Use of an Instrumented Tripod System to Examine Sediment Dynamics and Fine-Scale Strata Formation in Muddy Surfzone and Nearshore Environments

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ABSTRACT

A prototype instrumented tripod system designed for quantifying physical processes in muddy surfzone and nearshore regions was tested on tidal flats north of the Amazon River mouth. Physical data (i.e., wave characteristics, current velocities, suspended-sediment concentrations and seabed characteristics) recorded during a 14-hr deployment at 1.35 m water depth on this energetic, non-barred, fine-grained deposit demonstrate the value of this system to make field observations of sediment dynamics over an underconsolidated cohesive boundary. Significant sediment transport is occurring via resuspension of fine-grained particles and aggregates by wave-induced velocities up to 100 cm sec⁻¹. Tidal currents (0–3.5 cm sec⁻¹) are shore-normal with a low-frequency (residual) component advecting material alongshore. Physical data are supported by simultaneous coring which allows documentation of reworking for the uppermost seabed over a semi-diurnal tidal cycle. A fluid-mud layer (~10 cm) thick covers the "seabed" and changes in density and thickness with varying benthic shear stress. Muddy deposits accumulating in this setting are composed of physically stratified laminations of silt/clay (~1 to 4 cm-scale), cohesive-bed response to variable bottom stress. Field measurements are necessary to corroborate and refine existing models, and to provide a fundamental understanding of sedimentary responses that may not be possible in the laboratory. Pioneering work on the mudflats of Surinam (Wells, 1977; Wells and Coleman, 1981) demonstrated the value of quantitative field measurements by observing significant wave-induced sediment transport over an underconsolidated, cohesive seabed. Specific problems that need to be addressed include: (1) threshold characteristics of mud beds (e.g., critical erosional shear stresses, settling velocities of particles and aggregates); (2) erosion of soft mud by waves; (3) formation and transport mechanisms of fluid mud layers; and (4) the behavior and origin in the near-
bed of coarse particles in a predominantly fine-grained setting.

Quantitative predictive tools are also imperative to an understanding of strata formation in muddy depositional settings. Collection of time-series physical data and simultaneous coring at deployment sites permit an examination of process-response mechanisms controlling the formation of stratification in the seabed and enables time-scales to be inferred for the stratigraphy observed. This approach has been under-utilized and has great potential for the interpretation of mud-rock paleo-environments.

Physical data were collected using an instrumented tripod system developed for use on the mudflats of northern Brazil, as part of AMASSEDS: A Multidisciplinary Amazon Shelf SEDiment Study (AMASSEDS Research Group, 1990). The data are being used to address fundamental questions regarding controls on high-concentration suspended-sediment transport and fine-scale strata formation in cohesive sediment. This research was motivated by a need for quantitative physical measurements over underconsolidated muddy seabeds. Advances in instrument design have produced a variety of small, portable sensors applicable to the study of high-concentration suspensions and soft mud beds. These include electromagnetic current meters, optical backscatterance sensors, differential pressure transducers, accelerometers and gamma-ray density probes. Valuable use has been made of these sensors in multi-instrument bottom-deployed and profiling systems in estuarine and shelf settings (Caccione and Drake, 1979; Sternberg et al., 1986; Nichols, 1989) as well as sandy beach and nearshore environments (Beach and Sternberg, 1988; Greenwood et al., 1991; Wright et al., 1991). However, application of these instruments to muddy “beach” and nearshore (<5 m water depth) environments has been limited.

Muddy, non-barred coastlines provide a unique opportunity to examine the sediment response of “cohesive boundaries” (Parker, 1989) when physical stresses are applied. Typically, these open coastal environments are associated with major rivers (e.g., Amazon, Changjiang, Huanghe, Mississippi-Atchafalaya). Large river dispersal systems are characterized by variations (both spatial and temporal) in wave and current stresses. Temporal variations occurring on time-scales that range from individual wave periods to tidal cycles (semi-diurnal, spring-neap) to long-term (seasonal and longer) changes allow examination of the response for a given bed under a wide variety of energy conditions. Underconsolidated muddy seabeds and transitional fluid-mud layers (10–400 g L⁻¹) associated with rapid deposition are frequently found in these open coastal settings (Wells, 1983). Field measurements collected in such accretionary settings are readily applicable to the study of fluid-mud dynamics in harbors, estuaries and muddy shelves. Direct access to the seabed in shallow coastal environments allows for precise siting of instruments in the boundary layer. They can be deployed on a stable platform with close monitoring capability for periodic data retrieval which allows for high-frequency sampling and long time-series without large power requirements.

**EXPERIMENTAL METHODS**

**Instrumentation**

A number of requirements for working in muddy surf zones were considered in the instrumented tripod designed for this study:

1. **Stability.** A rigid platform is a necessity; not subject to settling in a soft and unstable seabed. The design must be capable of withstanding wave heights of 1–3 m and currents in excess of 150 cm sec⁻¹ without significant structural motion or scour.

2. **Portability.** The tripod and instrument package must be designed for rapid deployment from small boats. Instrument deployment in a surf zone requires installation and removal during the brief periods of minimal wave and current conditions.

3. **Unimpeded Flow.** The design must have minimal flow alteration in the vicinity of sensors.

4. **High-Frequency Sampling.** Rapid sampling capability (>1 Hz) is necessary in order to record short-period effects, such as sediment injection into the boundary layer with wave passage.

5. **Datalogging Capacity.** Memory storage extending over at least a semi-diurnal tidal cycle is necessary to examine tidal effects. Synchronous instrument sampling provided by the datalogger is imperative for examination of short-period events.

The prototype tripod design is illustrated in Figure 1. Galvanized pipes (4 cm diameter, 7 m in length) were driven into the seabed with the assistance of divers to a depth of 3.5 m. This tri-
angular design provided a stable foundation in consolidated muds underlying soft surface mud. The tripod "legs" were predrilled and linked together on site by 2-m-length crosspieces of the same material. To facilitate instrument mounting a second horizontal member spanned the seaward face 50 cm below the primary crosspiece. The prototype was designed to be deployed at low tide in 1–1.5 m water depth. Adjustment of the crosspiece level allows the prototype to be used in water depths (at low tide) ranging from 0 to 3 m. Deeper settings necessitate use of longer vertical members.

The prototype was deployed with the instruments listed in Table 1. Detailed specifications and calibration procedures for the current meter, OBS sensors, and CTD/datalogger may be found in Sternberg et al. (1991); Kineke and Sternberg (1992).

Instruments were mounted on the framework with hose clamps and powered by a 18 VDC, 30 AH battery. Power and signals were interfaced with a passive interconnection junction point also mounted on the frame. Sampling frequency for the prototype experiment was 0.935 Hz with 10-min bursts separated by 20-min intervals. Memory capacity (960K) allowed storage of 31 bursts of 10 different channels, sufficient to record a low-high-low tidal cycle. The CTD/datalogger was pre-programmed several hours prior to travel to the site. The entire instrument package and structure was mounted and deployed in less than 1.5 hr working from small boats.

Table 1. Instruments deployed in the prototype experiment.

<table>
<thead>
<tr>
<th>Instrument Type</th>
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<tr>
<td>CTD/Datalogger. An Ocean Sensors Model OS100 recorded temperature, conductivity and changing water depth due to wave and tidal motion. The CTD was deployed at $z = 70$ cm. The OS100 has a 14-bit resolution A/D converter and an internal memory (960K) and is capable of recording up to 8 external channels.</td>
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<tr>
<td>OBS Sensors. Two optical backscatterance sensors, made by D&amp;A Instruments, were deployed at $z = 1$ cm (within the fluid-mud layer and above the surface of a consolidated mud layer) and $z = 98$ cm, to measure suspended-sediment concentration. These sensors are capable of measuring particle concentrations from 5 mg l$^{-1}$ up to 300 g l$^{-1}$ (Downing et al., 1981; Kineke and Sternberg (1992)).</td>
</tr>
<tr>
<td>Current Meter. A Marsh-McBirney Model 512 electromagnetic current meter (4.5 cm diameter) was mounted at $z = 85$ cm, with the x-component oriented alongshore and the y-component offshore. This EM current meter is effective at current velocities up to 300 cm s$^{-1}$.</td>
</tr>
<tr>
<td>Pressure Transducer. A Genisco Tech differential pressure transducer ($\pm 5$ PSI) was deployed with entrance ports at $z = 1$ and 100 cm to measure density variations in the near-bed portion of the water column and within the surface mud layer.</td>
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<tr>
<td>Acoustic altimeter. A Datasonics model PSA-900 sonar altimeter (210 kHz) was deployed at $z = 105$ cm to record bed-level changes in response to erosion/deposition events.</td>
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Prototype Instrumented Tripod

Sediment cores were obtained during the 15 hr deployment using 2.5 x 10 cm plexiglass pushcore trays 70 cm long. These trays were examined by x-radiography for changes in fine-scale stratigraphy in the uppermost seabed, and the changes were correlated to physical data. Detailed micro-stratigraphic examination of selected intervals was performed using the thin-sectioning techniques of KUEHL et al. (1988). A 7-m vibracore (7.5 cm diameter) was taken at the tripod site for examination of long-term stratigraphy.

Setting

The instrumented tripod prototype was deployed on the mudflats of northern Brazil, 250 km north of the Amazon River mouth (Figure 1). This region is a prograding, muddy shoreline characterized by soft, low-gradient, mudflats backed by mangrove swamps (NETTROUER et al., 1991). The tripod system was deployed in late October, 1991, a period of low Amazon River discharge, when the mudflats were in an erosional phase (ALLISON et al., in press). Suspended sediment discharged from the Amazon is swept to the northwest by prevailing shelf currents at velocities reaching in excess of 50 cm sec^{-1} (CURTIN, 1986; GEYER et al., 1991). A seasonally variable band of low-salinity, high-turbidity (up to several hundred mg l^{-1}) water is present along the coastline. Mean tidal range is 2-3 m in the area of instrument deployment. The deployment occurred four days after spring tide in the shallow subtidal (1-3.5 m water depth; Figure 2). Persistent trade-winds blow from the northeast to southeast quarter in October with mean monthly wind stress 0.5-1 dyne cm^{-2} (PIERCEY et al., 1985). Waves incident along this coastline average 0.5-1 m height and 6-7 sec period (Meserve, 1974).

RESULTS AND INTERPRETATION

Instrument data were recorded over a 15-hr period. All the instruments except the lower OBS sensor were out of the water for 2-4 bursts during maximum low tide. Sediment intermittently plugged the entrance port on the differential pressure transducer, rendering some of that sensor's information unreliable; otherwise, instrument performance was excellent. Water depth varied from 0.8 to 3.3 m over the tidal cycle (Figure 2).

Figure 3 shows a 250-sec burst record of eight different physical parameters collected during late flood tide. Note particularly the effect of wave passage on suspended-sediment concentrations as material eroded from the bed was injected into the water column. This phenomenon was most apparent on burst records during passage of large waves, such as those at 160 and 220 sec (Figure 3).
3). Sediment resuspension events were immediately recorded by the lower optical sensor located within the fluid mud (z = 1 cm), followed by a return to pre-wave levels 1–3 sec later. An increase in sediment concentration often occurs 5–10 sec later at the water-column sensor (z = 98 cm). This pluming of sediment was visible as cauliflower-shaped clouds of turbid water several meters in...
diameter rising to the surface. OBS and current-meter records and visual observations indicate these plumes were rapidly dispersed by turbulence and/or tidal current shear. The inverse behavior of the upper and lower OBS is discussed below.

These data suggest that strong oscillatory shear stresses erode the seabed and resuspend sediment into the fluid-mud boundary layer. Turbulence can then release this material into the water column. Sediment rapidly settles out of the fluid-mud boundary layer following wave passage, indicating large flocs are predominant. Under ambient wave conditions (wave approach from WSW; H < 1 m; 7 sec^-1 period), oscillatory currents produced by these "solitary-like" dissipative waves (Wells and Coleman, 1981) are nearly unidirectional (landward). Burst-averaged onshore flow induced by waves was 7.1 cm sec^-1 during the deployment. Resuspension generates a net onshore sediment transport of flocs in the near-bed (0–5 cm). This supports observations in Surinam that solitary wave-induced currents are a primary mechanism for resuspension and transport of fine-grained sediment on underconsolidated mudflats (Wells and Coleman, 1981).

Tidal currents (0–35 cm sec^-1) were somewhat rectilinear with a shore-normal major axis. Peak currents occurred at middle flood phase. A broad current maximum was associated with the subsequent ebb phase (Figure 2). A residual current of 6 cm sec^-1, oriented to the northeast (alongshore), may indicate the presence of an unresolved low-frequency component. Co-spectral analysis of current meter and OBS (upper) data indicate that tidal currents account for >97% of the sediment concentrations measured during the deployment period. This suggests that volumetrically significant sediment transport by solitary waves is confined to the near-bed.

Surficial sediment at the tripod site is a silty clay (Figure 4) containing less than 1% sand. Grain-size distribution is unimodal and does not vary significantly on the mudflat, indicating derivation from a single source (i.e., Amazon River suspended sediment). Sand supply is variable and originates from local rivers draining the highly weathered coastal plain and Precambrian basement rocks to the west (Allison et al., in press). Total organic carbon is typically 0.6–0.8%, and the unstable seabed and high benthic shear stresses prevent significant colonization by an infaunal community. Sediment cores from the site are physically stratified, with virtually no evidence of bioturbation (Figure 5). Stratification consists of parallel to wavy laminations (typically <1–2 mm) of silt with a minor sand component. Saturated bulk density of the surface mud layer averages
Figure 5. X-radiograph positive of a sediment pushcore from the tripod site exhibiting primary physical stratification of silt- and clay-rich interlaminations. Dark layers represent coarse laminae. Arrow indicates the coarse lag formed by erosion at the base of the semi-diurnally reworked surface mud layer.
1.25–1.40 g cm⁻³ in October. However, OBS data records and x-radiographs at the tripod site and concentration profiles nearby reveal the presence of up to 10 cm of fluid-mud above this interface.

Suspended-sediment concentrations varied in the water column (upper OBS sensor) from a minimum of 0.25 g l⁻¹ during high water to about 5 g l⁻¹ during maximum flood currents. Data from the OBS sensor located within the fluid mud, x-radiographs, and acoustic altimeter records indicate that the fluid-mud layer varies in thickness and sediment concentration with changing tidal phase. The acoustic altimeter signal is a useful tracker of this behavior as it apparently reflected off the upper fluid-mud boundary (e.g., lutocline). The fluid-mud reaches maximum concentration (about 175–200 g l⁻¹) and minimum thickness about one hour after high water, when minimum benthic shear stresses permit consolidation. Several lutoclines were recorded settling past the OBS sensor during this time and the distance to the acoustic “bed level” increased by 3–4 cm. Concentrations within this layer decrease to a minimum of about 25–50 g l⁻¹ during maximum flood currents.

The fluid-mud layer responds differently to wave-induced bottom stress depending on concentration: at high concentrations (> 75–100 g l⁻¹), the current maximum associated with a passing wave crest causes an apparent instantaneous decrease in fluid-mud concentration (Figure 3). Fluid-muds of < 75 g l⁻¹ respond to wave passage with an apparent increase in concentration. A possible explanation is that the fluid-mud is behaving as a turbulent suspension at low concentrations. At higher concentrations (75–200 g l⁻¹), the fluid-mud has a weak sediment “framework” that is temporarily disrupted by wave passage. These fluid-mud “states” may correspond to the mobile vs. stationary suspensions defined by Kirby and Parker (1977); however, such conclusions are tentative.

Repetitive bed scouring on tidal time-scales (and by individual waves) probably generated the silty lag layer at the base of the fluid-mud layer (visible in x-radiograph; Figure 5), which is observed in sediment cores at successive low water phases. Low benthic shear stresses associated with neap tides may allow deposition of some fluid-mud and burial of this interface. This mechanism, acting in concert with seasonally variable sediment input (Allison et al., in press), represents an important means for generating physical stratification in the sediments.

SUMMARY

The successful test of the prototype instrumented tripod system validates the design concept for use in high-energy, muddy surf zones and nearshore settings. The instrument package can be preprogrammed and deployed rapidly from small boats. Potentially, this instrumented tripod system could be utilized in water depths up to 3 or more meters at maximum low tide.

Data reduction and synthesis indicate a great deal of quantitative information was obtained on current and wave stresses and bed response. Significant sediment transport was documented as occurring during this period of minimum suspended-sediment supply from the adjacent Amazon River (Allison et al., in press). Physical processes driving sediment transport include wave resuspension and tidal and low-frequency currents. Fluid-mud is an important component of sediment transport, and particle exchange with the underlying seabed is a potentially important mechanism for formation of μ- to cm-scale physical stratification. Ultimately, detailed study of the sediment dynamics and correlation with finescale stratigraphy will link process and sediment response in this shallow, muddy depositional setting. Experiments of this type contribute critical quantitative information about the processes that formed muddy deposits associated with major rivers in the geologic record.

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LITERATURE CITED


