane strength at 15 cm and 30 cm depths.

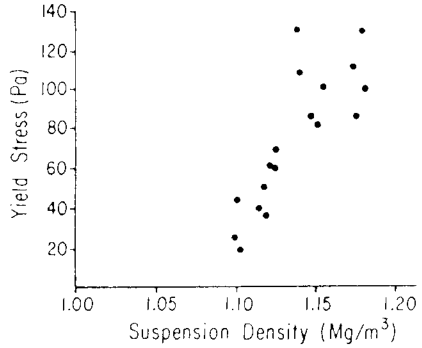

Figure 6. Yield stress versus suspension density for Cape Lookout Bight.

ratory to behavior in the field, we suggest that rheological behavior of the suspension, specifically the yield stress which increases with density, and the long interval of shear thickening flow behavior, may be responsible for keeping the muds in place in spite of the periodically energetic nature of Cape Lookout Bight. Shear thickening flow results from a parallel realignment of particles and the development of face-to-face fabric, possibly rigidly bonded together and possessing a lower water content and greater density. These conditions cause the suspension to exhibit an elastic response to shear (METZNER and WHITLOCK, 1958; UMEYA, 1970; MEWIS and SPAULL, 1976; MEWIS, 1980).

As a way of providing insight into the reasons for the shear thickening behavior, we have used the Scanning Electron Microscope (SEM) to take a closer look at the nature of the individual particles being sheared. For each SEM mount, a small quantity of natural sediment was heated to boiling for two hours in concentrated hydrogen peroxide to remove organic matter, filtered through a 0.45 micron Millipore membrane filter, rinsed thoroughly with distilled water, and allowed to air dry for 24 hours. A piece of the filter was mounted on an aluminum stub, carbon coated, and examined with an ISI Scanning Electron Microscope.

Figure 8 shows SEM photographs of individual particles. The particles can be classified under three types: single plates with sharp, angular corners and stepped surfaces; aggregates that display a high degree of surface roughness; and, platy aggregates that have at least one flat surface with significant surface texture. These particles are primarily silt-sized grains (Figure 3) and appear to be dominated by non-clay minerals such as quartz, feldspar, and mica (as suggested by cleavage surfaces and brittle conchoidal fracture surfaces). These larger grains control the shearing process and

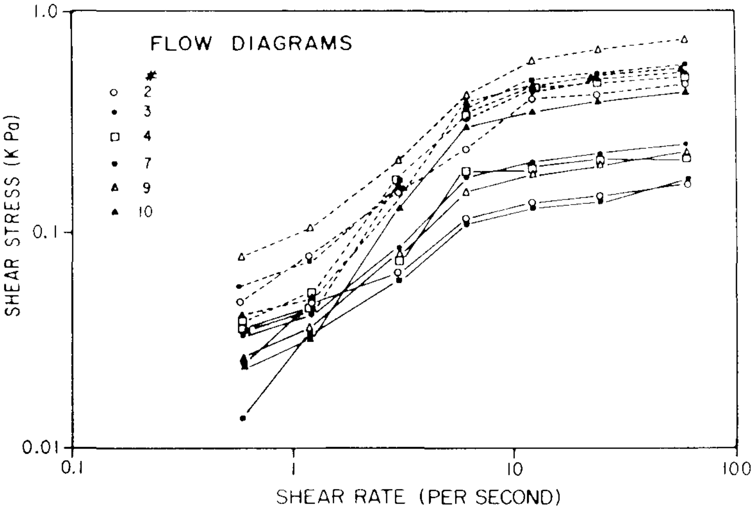

Figure 7. Flow diagrams from 1-hr settling (solid lines) and 2-hr settling (dashed lines) showing long interval of shear-thickening behavior between 1.2 and 8.0 s^{-1}.

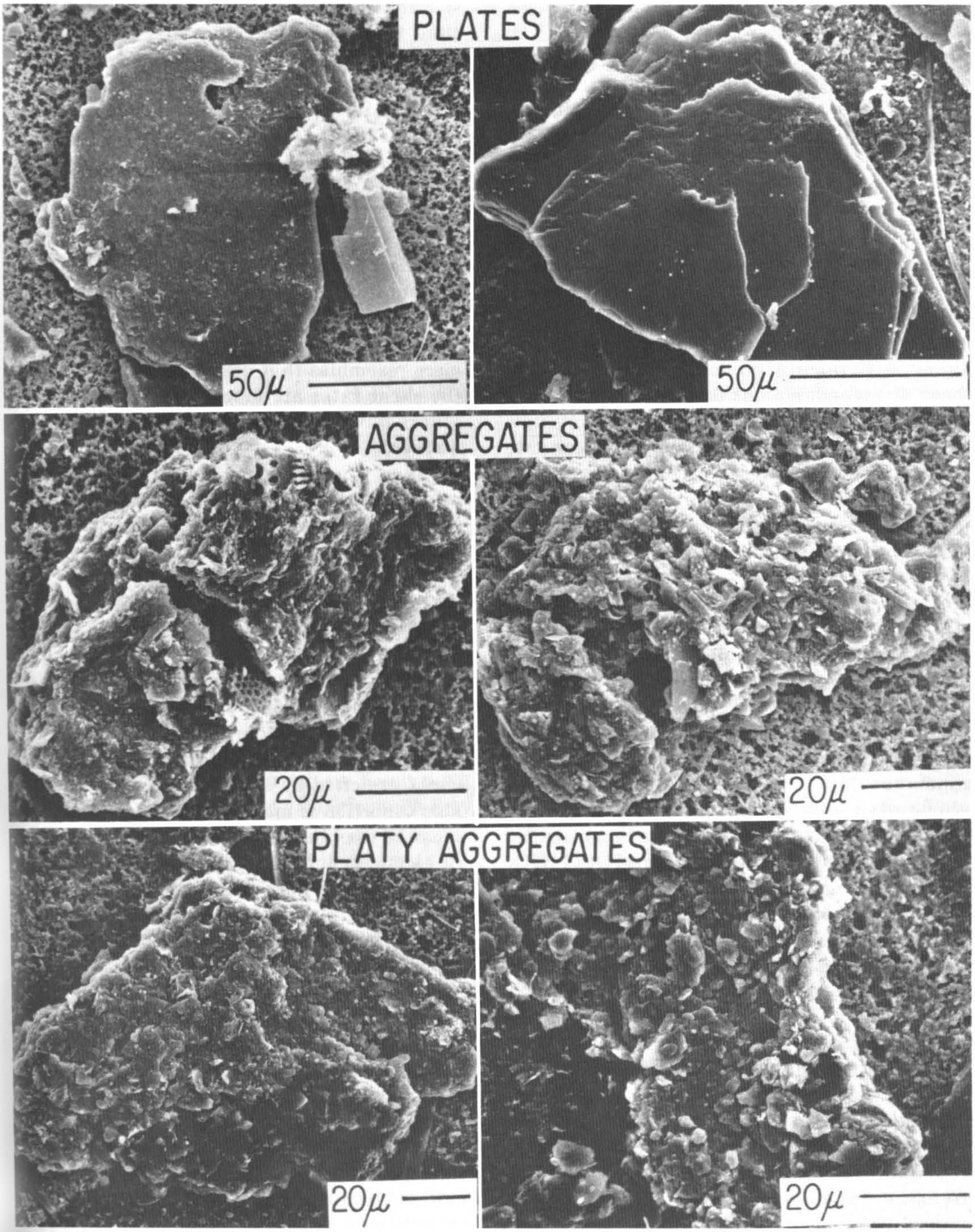

Figure 8. SEM photographs of bottom sediments showing plates with stepped surfaces and aggregates with rough surface texture.

effectively govern the rheological behavior. The general lack of clay minerals and clay-sized particles implies that physico-chemical (Van der Waals) bonding between the particles is minimal and that other processes provide internal strength to the sediment mass during shearing. One mechanism may be the mechanical interlocking of small mineral grains that have a rough surface texture and angular shape as shown by the SEM photographs.

The yield stress of the fluid-like mud (Figure 6) also serves to retain them in place until a shear stress greater than the yield stress is transmitted through the sediment. Consequently, a near-bottom deposit of density 1.15 Mg/m^3 will remain immobile until a critical shear stress, equivalent to approximately 0.10 kPa, is achieved. Since shear-thinning flow occurs initially only during a small shear-rate interval (0.5–1.2 per s, this early shear-thinning interval may be responsible for the observed low sediment concentrations in the water column (5–40 mg/l). In effect, the limited shear-thinning interval may represent the only time that material is resuspended during accelerating tides. Once resuspended, sediment remains in the water column until turbulent shear stresses have decreased to a level where settling of the particles again occurs.

In addition to mechanical interlocking, *in situ* yield stress may be enhanced by organic adhesives. Macroaggregates of marine snow which often dominate organic and inorganic sedimentation are generally bound together by organic mucus (ALLDREDGE and HARTWIG, 1986; ALLDREDGE and COHEN, 1987). JUMARS and NOWELL (1984) have suggested biological adhesives as a factor in increasing the level of shear stress required to initiate sediment resuspension on a flat, non-cohesive bed of abiotic sediment. Others (WEBB, 1959; FRANKEL and MEADE, 1973; RHOADES and BOYER, 1982) have hypothesized that the mucus produced by bacterial populations increases the shear strength and inhibits resuspension of surficial fine-grained sediments. Although the role of bacterial mucus in strengthening bottom sediments has not been quantified for Cape Lookout Bight, it has been firmly established that the glue for suspended sediments in the water column is a mucal polysaccharide (A.L. Shanks, *personal communication*). The result of this organic binding is to produce large aggregates that have settling speeds of 50–250 m/day and vertical flux sufficient to explain the occurrence of some fluid-like mud deposits (WELLS and SHANKS, 1987).

It is of interest to note that shear thickening (dilatant) behavior has also been described from experiments with high molecular weight polymers (VRAHOPOULOU and MCHUGH, 1987). Molecular entanglement, which forms during flow, is considered to be responsible for the dilatant behavior. At very high shear rates, the entanglement associations are destroyed and shear thinning flow behavior again resumes. The phenomena described with polymers resembles that described by us; however, the shear rates are much greater than we and others have observed in natural coastal environments.

Figure 9 is a diagram showing a model that relates particle behavior to rheological behavior during viscous shearing. Resistance to resuspension (shear thickening) is believed to occur when plates and platy aggregates are realigned from a loose honeycomb structure, dominated by large pore spaces, into a parallel face-to-face configuration. A low pore space, high density fabric then forms with mechanical interlocking of stepped surfaces and angular corners of silt-sized particles. Situations in which this may occur in high water content sediment are cited by MOON and HURST (1984). This condition is maintained until a maximum shear stress is exceeded which unlocks the fabric elements and destroys any molecular entanglements, at which time flow again becomes shear thinning and resuspension of dispersed single particles may occur.

The quadratic stress law provides a rough measure of shear velocities (u_*) and corresponding current speeds (1-m above the bed) that are required for sediment resuspension under given or assumed shear stresses. The shear velocities required for resuspension, even in the initial period of flocculated shear thinning (shear stresses 0.024–0.032 kPa) are 15–18 cm/s. This range of u_* values is achieved over a smooth bottom by minimum currents of 280–320 cm/s (assuming a drag coefficient of 0.003; DYER, 1986). Moreover, in order for shear thinning to again occur requires a shear stress of 0.3 kPa, a critical shear velocity of 54 cm/s and a U_{100} of nearly 10^3 cm/s. Even as order of magnitude

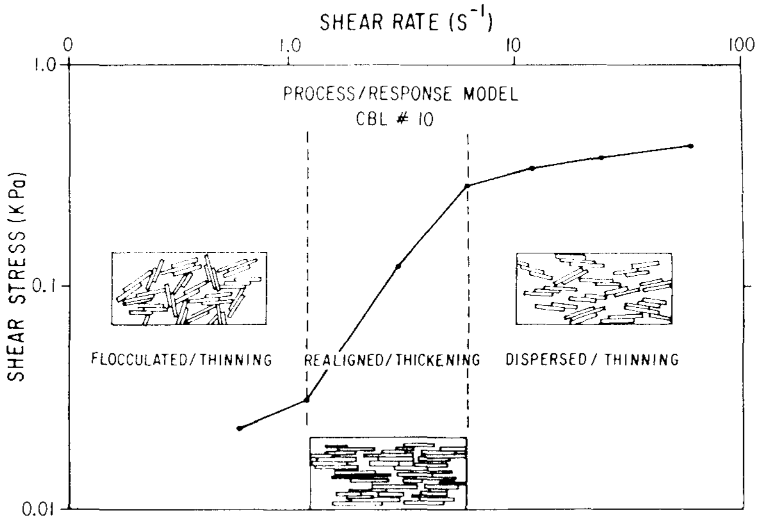

Figure 9. Model for particulate behavior, based on shear stress-shear rate relationships observed in sample #3 for 1-hr (solid) and 2-hr (open) settling times.

estimates these values are higher than are ever likely to be experienced in Cape Lookout Bight.

The strength of actual near-bottom currents, summarized from 4 sets of observations in Figure 2, is shown by peaks that reach 40–50 cm/s during spring tide and storms of 1–3 hr duration. Instantaneous currents (averaged over 1 min) are approximately 10% higher than the 15 min averages plotted in Figure 2. Although each set of observations provided a continuous record that was only 25 hr in duration, the observations covered a wide range of wind and tide conditions and are probably representative of the fairweather regime. Since currents exceeding 1 kt (50 cm/s) are probably unusual in Cape Lookout Bight, except perhaps during hurricanes, the sediments are likely to continue to accumulate and to remain in place as soft, highly resistant fluid-like muds.

CONCLUSIONS

Silt- and clay-sized particles that accumulate rapidly as anoxic to hypoxic fluid-like muds in Cape Lookout Bight are retained within the basin as a result of their rheological response to shear stresses. Specific characteristics, determined from laboratory tests, that may be responsible for making the sediment resistant to resuspension are: development of a density-dependent yield stress; a long shear-rate interval during which the sediments exhibit shear-thickening behavior; angular particles of silt-sized quartz, feldspar, and mica that may provide mechanical interlocking; and biogenic secretions that are ubiquitous in the water column of Cape Lookout Bight and provide a glue for binding the aggregates.

The broad implication of fluid-like muds in backbarrier environments is that they may behave in a fundamentally different fashion because of the high content of angular silt-sized particles derived from surrounding barrier islands. Mechanical interlocking of very small quartz grains and platy aggregates which have become face-to-face oriented under shear stresses and give rise to certain rheological responses, *e.g.* low-density yield stress and shear thickening flow behavior which favor sediment retention, may be more important in resisting resuspension than cohesive effects of similar-sized clay minerals derived from a terrigenous source.

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LITERATURE CITED

ALLDREDGE, A.L. and HARTWICK, E.O., 1986. Aggregate dynamics: Biological processes which form, alter, and destroy aggregates in the ocean. Aggregate Dynamics in the Sea. *Office of Naval Research Workshop Report*, Pacific Grove, California, pp. 109–130.

ALLDREDGE, A.L. and COHEN, Y., 1987. Can microscale chemical patches persist in the sea? Microelectrode study of marine snow, fecal pellets. *Science*, 235, 689–691.

AU, S.F., 1974. Vegetation and ecological processes on Shackleford Banks, North Carolina. *Monograph Series No. 6*, National Park Service, 86p.

BARTLETT, K.B., 1981. Seasonal variation in sulfate reduction and macrofaunal irrigation rates in an organic-rich coastal sediment. Unpublished M.S. Thesis, University of North Carolina, 222p.

BOOTH, J.S. and DAHL, A.G., 1986. A note on the relationships between organic matter and some geotechnical properties of a marine sediment. *Marine Geotechnology*, 6, 281–297.

BISCAYE, P.F., 1965. Mineralogy and sedimentation of deep sea clay in the Atlantic and adjacent oceans. *Bulletin of the Geological Society of America*, 76, 803–832.

BUSCH, W.H. and KELLER, G.H., 1981. The physical properties of Peru-Chile continental margin sediments–the influence of coastal upwelling on sediment properties. *Journal of Sedimentary Petrology*, 51, 705–719.

CHASSEFIERE, B., 1987. Mass-physical and geotechnical properties of superficial sediments of the lagoon of Guarapina-State of Rio de Janeiro-Brazil. *Marine Geotechnology*, 7, 275–288.

DAVIES, B.E., 1974. Loss-on-ignition as an estimate of soil organic matter. *Soil Science of America, Proceedings*, 38, 150.

CHANTON, J.P., 1979. Lead-210 geochronology in a changing coastal environment: Cape Lookout Bight, North Carolina. Unpublished M.S. Thesis, University of North Carolina, 85p.

CHANTON, J.P.; MARTENS, C.H., and KIPPHUT, G.W., 1983. Lead-210 sediment geochronology in a changing coastal environment. *Geochimica Cosmochimica Acta*, 47, 1719–1804.

DOLAN, R.; HAYDEN, B.; REA, C., and HEYWOOD, J.E., 1980. Erosion at Cape Lookout: will the lighthouse fall? *Shore and Beach*, 48, 13–20.

DYER, K.R., 1986. *Coastal and Estuarine Sediment Dynamics*. New York: Wiley, 342p.

FAAS, R.W. and WARTEL, S., 1977. The effect of gas bubble formation on the physical properties of recently deposited fine-grained sediments. *Geologie en Mijnbouw*, 56, 211–218.

FRANKEL, L. and MEADE, R.J., 1973. Mucilaginous matrix of some estuarine sands of Connecticut. *Journal of Sedimentary Petrology*, 43, 1090–1095.

HERON, S.D., Jr.; MOSLOW, T.F.; BERELSON, W.M.; HERBERT, J.R.; STEELE, G.A., III, and SUSMAN, K.R., 1984. Holocene sedimentation of a wave-dominated barrier-island shoreline: Cape Lookout, North Carolina. *Marine Geology*, 60, 413–434.

JUMARS, P.A. and NOWELL, A.R.M., 1984. Effects of benthos on sediment transport: difficulties with functional grouping. *Continental Shelf Research*, 3, 115–130.

LAMBE, W.T., 1967. *Soil Testing for Engineers*. New York: Wiley, 165p.

MARTENS, C.S. and KLUMP, J.V., 1984. Biogeochemical cycling in an organic-rich coastal marine basin. 4: An organic carbon budget for sediments dominated by sulfate reduction and methanogenesis. *Geochimica Cosmochimica Acta*, 48, 1987–2004.

MARTENS, C.S.; BLAIR, N.E.; GREEN, C.D., and DES MARAIS, D.J., 1986. Seasonal variations in the stable carbon isotopic signatures of biogenic methane in a coastal sediment. *Science*, 233, 1300–1303.

METZNER, A.B. and WHITLOCK, M., 1958. Flow behavior of concentrated (dilatant) suspensions. *Transactions of the Society of Rheology*, II, 239–251.

MEWIS, J., 1980. Rheology of suspensions. *In:* Astarita, G., Marrucci, G. and Nicolais, L. (eds.), *Rheology, v. 1, Principles*, New York: Plenum, pp. 149–168.

MEWIS, J. and SPAULL, A.J.B., 1976. Rheology of concentrated dispersions. *Advances in Colloid and Interface Science*, 6, 173–200.

MITCHELL, J.K., 1976. *Fundamentals of Soil Behavior*, New York: Wiley, 422p.

MOON, C.F. and HURST, C.W., 1984. Fabric of muds and shales: an overview. *In:* Stow, D.A.V. and Piper, D.J.W. (eds.), *Fine-Grained Sediments: Deep-Water Processes and Facies*, London: Blackwell, pp. 579–593.

NICHOLS, M.M. and BIGGS, R.B., 1985. Estuaries. *In:* Davis, R.A. (ed.), *Coastal Sedimentary Environments*. New York: Springer-Verlag, pp. 77–185.

NITTROUER, C.A. and DeMASTER, D.J., 1986. Sedimentary processes on the Amazon continental shelf: past, present and future research. *Continental Shelf Research*, 6, 5–30.

NUMMEDAL, D.; OERTEL, G.F.; HUBBARD, D.K., and HINE, A.C., III, 1977. Tidal inlet variability. *Proceedings, Coastal Sediments '77* (Charleston, South Carolina).

ODELL, R.T.; THORNBURN, T.W., and MCKENZIE, L.G., 1960. Relationship of Atterberg Limits to some other properties of Illinois soils. *Soil Science of America, Proceedings*, 24, 297–300.

PORTER, H.J., 1985. Three year environmental atlas (1979–1980). *Special Publication*, Institute of Marine Sciences, University of North Carolina at Chapel Hill, 86p.

RASHID, M.A. and BROWN, J.D., 1975. Influence of marine organic compounds on the engineering properties of a remolded sediment. *Engineering Geology*, 9, 141–154.

RHOADES, D.C. and BOYER, L.F., 1982. The effects of marine benthos on physical properties of sediments: a successional perspective. *In:* McCall, P.L. and Tevesz, M.J.S. (eds.), *Animal-Sediment Relations: The Biogenic Alteration of Sediments*. New York: Plenum, pp. 3–52.

SEED, H.B.; WOODWARD, R.J., and LUNDGREN, R., 1964. Fundamental aspects of the Atterberg Limits. *Journal of Soil Mechanics and Foundations Division*, American Society of Civil Engineers, 90, 107–131.

SHEPARD, F.P., 1954. Nomenclature based on sand-silt-clay ratios. *Journal of Sedimentary Petrology*, 24, 151–158.

THOMPSON, E.F., 1977. Wave climate at selected locations along U.S. coasts. *Report Number 77-1*, Coastal Engineering Research Center, U.S. Army Corps of Engineers, 364p.

UMEYA, K., 1970. On the dilatant behavior of some suspensions. *In:* Onogi, E.S. (ed.), *5th International Congress on Rheology* (Tokyo, Japan) pp. 295–308.

VRAHOPOULOU, E.P. and MCHUGH, A.J., 1987. Shear-thickening and structure formation in polymer solutions. *Journal of Non-Newtonian Fluid Mechanics*, 25, 157–175.

WEBB, J.E., 1969. Biologically significant properties of submerged marine sands. *Proceedings of the Royal Society of London, Serial B*, 174, 355–402.

WELLS, J.T., 1988. Accumulation of fine-grained sediments in a periodically energetic clastic environment, Cape Lookout Bight, North Carolina. *Journal of Sedimentary Petrology*, 58, 596–606.

WELLS, J.T. and SHANKS, A.L., 1987. Observations and geologic significance of marine snow in a shallow-water, partially-enclosed marine embayment. *Journal of Geophysical Research*, 92, 13, 185–13, 190.

□ RÉSUMÉ □

Dans le bassin central de Cape Lookout Bight, des vases fluides anoxiques à hypoxiques s'accumulent à une vitesse moyenne de 10cm/an, ce, en dépit des faibles concentrations de sédiments en suspension dans la tranche d'eau, et malgré les courants à énergie périodique de fond. Les propriétés physiques de sédiments qui sont classés comme “argiles inorganiques fortement plastiques” dans la charte de plasticité de Casa Grabde, sont remarquablement uniformes: la taille de la particule médiane est comprise entre 13 et 18 microns, les teneurs en particules organiques représentent entre 5 et 15%, et le rapport silt/argile est compris entre 3 et 6. Le comportement rhéologique des vases conduit à inhiber la resuspension des particules et à retenir les sédiments sur le lit. Une analyse de la fraction argileuse aux rayons X indique la présence d'illite et de kaolinite, pourtant, la spectrographie électromagnétique révèle que ces minéraux argileux ne dominent pas dans la vase de l'anse; ils comprennent une quantité significative silteuse de quartz, feldspaths et micas. On peut expliquer ce comportement rhéologique inhabituel et la rétention de vase sur le fond par une structure emboitée avec abondance de mucilage bactérien (servant de colle biologique aux macro-agrégats de la tranche d'eau).—*Catherine Bressolier (Géomorphologie EPHE, Montrouge, France).*

□ RESUMEN □

Los fluídos anaerobios o con pequeños contenidos de oxígeno se acumulan a una media de 10 cm/año en la laguna central de Cape Lookout Bight, a pesar de las bajas concentraciones de sedimento en suspensión y de las corientes, relevantes, periódicamente, en el lecho. Las propiedades físicas de los sedimentos, clasificados como “arcillas inorgánicas de alta plasticidad” según la tabla de plasticidad de Casagrande, son notablemente uniformes: partículas de tamaño medio en una estrecha banda de entre 13 y 18 micras, contenidos en materia orgánica entre 9 y 15% y relaciones limo/arcilla entre 3 y 6. El comportamiento reológico de los lodos, es decir, la baja desidad debida a la aparición de tensiones, en particular el esponjamiento debido a tensiones tangenciales, actúa de manera que evita la suspensión y retiene sedimentos en el lecho. El análisis de Rayos X de la fracción arcillosa refleja la presencia de illita y caolinita; de todas marenas, el estudio SEM revela que en los lodos de esta cala no son dominantes estos minerales arcillosos, pero contienen cantidades importantes de cuarzo, feldespato y mica de tamaño limoso, con superficies quebradas y vértices angulosos. Una malla de engranajes mecánicos, unido a la abundancia be mucílagos bacterianos (que sirven como adhesivo biológico para macroagregados en la columna de agua), sirce como explicación de la extraña conducta reológica y la retención de lodos en el lecho marino.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

□ ZUSAMMENFASSUNG □

Die Schlicksedimentationsrate im zentralen Becken der Cape Lookout Bight beträgt durchschnittlich 10 cm/a. Diese Sedimentationsrate des z.T. mit Sauerstoff gesättigten, z.T. untersättigten Schlicks ist indofern erstaunlich, als im Wasser nur eine geringe Menge suspendierter Sedimentfracht gemessen wurde und periodisch energiereiche Strömungen das Ablagerungsbett beeinflussen. Die physikalischen Eigenschaften der Sedimente sind bemerkenswert einheitlich: die anhand der “Casagrande Plasticity Chart” als “hochplastische anorganische Tone” eingestuften Ablagerungen haben eine Korngröße, die zwischen 0,013 und 0,018 mm liegt, der Gehalt organischer Substanz beträgt 9-15% und das Schluff/Ton-Verhältnis liegt zwischen 3 und 6. Das Fließverhalten des Schlicks bewirkt, daß i.w. keine Resuspendierung stattfindet und das Sediment am Boden gehalten wird. Röntgendiffraktometrische Analysen der Tonfraktion belegen die Existenz von Illit und Kaolinit; rasterelektronenmikroskopische Aufnahmen zeigen, daß diese beiden Tonminerale nicht dominieren, dafür aber signifikant hohe Gehalte von Quarz, Feldspat und Glimmer existieren. Diese Komponenten liegen in der Korngrößenfraktion Schluff; die Glimmer sind durch eine getreppte Oberfläche und kantige Ecken charakterisiert. Das ungewöhnliche Fließverhalten des Schlicks und die starke Bodenhaftung kann u.U. durch die Tatsache erklärt werden, daß hier eine Matrix existiert, die—in Verbindung mit einem biologischen “Kleber” aus Bakterienschleim für die Makroaggregate—auf mechanischem Wege stark zusammenhaltend wirkt.—*Ulrich Radkte, Geographisches Institut, Universität Düsseldorf, F.R.G.*