Tidal and seasonal dynamics of a muddy inner shelf environment, Gulf of Papua

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[1] Subaqueous delta clinoforms are accretionary features created on the continental shelf where there is a large supply of sediment. Sediment is transported across the shallow topset region and accumulates rapidly in the deeper foreset region. In the Gulf of Papua, Papua New Guinea, the absence of cyclonic storms makes tidal currents and seasonal variation of wind direction primary controls on the timing and magnitude of across-shelf sediment transport. To investigate processes that disperse sediment across the topset of the Fly River clinoform, anchor stations were occupied during spring and neap tidal cycles of the trade wind season, the monsoon season, and the transition period. During the energetic trade wind season, surface waves coupled to strong spring tide currents generated peaks in suspended-sediment concentration (>100 g L\(^{-1}\) at some locations). However, seabed erosion and deposition over tidal timescales could not be discerned, indicating that sediment was being advected across the outer topset. Although seaward gravity flows occur with significant spatial heterogeneity, they are important for carrying sediment to the foreset region because the near-bed circulation generally has a landward net flow. Seaward transport is restricted to the energetic trade wind season. During the quiescent monsoon season, 4–11 cm of erosion occurs on parts of the outer topset as fluvial sediment is temporarily deposited closer to shore. Seasonal patterns in sediment dispersal are likely impacted by El Niño–Southern Oscillation, and consideration of El Niño conditions of 2002–2003 are reflected in the interpretation of observations.


1. Introduction

[2] In mesotidal to macrotidal shelf settings, tidal currents can have a dominant impact on sediment-transport processes, especially when integrated over timescales of fortnightly spring-neap cycles (~14 d) and monthly cycles (~28 d). In wet tropical equatorial locations, the relatively small variability of river discharge and the absence of cyclonic storms make tidal variability especially important for mediating shelf sediment dispersal. As an example from the macrotidal Amazon shelf, spring-neap variations in water column mixing alternately inhibit and promote the formation of high-concentration sediment suspensions (fluid muds) [Kineke et al., 1996]. Fluid muds are held in suspension by waves, currents, and/or convergent processes. When these conditions are not met, dissipation of the fluid muds occurs, resulting in rapid deposition of muddy sequences that may display unique sedimentary microfabric and nonsteady state radiochemical signatures [Allison et al., 1995; Kuehl et al., 1996]. On the Amazon inner shelf, alternating periods of bed load transport and fluid mud formation are recorded in the seabed as interbedded sand and mud [Jaeger and Nittrouer, 1995]. Investigation revealed that the formation of fluid mud along the Amazon inner shelf dominates seaward transport by inducing high-concentration sediment gravity flows [Kineke and Sternberg, 1995]. Other systems that have been studied recently reveal that where fluid mud processes occur on the continental shelf, they play an important role in sediment dispersal. However, there is limited direct observation of sedimentary deposits and seaward transport associated with fluid muds.

[3] The Fly River dispersal system in the Gulf of Papua (GOP) provides an opportunity to examine the role of tidal fluctuations on a mesotidal continental shelf where the river discharge is significantly less than on the Amazon shelf. Sediment delivered to the GOP by a line source of fluvial input has formed an actively prograding clinoform on the continental shelf (Figure 1) [Harris et al., 1993; Walsh et al., 2004]. The sigmoidal-shaped deposit is characterized by: limited accumulation on the topset due to intense reworking by waves and tidal currents, enhanced accumulation of fine-grained sediment on the foreset as shear stress decreases seaward, and slow accumulation on the bottomset due to restricted sediment supply. Rapid accumulation on the foreset region produces the highest-resolution stratigraphic record. To understand this type of system, it is crucial to evaluate sediment transport processes on the clinoform topset, where sediment from the river is transferred seaward to the foreset. On the Amazon topset,
estuarine processes concentrate suspended sediment, forming fluid muds that flow down slope to the foreset. The GOP allows investigation of a system where estuarine processes are confined to delta distributary channels, rather than occurring on the clinoform topset. Therefore resuspension by a combination of tidal currents and surface gravity waves control sediment transfer to the foreset region.

To capture processes varying on hourly to seasonal timescales, time series data were collected throughout the water column and upper seabed at anchor stations occupied during the trade wind season of 2003, the monsoon season of 2004, and the transition period from monsoon to trade wind conditions during 2004. Together, these data sets provide a rare opportunity to examine how the seabed and water column respond to forcing mechanisms. By making observations on timescales at which processes operate, we could preclude data aliasing that may occur when attempting to integrate observations over longer timescales. Additionally, by linking process (i.e., sediment entrainment and water column dynamics) with product (i.e., development of sedimentary structures within the seabed), we could provide insight to the history of sediment transport processes recorded in the seabed.

The objectives of this investigation are (1) to measure suspended-sediment concentration as a function of tidal stage and season; (2) to evaluate the potential role of fluid mud generation in across-shelf transport; (3) to examine seabed height and sedimentary structures over hourly, fortnightly, and seasonal timescales; and (4) to document the spatial heterogeneity in sedimentary processes that may exist along the outer topset.

2. Background

2.1. Tidal Sedimentation

Sediment transport mechanisms in tide-dominated shelf settings vary cyclically on timescales governed by tidal forcing, with fluctuating amounts and directions of bed load and/or suspended-load transport. As sediment accumulates, the sedimentary structures produced within the seabed can record these processes [Klein, 1998]. Sequences of interlaminated sands and muds displaying characteristic tidal cyclicities are described as tidal rythmites [Reineck,
On timescales of hours, peak flow and slack water cycles (i.e., flood-ebb cycles) produce sand-mud couplets. One type is flaser bedding, where sand laminae contain small-scale current ripples, and mud laminae drape the crests and troughs [Reineck and Wunderlich, 1969]. In a mud-dominated setting, current ripples produce lenticular bedding, but neither flaser nor lenticular bedding is wholly diagnostic of tidal environments [Nio and Yang-chang, 1991]. Progressive thickness changes in sequences of couplets represent fortnightly and monthly cycles [Tessier et al., 1988] and are definitive indicators of tidal processes.

Shelf tidal currents may influence estuarine processes and control sedimentation on spring-neap timescales [Allen et al., 1980]. For example, during neap tide at the toe of the salinity front, the water column can be stratified with a well-defined turbidity maximum marked by large suspended-sediment concentrations (SSC), even reaching fluid mud concentrations (>10 g L\(^{-1}\)) [Allen, 1991; Kineke and Sternberg, 1995]. Spring tide currents and a large tidal range can mix the water column and dilute the turbidity maximum, inhibiting the formation of near-bed fluid muds. Jaeger and Nittrouer [1995] showed that sedimentary structures and seabed elevations vary on fortnightly cycles. A 15-cm-thick bed of mud was observed on the Amazon inner shelf during neap tide, but spring tide currents removed most of the mud and a 3-cm-thick cross-laminated sand bed was emplaced at the seabed surface. The net result of this process is to produce interbedded sand and mud, with thicknesses dependent on sediment supply, consolidation rate, and energetics of the water column [Jaeger and Nittrouer, 1995].

### 2.2. Fly River Basin

The inner shelf in the GOP is a mesotidal environment, which is actively receiving fine-grained sediment. The Fly River and its primary tributary, the Strickland River, drain the highlands of New Guinea forming a 75,000-km\(^2\) catchment. Mean discharge of the Fly River is large (~6500 m\(^3\) s\(^{-1}\)), and mean intra-annual variability is a factor of 2–3 [Harris et al., 1993]. Interannual variability exceeds a factor of 7 and is tied to strong El Niño–Southern Oscillation (ENSO) signal in the region [Dietrich et al., 1999]. Because seasonal variability of the Fly River is small, the reduction in freshwater and sediment discharge to the Gulf of Papua during El Niño conditions, such as those present in 1997 and moderately in 2003, can have a significant impact on sedimentation across the inner shelf [Ogston et al., 2008]. During normal conditions, an estimated natural sediment load of 85 × 10\(^6\) t a\(^{-1}\) [Harris et al., 1993] is attributed to the rugged topography, high precipitation, earthquakes, and landslides [Pickup, 1984]. Mining activities in the highlands since 1985 have increased the sediment load to 115 × 10\(^6\) t a\(^{-1}\) [Milliman et al., 1999], but lack of artificial levees, dams, diversions or dredging, as well as very limited deforestation, have otherwise kept the natural system intact. The gentle gradient of the lower Fly River promotes deposition of most coarse sediments at the mountain front and within the meandering channels of the floodplain [Aalto et al., 2008; Day et al., 2008; Dietrich et al., 1999; Swanson et al., 2008], and ~90% of the sediment load reaching the GOP is transported as suspended silt and clay [Baker, 1998]. Much of the lower Fly River is tidally influenced [Wolanski and Eagle, 1991] and, at its mouth, creates a classic funnel-shaped delta with distributary channels separated by longitudinal islands [Fisher et al., 1969; Galloway, 1975].

### 2.3. Gulf of Papua Hydrodynamic Setting

Broad, low-gradient continental shelves associated with foreland basins contribute to the large amplitude of tides in regions like the Gulf of Papua [Craun, 1979]. Tides at the river mouth are semidiurnal with a large diurnal inequality and a 4-m spring tide range [Ogston et al., 2008; Wolanski and Eagle, 1991]. The semidiurnal component is most pronounced throughout spring tides, and during neap tides becomes almost diurnal in nature. Neap tides can have 10-h intervals when sea level change is less than 0.5 m, leading to long periods of slack water [Baker et al., 1995]. Within the delta, flood tide currents near the seabed are stronger than ebb tide currents, reaching maxima of ~1.2 and ~0.8 m s\(^{-1}\), respectively [Wolanski and Eagle, 1991]. Strong tidal currents within distributary channels limit deposition of fine material, and, during spring flood tides, have been shown to produce elevated SSC, including fluid muds with concentrations >40 g L\(^{-1}\) [Ogston et al., 2008; Wolanski and Eagle, 1991; Wolanski and Gibbs, 1995]. Estuarine circulation and tidal asymmetry within the delta result in a residual landward bottom current and the formation of a turbidity maximum [Wolanski et al., 1995, 1997].

The wave climate in the Gulf of Papua is tied to the monsoon cycle and is strongly seasonal. From December to March, the northwest monsoon winds blow off the land at ~5 m s\(^{-1}\) [McAlpine and Keig, 1983; Slingerland et al., 2008], the limited fetch and mild wind speeds lead to very calm seas with significant wave heights averaging 0.3 m [Thom and Wright, 1983]. From May to October, the southeast trade winds persistently blow >5 m s\(^{-1}\) onshore [McAlpine and Keig, 1983; Slingerland et al., 2008]. The larger fetch leads to greater swells, having an average significant wave height of 1.3 m [Thom and Wright, 1983]. November and April are transitional months with variable conditions. Large cyclonic storms do not directly impact the GOP, due to the proximity of the region to the equator [McAlpine and Keig, 1983].

### 2.4. Shelf Sedimentation

Adjacent to and northeast of the river mouth, sedimentation on the shelf is likely dominated by the Fly River due to a clockwise gyre in that region [Wolanski and Eagle, 1991]. However, the influence of sediment contributed by the Purari, the Kikori, and other rivers around the Gulf of Papua becomes increasingly important northeastward along the shelf [Walsh et al., 2004]. The total sediment load of all the rivers flowing into the Gulf of Papua is ~385 × 10\(^6\) t a\(^{-1}\) [Milliman et al., 1999]. The combination of sediment supply and oceanographic conditions has led to the formation of a subaqueous delta with a distinct clinoform structure [Harris et al., 1993; Walsh et al., 2004], resembling those found in other similar settings, e.g.: the Amazon shelf [Kuehl et al., 1986; Nittrouer et al., 1986], the Ganges-Brahmaputra shelf [Kuehl et al., 1989; Michels et al., 1998], and the Yellow Sea [Alexander et al., 1991; Liu et al., 2004]. The rollover point separating the topset and foreset in the Gulf of Papua is located between the 25-m...
and 40-m isobaths (becoming deeper in a northeast direction). Transitions to the maximum seabed gradients and accumulation rates (>1.4 cm a\(^{-1}\)) on the shelf [Walsh et al., 2004] occur seaward of the rollover point. Net accumulation of sediment on the outer topset is limited due to the shallow depths and resuspension by waves and tidal currents, however, ephemeral deposition likely occurs on the inner topset as sediment is supplied from rivers during the quiescent monsoon season [Walsh et al., 2004]. Morphology varies considerably along the clinoform (Figure 1), including incised valleys (e.g., Umuda Valley and Kiwai Valley [Crockett et al., 2008]), which enhance currents associated with tides and regional circulation, and act as conduits for transport of sediment to deeper water.

3. Methods

[12] To gain adequate temporal coverage of hydrodynamic conditions in the Gulf of Papua, three cruises were conducted during August-September 2003, January-February 2004, and April-May 2004. These periods represented the trade wind season, the monsoon season, and the transition between them, respectively. Time series observations of the seabed and water column were made during each of the three cruises. Using dynamic positioning, the R/V Melville occupied three anchor stations (Figure 1) near the Fly River mouth at ~15-m water depth for 25 h during spring tides and 13 h during neap tides. The sites are dominantly fine-grained (>98% mud) and are located on the outer topset of the Gulf of Papua clinoform. These locations were chosen to examine spatial heterogeneity of sediment transport processes at different sites along the shelf. T8-18 lies closest to the Fly River mouth within Umuda shelf valley and shares the closest link to processes occurring within the Fly River delta. T13-17 is located ~65 km to the northeast of the Fly River, on the broad, low-gradient outer topset of the open clinoform where seaward delivery of sediment is likely more dependant on local mechanisms. GH-14 is positioned on the open clinoform, ~90 km to the northeast of the Fly River, where regional circulation may play a more prominent role in delivering and concentrating suspended sediment [Slingerland et al., 2008], and the sediment supply is augmented by the discharge of several smaller rivers around the Gulf of Papua. Anchor-station data are supplemented by time series measurements from two benthic boundary layer (BBL) tripods that were deployed throughout the duration of each cruise (~30 d) in Umuda Valley and at the NE Fly outer topset. A kasten core was collected at each anchor station site, to document the longer-term sedimentation histories.

3.1. Field Methods

[13] Water column profiles were collected every hour at the anchor stations using a Boundary Layer In Situ Profiler (BLISP). The BLISP is a small, instrumented tripod that measures temperature, salinity, pressure, and SSC profiles through the water column. It is similar to the instrument described in detail by Sternberg et al. [1991]. The instrument, shaped like a weather vane to keep sensors oriented into the current, houses a small conductivity, temperature, and depth (CTD) sensor and an optical backscatter sensor (OBS) mounted 10 cm above ski-shaped feet (Figure 2). When the unit reaches the seabed, a system of in situ pumps obtains a water sample within 10 cm of the seabed, and another sample is collected at a preprogrammed water depth selected by the operator.

[14] The BBL tripods were used to correlate current speed with tidal stage at the anchor station locations. Instrumentation on the tripods included an acoustic Doppler velocimeter (ADV) to record near-bed currents, an acoustic Doppler current profiler (ADCP) to measure water column currents, a pressure sensor to document sea surface height, and an OBS to record SSC.

[15] Box cores were collected every 2 h throughout the anchor stations. Once onboard, the box was subcored with a 15-cm-diameter PVC tube. The subcore was sampled in 1-cm intervals for the upper 15 cm and from alternate centimeters for the remainder of the core. Plexiglas slabs (3 cm thick) were obtained from the same box and X-radiographed with a portable X-ray machine. Effort was made to take slabs in the least disturbed sediment away from box core sides. Direct subsampling of kasten cores was permitted by removing one side of the core barrel.

3.2. Laboratory Procedures

[16] Near-bed SSC was determined by filtering a known volume of pumped bottom water to get mass concentration. The SSC then allowed calibration of the OBS for each cruise and for differing areas of the study region. Calibration to very high concentrations of suspended sediment (>10 g L\(^{-1}\)) was done using the method described by Kineke and Sternberg [1992]. The sensor range was ~0.01–150 g L\(^{-1}\), although concentrations between ~2 and 30 g L\(^{-1}\) were difficult to resolve because the sensor had a flat response for that range of SSC.

[17] X-radiograph negatives were digitized with a transmissive flat bed scanner at 300 DPI resolution. Enhancement of brightness and contrast helped to identify grain size differences and sedimentary structures. To compare seabed evolution over hourly, fortnightly, and seasonal timescales, distinct laminae at depth within the cores allowed alignment of radiographs relative to each other.

[18] Grain size distribution was determined by a combination of wet sieving and Sedigraph analysis. The sample was homogenized, and a 7-g subsample was disaggregated by ultrasonification in a 0.05% solution of sodium hexametaphosphate. The disaggregated sample was then wet sieved at 63 \(\mu\)m to separate the sand fraction from the mud (i.e., silt and clay), and relative weights were calculated for the fine and coarse fractions. The grain size of the mud fraction (the dominant material) was determined using a Sedigraph 5100.

[19] Sedimentation over the past century was examined using \(^{210}\)Pb geochronology adapted from Nittrouer et al. [1979]. Approximately 5 g of dried and homogenized sample were crushed, spiked with a known activity of \(^{209}\)Po, and digested with 16 N HNO\(_3\) acid followed by 6 N HCl acid. \(^{209}\)Po and the granddaughter of \(^{210}\)Pb, \(^{210}\)Po, were plated onto silver planchets and alpha decay was counted for 24 h. Activities were normalized to the salt-corrected dry mass assuming a sediment density of 2.65 g cm\(^{-3}\), and are reported as disintegrations per minute per gram (dpm g\(^{-1}\)). Porosity was also determined during the procedure by taking the difference between the sample
weight before and after drying and calculating the volume change assuming a seawater density of 1.025 g cm$^{-3}$.

4. Results

4.1. Water Column Profiles

[20] BLISP anchor station data are available for spring and neap tidal cycles during the trade wind season, monsoon season, and transition period at Umuda Valley and the NE Fly outer topset. BLISP anchor station data at the central gulf outer topset are available for the monsoon season and transition period only. During the trade wind season, one BLISP cast was completed at the central gulf outer topset station. Time series pressure and current data for Umuda Valley and the NE Fly outer topset are provided by tripods near those stations, but the data are not available for the central gulf outer topset. Salinity dominantly determines the density structure of the water column at all sites during all seasons, because the temperature signal does not vary significantly on the shelf (horizontally or vertically). A summary of maximum near-bed SSC, maximum current speeds, and bottom salinity range during spring and neap tides is provided in Table 1.

4.1.1. Umuda Valley

[21] In Umuda Valley, the maximum tidal range was $\sim$3.7 m with maximum spring tide currents (78 cm above the bed) reaching 90 cm s$^{-1}$ (Figure 3). Tides are mixed semidiurnal with a strong spring/neap variation. Smaller monthly neap tides become nearly diurnal and tidal range was as low as 0.5 m with maximum currents of 15 cm s$^{-1}$, causing extended periods of nearly slack water ($<10$ cm s$^{-1}$).
Table 1. Maximum Near-Bed Suspended-Sediment Concentration and Bottom Water Salinity Ranges at the Anchor Stations Measured by Hourly BLISP Casts.

<table>
<thead>
<tr>
<th>Site (Tide)</th>
<th>Maximum Near-Bed SSC, g L(^{-1})</th>
<th>Maximum Currents, cm s(^{-1})</th>
<th>Maximum (Minimum) Bottom Salinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trade Wind</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Umuda Valley (spring)</td>
<td>~125</td>
<td>no data</td>
<td>32.1 (20.9)</td>
</tr>
<tr>
<td>Umuda Valley (neap)</td>
<td>1.0</td>
<td>no data</td>
<td>32.7 (31.7)</td>
</tr>
<tr>
<td>NE Fly (spring)</td>
<td>1.8</td>
<td>73.0</td>
<td>32.6 (24.5)</td>
</tr>
<tr>
<td>NE Fly (neap)</td>
<td>0.5</td>
<td>33.8</td>
<td>32.1 (31.0)</td>
</tr>
<tr>
<td>Central gulf (spring)</td>
<td>~30</td>
<td>no data</td>
<td>no data</td>
</tr>
<tr>
<td>Central gulf (neap)</td>
<td>0.25</td>
<td>no data</td>
<td>33.2 (31.7)</td>
</tr>
<tr>
<td>Monsoon</td>
<td>0.06</td>
<td>no data</td>
<td>32.7 (31.7)</td>
</tr>
<tr>
<td>Umuda Valley (spring)</td>
<td>0.50</td>
<td>65.3</td>
<td>33.2 (32.2)</td>
</tr>
<tr>
<td>Umuda Valley (neap)</td>
<td>0.28</td>
<td>no data</td>
<td>32.3 (30.8)</td>
</tr>
<tr>
<td>Central gulf (spring)</td>
<td>0.20</td>
<td>no data</td>
<td>32.4 (31.3)</td>
</tr>
<tr>
<td>Central gulf (neap)</td>
<td>0.20</td>
<td>no data</td>
<td>32.4 (31.3)</td>
</tr>
<tr>
<td>Transition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Umuda Valley (spring)</td>
<td>0.38</td>
<td>76.7</td>
<td>32.6 (31.0)</td>
</tr>
<tr>
<td>Umuda Valley (neap)</td>
<td>0.49</td>
<td>15.6</td>
<td>no data</td>
</tr>
<tr>
<td>NE Fly (spring)</td>
<td>0.70</td>
<td>71.2</td>
<td>31.9 (29.1)</td>
</tr>
<tr>
<td>NE Fly (neap)</td>
<td>0.22</td>
<td>53.6</td>
<td>32.0 (30.0)</td>
</tr>
<tr>
<td>Central gulf (spring)</td>
<td>0.47</td>
<td>no data</td>
<td>31.9 (29.6)</td>
</tr>
<tr>
<td>Central gulf (neap)</td>
<td>0.40</td>
<td>no data</td>
<td>31.6 (30.1)</td>
</tr>
</tbody>
</table>

*Maximum near-bed currents in Umuda Valley and at the NE Fly outer topset were recorded by benthic boundary layer tripods. Tidal displacement of fresh water from the Fly River leads to maxima and minima in bottom water salinity during high and low tide, respectively.

lasting up to 12 h. Asymmetry in currents existed between the flood and ebb stages (Figure 3d), such that flood tides had greater velocities, and longer duration. In one example from spring tide of the transition period, flood tide currents reached 89 cm s\(^{-1}\) and ebb tide current speeds within the same semidiurnal tidal cycle reached only 55 cm s\(^{-1}\).

Near-bed SSC (measured with BLISP) fluctuates with tidal currents, but the most significant differences in peak concentrations existed on fortnightly and seasonal timescales (Figure 4 and Table 1). During spring tide of the trade wind season, fluid mud concentrations >100 g L\(^{-1}\) were measured (Figure 4b), with a peak in fluid mud thickness and concentration occurring at the onset of flood currents in the tidal cycle. When fluid mud was present, thickness increased with current speed. Thicknesses reached maxima of ~130 cm and ~60 cm midway through flood and ebb tide flows, respectively, and fell to minima at high and low tides (<20 cm). Fluid muds were not observed at neap tides in the trade wind season (maximum of 1.0 g L\(^{-1}\)) or at any tidal stage in the monsoon and transition (maximum ~0.38 g L\(^{-1}\)). Maximum near-bed SSC occurred with the onset of spring tide flood currents in all seasons, and smaller peaks in SSC were observed just before and after low tide (Figure 3e). Neap tide conditions during the monsoon season produced the smallest semidiurnal maximum in SSC (~0.06 g L\(^{-1}\)).

During the trade wind season, water column stratification decreased slightly from neap to spring tide, but the water column was never well mixed nor highly stratified (Figure 4a). The water column structure varied over the semidiurnal tidal cycle as the surface buoyant layer moved past the anchor station site. For spring tide, bottom salinity reached a minimum (29.0) at low tide and reached a maximum during flood tide (32.1). Bottom salinity remained relatively high through neap tide, but reached a minimum (31.4) at low-tide slack water. At spring and neap tide, maximum stratification occurred just after low water, with the water column becoming most mixed with the onset of ebb currents.

### 4.1.2. NE Fly Outer Topset

Tidal currents were similar to those observed in Umuda Valley with the exception that flood-ebb asymmetry at this site was small and maximum current speeds were ~10 cm s\(^{-1}\) slower (Figure 3d). Maximum tidal range was slightly less at 3.5 m.

Near-bed SSC is a function of the seasonal wave climate and has a periodicity related to tidal current speed (Figure 3e). During the trade wind season, maximum near-bed SSC reached about 1.8 g L\(^{-1}\) at the onset of spring flood currents and minimum concentrations occurred at high tide (Figure 4d). Neap tide conditions produced a significantly reduced maximum near-bed SSC of ~0.50 g L\(^{-1}\). Near-bed SSC reached maxima of ~0.50 and ~0.70 g L\(^{-1}\), during the monsoon season and transition period spring tides, respectively, and exceeded SSC observed during those periods at Umuda Valley and the central gulf outer topset (Table 1).

The water column appeared fresher and more stratified on the NE Fly outer topset than in Umuda Valley and varied between neap and spring tide (Figure 4e), with bottom salinities ranging from 24.5 to 32.6. During spring tide, the water column became most stratified for flood currents and most mixed at high tide. The neap tide water column was most stratified during low water and onset of flood currents.

### 4.1.3. Central Gulf Outer Topset

On the central gulf outer topset, long-term tidal elevation and current data are not available. An anchor station during trade wind conditions was not part of the designed study, but a spatial survey of the central gulf during spring tide revealed fluid mud concentrations of ~30 g L\(^{-1}\). In the following monsoon season and transition period, anchor stations were performed. Through spring tide of the monsoon season, peaks in near-bed SSC reached 0.28 g L\(^{-1}\) (Figure 4f). During the transition period, peak concentrations were observed just before and after slack water, reaching maximum values of 0.47 g L\(^{-1}\). Neap tides produced similar peaks in near-bed SSC of 0.20 and 0.40 g L\(^{-1}\) for the monsoon season and transition period, respectively.

For the transition period, the water column showed a distinct surface lens following low tide, which had a minimum salinity of 13.9. Through all observations, salinity within bottom water varied by only 2.3, which is less than at Umuda Valley and the NE Fly outer topset (Figure 4e and Table 1). During spring tide, the water column was most stratified during the larger semidiurnal tide and most mixed with the smaller tide, indicating that the larger tide was necessary to draw the freshwater lens to the outer topset. The neap tide water column changed very little over the tidal cycle and the freshwater lens was not as distinct.

### 4.2. Seabed Observations

Time series seabed data are available over spring and neap tidal cycles during the trade wind season, monsoon season, and transition period at Umuda Valley and the NE
Fly outer topset, and only during the monsoon season and transition period at the central gulf outer topset.

4.2.1. Umuda Valley

[30] The seabed at this location is characterized by the presence of interlaminated sand and mud interbedded with massive mud (Figure 5). Interlaminated sequences are commonly marked by a sharp basal contact overlain by thin laminae of coarse sediment (sand; Figure 6a). The transition upward from interlaminated sand and mud to massive mud is gradational – the coarse laminae disappear upward until they cannot be resolved within the massive mud. Physical structures include planar lamination, ripple cross lamination, and upward fining beds consisting of millimeter-thick laminae. Biogenic structures are evident in cores from all three seasons, and are concentrated below the base of some interlaminated-sand-and-mud sequences and near the seabed surface. Biogenic structures include burrows millimeters to centimeters thick, which are open or filled with fine sand.

[31] Seabed elevation on semidiurnal and fortnightly timescales fluctuated <3 cm. Because of small-scale temporal and spatial variability, however, fluctuations cannot be correlated to tidal current speed. Variability in thickness of distinct beds (i.e., massive mud; Figure 5) sampled multiple

Figure 3. Time series records of pressure, current speed, and suspended-sediment concentration provided by bottom boundary layer tripods. (a) Dashed lines illustrate tidal variation on the outer topset and identify ~28-d monthly, ~14-d fortnightly, ~24-h diurnal, and ~12-h semidiurnal tidal cycles within Umuda Valley during the transition from the monsoon season to the trade wind season. (b) Tidal periodicities are also reflected by variations in current speed. (c) Comparison between Umuda Valley and the NE Fly outer topset shows that although maximum tidal range is similar with values of ~3.7 m and ~3.5 m, respectively, (d) there exists a pronounced semidiurnal current asymmetry within Umuda Valley and a slight asymmetry on the NE Fly outer topset. These data suggest that Umuda Valley shares a closer link to estuarine processes occurring within the Fly River delta. (e) Vertical dashed lines identify two prominent peaks in suspended-sediment concentration (SSC). SSC varies as a function of the semidiurnal tidal currents with maxima occurring during flood tide. Current meters within Umuda Valley and on the NE Fly outer topset are located at 78 and 100 cm above the seabed (cmab), respectively. OBS sensors are located at 42 and 50 cmab, respectively.
Figure 4. A record of salinity structure and suspended-sediment concentration (SSC) for Umuda Valley, the NE Fly outer topset, and the central gulf outer topset for a spring and neap tidal cycle. (a and c) During the energetic trade wind season, the water column at Umuda Valley and the NE Fly outer topset never became well mixed. (e) The same was observed at the central gulf outer topset during the transition period; however, salinity structure varied less over the semidiurnal tidal cycle, and the interface between low-salinity surface water and ocean water was more abrupt. (b and d) During the trade wind season, near-bed SSC was found to vary with both a semidiurnal and a fortnightly periodicity, and maximum concentrations often occurred soon after low water during spring tide. Fluid mud results from a combination of resuspension during spring tide and local flow convergence. This differs from the macrotidal Amazon topset, where spring tide currents distribute sediment throughout the well-mixed water column, and stronger stratification during neap tide concentrates fluid mud near the seabed. (f) SSC was similar for spring and neap tides at the central gulf outer topset during the transition period.
times at one location indicate that the seabed itself has similar relief (~1–3 cm). The seabed surface did not develop distinct sedimentary structures over semidiurnal or fortnightly timescales (Figure 7). Millimeter-thick silt laminae at the seabed surface occurred during spring tide of the trade wind season but were not evident throughout the complete tidal cycle and cannot be correlated to tidal current speed or SSC.

[32] Between the trade wind and monsoon seasons, the seabed decreased in elevation (~2 cm) and by the transition period a total decrease of ~4 cm was observed (Figure 8a). To minimize effects of aliasing, the average seabed heights during spring and neap conditions were used for comparison on the seasonal timescale. The sandy laminae evident in the upper 6 cm of the trade wind cores were partially eroded by the monsoon season and were almost completely eroded and/or biologically mixed by the transition period. A progression in the extent of bioturbation through time was observed. By the transition period, the upper 3–5 cm of the cores contained many small burrows and other evidence of bioturbation. In some cases, the upper 3–5 cm of the transition period cores were heavily mottled.

[33] Excess 210Pb activity within the seabed is relatively low (<2 dpm g⁻¹), and comparison to the grain size distribution profile confirms that variation in activity is attributed to shifts in grain size within the core (i.e., coarse sediment has low activity). Kasten core 210Pb profiles contain ~135 cm of excess activity with no evidence of logarithmic decrease with depth (Figure 9). Below ~135 cm, the activity drops to supported levels. Sediment accumulation rates could not be determined from these profiles, however the presence of excess 210Pb indicates that sediment above ~135 cm was deposited within the last 100 a. Porosity profiles abruptly decrease below ~135 cm (Figure 9), also indicating a change of sediment emplacement in the seabed.

Figure 5. Sedimentary structures evident within X-radiograph negatives of cores collected in Umuda Valley. These structures are characteristic of the GOP outer topset. In general, physical structures are more common than biological structures, forming interlaminated sand-and-mud sequences (ISM) interbedded with massive mud (MM). Biological structures (BS) are concentrated near the seabed surface and beneath erosional horizons (EH), and a mottled texture (MOT) exists at the surface of some transition period cores. Physical structures commonly include planar lamination (PL), ripple cross lamination (RCL) (also see Figure 6b), and soft sediment deformation (SSD). Reactivation surfaces (RS) are also present but are usually observed within a distinct interlaminated sand-and-mud unit near the base of Umuda Valley and NE Fly outer topset cores.
4.2.2. NE Fly Outer Topset

The seabed at this site is similar in character to Umuda Valley. The box cores are composed of interlaminated sand and mud, which fine upward into finely laminated and massive mud (Figure 8b). The next interlaminated sequence is marked by a sharp, basal contact and the presence of a coarse lag layer containing shell hash in some cases. A 1-2-cm-thick sand layer is present in the upper 6 cm with well developed ripple cross lamination (Figure 6b). This layer was not present near the surface of all the trade wind cores collected at this location, probably indicating small-scale spatial variability. The sedimentary structure is physically dominated, with some biogenic structures concentrated beneath erosional horizons. Biological mixing appears to be less effective than at Umuda Valley, and there are fewer large biogenic structures.

[35] Small-scale spatial variability, similar to that observed at Umuda Valley, likely masks any seabed height changes resulting from semidiurnal and fortnightly variability. In addition, there is no apparent evolution of near-surface sedimentary structures observed on these timescales. Seabed height and sedimentary structure change significantly between each of the seasons (Figure 8b). From the trade wind season to the monsoon season, the seabed decreased ~5.5 cm in elevation, eroding completely through the coarse layer discussed above. A total of ~8.5 cm of erosion occurred by the transition period. Bioturbation increased near the seabed surface throughout the same time interval.

4.2.3. Central Gulf Outer Topset

[36] The seabed at this site is characterized by interlaminated sand and mud, which fines upward into massive mud (Figure 8c). The basal boundary of the interlaminated sand and mud is sharp, usually punctuated by a coarse lag layer with a thin zone of shell hash (Figure 6c). Transition upward to massive mud is abrupt but conformable. The coarse laminae disappear upward, until they cannot be resolved within the massive mud. Though interlaminated-sand-and-mud sequences are much thinner than at Umuda Valley and the NE Fly outer topset, and the massive mud is thicker, the sedimentary pattern is similar.

[37] Other sedimentary structures are also similar. Most biogenic structures are concentrated beneath the bases of interlaminated-sand-and-mud sequences and extend into the massive mud just below. The most common biogenic structures include burrows that are millimeters to centimeters thick and can extend >15 cm into the strata below. The origin of small (~5 cm length) burrows is generally indicated by the presence of gastropod shells within the burrows.

[38] Changes in seabed height over semidiurnal and fortnightly timescales cannot be correlated to tidal current speed at this site. The total decrease in seabed elevation between the monsoon and transition periods (Figure 8c) was 11 cm. This was greater than the total erosion observed at either Umuda Valley or the NE Fly outer topset. The degree of mottling observed near the seabed surface during the monsoon season was similar to that observed during the transition period.

5. Discussion
5.1. Role of Tides and Waves in Generating Gravity-Driven Flows on the Fly River Shelf

[39] Gravity-driven sediment transport is potentially an important mechanism for supplying sediment to regions of rapid accumulation on continental shelves. Fluid muds have been identified (1) as a mechanism for seaward growth of clinoforms on the Amazon River shelf [Kineke et al., 1996; Kuehl et al., 1995] and on the Atchafalaya River shelf [Veil and Allison, 2005]; (2) as a means of delivering sediment to a modern midshelf mud deposit on the Eel River shelf [Ogston et al., 2000; Traykovski et al., 2000]; and (3) as an agent of seaward sediment transport on the inner shelf in the Gulf of Bohai [Wright et al., 2001, 1988]. For each of these
Figure 7. A 12-h time series of the seabed within Umuda Valley during the transition period spring tide illustrating the horizontal continuity of depositional units. Cores are correlated by top of planar beds ~15 cm deep. Differences in seabed height during anchor stations are commonly attributed to a combination of spatial variability of the seabed and temporal variability in tidal currents. During the tidal cycle, this variability exists on similar length scales, making it difficult to identify either mechanism as the cause for observed changes in seabed height.

Figure 8. Seasonal erosion of the seabed (a) within Umuda Valley, (b) on the NE Fly outer topset, and (c) on the central gulf outer topset. Distinct sedimentary structure signatures allow direct comparison of trade wind season cores to those collected during the monsoon season and the transition period. Seabed loss is documented to be ~4 cm in Umuda Valley, ~8.5 cm on the NE Fly outer topset, and ~12 cm on the central gulf outer topset. Note that each of these cores has many replicates associated with the anchor station observations at the respective times.
examples, across-shelf advection of sediment occurs episodically with the formation of fluid mud in response to fluvial and/or oceanographic conditions. Previous studies of sedimentation on the GOP clinoform have suggested that much sediment is delivered to the clinoform foreset by gravity-driven flows [Harris et al., 1993; Walsh et al., 2004].

5.1.1. Conditions for Gravity-Driven Flows on the Clinoform Topset

On the Amazon River shelf, seaward transport of thick layers of fluid mud results from resuspension and dynamic trapping at the base of the frontal zone, which is always found on the shelf due to the extremely high water discharge [Kineke et al., 1996]. These fluid muds can deliver sediment to the forest in the form of gravity flows, as illustrated by the partial burial of a benthic tripod deployed at 65-m water depth on the Amazon shelf [Cachione et al., 1995]. In contrast, on the Eel River shelf, fluid mud transport in thin wave boundary layers occurred when flood discharge of the Eel River basin coincided with increased wave activity during winter storms [Ogston et al., 2000; Traykovski et al., 2000] and contributed to a midshelf mud deposit. Fluid mud formation on the Fly River shelf was only observed under trade wind conditions at spring tides, suggesting a formative process intermediate between the Amazon and Eel River systems.

On the Fly River shelf, fluid mud formation appears to require three components: trade wind conditions, spring tide currents, and local trapping. Fluid muds were observed in both Umuda Valley (maximum ~125 g L\(^{-1}\)) and on the central gulf outer topset (maximum ~30 g L\(^{-1}\)) under these conditions, but were not observed on the NE Fly outer topset, where local trapping may have played less of a role when the site was investigated. Unlike fluid muds observed on the Amazon topset, those in Umuda Valley did not persist throughout the complete tidal cycle and only reached a moderate thickness of 130 cm. Details were not available for fluid mud observed on the central gulf outer topset, but similar hydrodynamic conditions at the site (i.e., wave heights, tidal current speeds, and water depth), suggest similar behavior. Unlike the Eel River shelf, storms do not play a significant role in sediment transport due to the location of the GOP near the equator, but wave energy is apparently necessary to provide sufficient stress from wave current interactions to produce fluid muds. Conditions typical of the trade wind season were observed during the study and correlate with observations of increased suspended sediment along the topset [Ogston et al., 2008]. Because wave energy is significantly reduced outside of the trade wind season, the criteria for fluid mud formation were not met during the more quiescent monsoon season, or during the anchor stations of the transition period.

Although fluid mud only forms under fairly specific conditions, the resulting gravity-driven flows must be the key mechanism feeding clinoform progradation, as transport of sediment during neap tides and less energetic times of the year is generally directed landward [Ogston et al., 2008]. Current measurements obtained from the Umuda Valley tripod (Figure 3d) confirm this pattern of suspended-sediment transport, with dominantly landward near-bed flow in the region close to the Fly River mouth.

5.1.2. Impact of Tides on Gravity-Driven Flows

On a tide-dominated continental shelf like that adjacent to the Fly River, currents modulate gravity-driven transport on timescales governed by tidal forcing. For the case of a fluid mud layer on a gently sloping seabed, an estimate of the mean velocity for the fluid mud layer can be made using the Chezy equation [Wright et al., 1990]. For simplification, this calculation ignores Coriolis forcing and dynamic processes within the fluid mud layer, but does
consider the effect of drag at the bed and at the layer’s interface with the overlying water column. Mean velocities between 3 and 6 cm s\(^{-1}\) are expected for fluid muds observed at the Umuda Valley anchor station in the absence of other currents. These velocities are comparable to values calculated for fluid muds of similar thickness and concentration on the Amazon topset [Kineke et al., 1996]. In that study, the authors hypothesize that seaward transport by gravity flows occurs episodically, as landward forcing is relaxed.

Wright et al. [2001] highlight the importance of thin, fine-grained, high-concentration gravity flows in across-shelf sediment flux for the Gulf of Bohai. They observed that waves and currents play a vital role in generating fluid mud by increasing bed shear stress, yet along-shelf or landward currents hinder down-slope flow on the gently dipping continental shelf by increasing the frictional resistance acting on the gravity current. This observation is particularly relevant to a tide-dominated continental shelf, such as that adjacent to the Fly River. In concert with seaward river flow, landward flood tide currents act to converge sediment fluxes in shallow water. When tidal currents reverse, drag acting on the surface of the fluid mud layer favors seaward transport. In addition, when flood tide currents cease, turbulence within the fluid mud layer is dampened, reducing bottom drag and allowing rapid down-slope transport.

Observations of fluid mud thickness and concentration at the Umuda Valley anchor station during spring tide of the trade wind season are consistent with this scenario (Figure 10). Flood tide currents in Umuda Valley generated a convergence zone and relatively thick fluid mud layers, but their transport down slope was likely hindered by those same currents. Once the flood tide currents relaxed, the thickness of the fluid muds decreased in response to reduced convergence between the gravity flow and flood tide current, and down-slope flow of the dense layer was likely more rapid. At high- and low-swell water, high-concentration (>50 g L\(^{-1}\)) fluid mud layers were present but were <20 cm thick. Though relatively thin in comparison to fluid muds observed during flood tide (maximum ~130 cm), the layers likely moved down slope as drag acting on the surface of the gravity flow was decreased, and turbulence within the flow was dampened. Subsequent ebb tidal currents would enhance seaward transport of the fluid mud layer, when it existed (Figure 10b).

### 5.1.3. Seabed Response to Gravity-Driven Flows

Fluid muds observed in Umuda Valley reached their maximum thickness and concentration during flood tide. Applying the observed porosity of ~0.8 for the upper seabed, more than 9 cm of seabed would have to be emplaced to account for the entire mass of sediment in the overlying water column. These changes in seabed elevation were not observed and box core X-radiographs clearly show that erosion/deposition of the seabed surface was <3 cm throughout the spring tidal cycle of the trade wind season and could not be correlated to tidal variation. The sediment was likely advected to deeper parts of the shelf under the influence of tidal currents and gravity.

Although fluid muds were recorded at the Umuda Valley anchor station site during spring tide of the trade wind season, they were never observed on the NE Fly outer topset. The resemblance between X-radiographs from the two sites suggests that processes leading to the formation of sedimentary strata are probably similar. It is possible that fluid muds were not observed at the latter site because the necessary conditions occur with spatial heterogeneities and the anchor station missed them. It is also possible that the NE Fly outer topset was significantly impacted by interannual variability of Fly River discharge during sampling in 2003–2004 (see section 5.2).

The extremely high freshwater discharge of the Amazon River sustains large-scale estuarine convergence, generating fluid muds over a vast area of the Amazon inner shelf. The Fly River system is more typical of continental shelf settings where the estuarine turbidity maximum (ETM) is confined within the river mouth, placing a more important role on local conditions, especially convergent flows, in generating fluid muds. In such a setting, spatial heterogeneity equivalent to that observed among the anchor station sites on the GOP outer topset is expected. In addition, where local conditions are important in generating fluid mud suspensions, the bathymetry becomes a more important control over where fluid muds are likely to form.

The seasonal transport of sediment to the forest of the clinoform during the trade wind period may be reflected in the episodic nature of sedimentary deposits in some cores. Comparison of \(^{210}\)Pb profiles to grain size profiles from regions of rapid accumulation illustrate the episodic nature of sedimentation. Reduced \(^{210}\)Pb activities corresponding to elevated clay content of physically stratified units occur within some cores collected from the forest of the GOP clinoform [Crockett et al., 2008; Walsh et al., 2004]. Decreases in \(^{210}\)Pb activities at the seabed can be attributed to increases in sediment supply from shallow water. In the GOP, high-concentration, gravity-driven flows occur as a result of trade wind conditions, spring tide currents, and local trapping. It can be inferred that episodic sedimentation on parts of the forest is driven by the same conditions controlling gravity-driven flows on the clinoform topset.

### 5.2. Seasonal Sedimentation on the Tide-Dominated Inner Shelf

Seasonal patterns of inner shelf sedimentation have been observed for several environments in response to changes in riverine discharge and hydrodynamic forcing. For example, on the inner shelf of the Chiangjiang (Yangtze) River, monthly deposition rates exceed 100-t accumulation rates by an order of magnitude during the peak discharge interval [DeMaster et al., 1985; McKee et al., 1983]. The sediment deposited nearshore during the river flood period of three to four months (which constitutes 75% of the annual sediment supply) is subsequently transported to more distal parts of the dispersal system by winter storms and an intensified southward current. Though much smaller in
spatial scale, the Atchafalaya River inner shelf also shows seasonal development and reworking of flood deposits [Allison et al., 2000]. The period of rising discharge coincides with the occurrence of winter cold fronts lasting 3–7 d. During this time period, the formation of recognizable river flood deposits is hindered due to seaward transport as fluid muds, which form as suspended sediment settles with the passage of the cold fronts [Kineke et al., 2006]. When wind stress is reduced (i.e., winter cold fronts subside), flood deposits created during high discharge are clearly evident on the inner shelf seabed.

5.2.1. Across-Shelf Variability on the Fly River Inner Shelf

[51] Significant variation in seafloor elevation on semidiurnal or fortnightly timescales could not be detected at GOP anchor stations. However, much removal of surficial sediments occurred during the time between the trade wind season and the transition period (8 months later) at the sites of all three anchor stations. Over the sampling period, there was also an apparent increase in bioturbation within the upper 5 cm of cores collected at all three sites, with near-surface bioturbation being most extensive in Umuda Valley.

Figure 10. Schematic of fluid-mud formation within Umuda Valley during (a) spring flood tide and (b) spring ebb tide of the trade wind season. Strong tidal currents act in concert with waves to resuspend and advect sediment derived from the Fly River delta and the inner topset (31 salinity contours are shown). During flood tides, fluid mud gravity flows grow in thickness (to a maximum of ~130 cm) and in concentration (>100 g L\(^{-1}\)) as their downslope flow is impeded by shoreward currents (a local convergence mechanism) (Figure 10a). During ebb tides, downslope transport of fluid mud is assisted by seaward currents, and flows only reach a thickness of ~60 cm (Figure 10b).
[53] Walsh et al. [2004] observed an ephemeral mud deposit during the monsoon season (January 1999) on the inner topset of the GOP, shallower than 15 m. The deposit was ~20 cm thick, as indicated by uniform excess 210Pb activity. It was interpreted as being emplaced during the calmer monsoon conditions and subsequently remobilized during the more energetic trade wind conditions. The nearshore storage of sediment during the monsoon season results in reduced sediment supply to areas seaward of the inner topset region during the same time interval. The core locations in the present study are from deeper topset zone that is sediment starved during the monsoon season. The reduced sediment supply likely allows benthic organisms to temporarily colonize the seabed, leading to motting of sedimentary fabric on the outer topset of the GOP clinoform [Walsh et al., 2004].

[54] The release of seasonally stored sediment from the inner topset likely occurs as bed shear stress increases with the onset of the trade wind season. Transport at the beginning of the trade wind season would be episodic as spring-neap variations in tidal currents combine with shifting winds and periodically increased waves to produce high-concentration suspensions, which are transported across the clinoform outer topset and to the foreset. Fluid mud flows do occur in this system, as seen in the water column observations of Umuda Valley and central gulf outer topset during the trade wind season. Sequences of interlaminated sand and mud (which display minimal biological reworking) are observed down core on the NE Fly outer topset, likely reflecting similar mechanisms of sediment transport among sites located on the outer topset.

5.2.2. Temporal Variability on the Fly River Inner Shelf: Impact of El Niño Conditions

[55] Episodic suspension and deposition on the Amazon inner shelf is believed to result in long-term preservation of decimeter-thick, hiatus-bounded layers [Kuehl et al., 1995]. Though smaller in scale, the nature of dynamic processes influencing seasonal sedimentation on the topset of the GOP clinoform likely results in similar deposits. The difference in mass discharge of the two systems (i.e., Amazon discharges an order of magnitude more sediment) could place more importance on seasonal variation for preservation of hiatus-bounded sequences observed on the GOP inner shelf. The exception would apply to El Niño years when discharge of the Fly River drops below 1,000 m³ s⁻¹. During 2002–2003, the GOP experienced moderate El Niño conditions, indicated by a mean Southern Oscillation Index of ~−8.3 (Australian Bureau of Meteorology, http://www.bom.gov.au). Surface layers of cores collected during this study were likely affected by the 2002–2003 El Niño–Southern Oscillation (ENSO) [Ogston et al., 2008].

[56] Interlaminated sand and mud were present near the surface of cores collected during the trade wind season on the outer topset (including all the anchor station locations). By the transition period, these deposits were eroded completely (Figure 8). The presence of a bioturbated sequence of interlaminated sand and mud at the surface of the trade wind cores indicates that deep burial of this sequence did not occur. Similar sequences, with less biological mixing, exist down core and are capped by up to ~8 cm of massive/finely laminated mud (Figure 5). The thickness of these deposits and/or subsequent deposition of more massive mud results in their preservation. The amount of both interlaminated and massive mud could be affected by reduced sediment discharge resulting from lower river flow.

[57] During non-El Niño conditions, the discharge of the Fly River places the ETM near the mouth of the distributories to allow for interaction with shelf currents. As the tide ebbs, this positioning promotes discharge of sediment primarily through the northernmost distributary channel [Ogston et al., 2008]. Reduced freshwater discharge during El Niño years shifts the ETM more landward within the distributary channels, increasing the trapping efficiency of the delta and limiting sediment discharge to the shelf. El Niño conditions during the monsoon season of 2002–2003 likely limited deposition in the storage zone of the shallow inner topset, which, in turn, limited redistribution of this material to the deeper topset region represented by the anchor stations. As a result, the interbedded-sand-and-mud sequence created at the onset of the 2003 trade wind season was not adequately buried and/or sufficiently thick to insure its preservation throughout the rest of the seasonal cycle.

[58] Reduced delivery of sediment to the shallow inner topset throughout 2003 El Niño conditions may have contributed to the lower suspended-sediment concentrations observed at the NE Fly outer topset during the trade wind season spring tide anchor station. Fluid muds persisted throughout this time in Umuda Valley, because of its proximity to the Fly River mouth, channelized morphology, and steeper slope. The presence of uniform excess 210Pb to depths >100 cm in the seabed suggests that substantial amounts of modern sediment reach Umuda Valley (and the other anchor stations) under normal river flows.

5.3. Heterogeneity of Processes and Structures: A Comparison to the Amazon Shelf

5.3.1. Mesotidal Versus Macrotidal Shelf Environments

[59] Like the Fly River, the Amazon is a large tropical river that debouches onto a broad, low-gradient continental shelf, nourishing an active, prograding clinoform [Kuehl et al., 1986; Nittrouer et al., 1986]. Though the water discharge of the Amazon River (~160,000 m³ s⁻¹ [Milliman and Meade, 1983]) is much greater than the Fly River, both dispersal systems are composed predominantly of fine-grained sediment, are significantly influenced by semidiurnal tidal currents, and have had little anthropogenic impact, and are located close to the equator (ruling out significant cycloic storms). These similarities between the Fly and Amazon shelves suggest a common mechanism for the emplacement of interbedded sand and mud observed at both localities. Anchor station observations on the Fly River outer topset, however, highlight significant differences between these two environments.

[60] Estuarine processes modulated by tidal currents have been shown to produce sequences of interbedded sand and mud within a macrotidal estuary [Allen et al., 1980] and on a macrotidal inner shelf [Jaeger and Nittrouer, 1995; Kineke et al., 1996]. Water column observations of the Gironde Estuary [Allen et al., 1980] and Amazon clinoform topset [Geyer, 1995] revealed that salinity stratification at the estuarine front broke down as a result of spring tide currents, which reached >200 cm s⁻¹ [Kineke et al., 1996].
5.3.2. Process and Preservation of Tidal Deposits

For many sedimentary systems, water column stratification plays a large role in producing signals within the seabed [Jaeger and Nittrouer, 1995]. For many sedimentary systems, water column stratification plays a large role in producing signals within the seabed [Jaeger and Nittrouer, 1995].

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Jaeger and Nittrouer [62] Another significant observation was that fluid muds that persist for extended periods of time suppress mixing with the overlying water column, even when across-shelf advection occurs. If fluid muds alternate form and dissipate in response to waves and tides, as in the GOP, a discrete layer cannot be maintained and the nearshore salinity signal is lost. [63] For semidiurnal and fortnightly tidal sequences to be preserved, deposition must be sufficient to capture and record changes in water column and seabed dynamics, commonly representing very short time intervals [Klein, 1998]. Anchor stations occupied on the Amazon topset revealed that significant changes in seabed elevation occurred on a semidiurnal timescale (up to 5 cm of erosion and redeposition) and >15 cm of sediment could be deposited on a fortnightly timescale [Jaeger and Nittrouer, 1995]. Consequently, coarse-grained, ripple-cross-laminated deposits were preserved during times of high shear stress and bed load transport associated with spring tide currents. Thick, fine-grained units resulted from the deposition of fluid muds during subsequent conditions of reduced shear stress associated with neap tide.

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more rapid decadal accumulation rates (i.e., the clinoform foreset).

6. Conclusions

On the tropical, mesotidal, outer topset of the Gulf of Papua (~15 m water depth), the dominant controls on sediment transport processes occur on tidal and seasonal timescales. Sediment transport events on the Fly River shelf occur cyclically and are related to the seasonal change in direction and magnitude of winds, and are modulated on hourly timescales by strong, semiidiurnal, spring tide currents. In contrast, for dispersal systems located at higher latitudes, cyclonic storms and river floods are the dominant signals observed in the water column and recorded in the seabed.

On the GOP outer topset, the most dynamic periods of sediment transport (i.e., largest variations in SSC) occur during spring tides of the trade wind season. The more energetic wave climate during this period remobilizes sediment deposited on the inner topset through the previous monsoon season, facilitating transport to regions of rapid accumulation on the shelf (i.e., the clinoform foreset). Strong spring tide currents help generate and maintain fluid muds on the topset and, with a sufficient seabed slope, deliver sediment seaward. Flood tide currents, which are directed landward, impede gravity flows, allowing fluid muds to build in thickness and concentration. Subsequent ebb tide currents complement the seabed slope, facilitating seaward transport. This form of sediment trapping and seaward delivery is fundamentally different from the Amazon shelf, where estuarine processes maintain fluid mud on the topset. Near the Fly River mouth, where asymmetric tidal flows produce a net transport landward in the benthic boundary layer, these observations of gravity flows are particularly important as they provide a mechanism to transport material to deeper parts of the shelf.

On the outer topset, physical sedimentary structures in the seabed prevail over biological structures. However, neither formation of sedimentary structures nor significant change in seabed height was observed on the semidiurnal timescale during any of the three spatially distributed anchor stations on the outer topset. Though the observations suggest that the seabed in these regions is not dynamic on tidal timescales, there are reasons to hypothesize otherwise. From mid-2002 to mid-2003, El Niño conditions resulted in reduced Fly River discharge, probably limiting sediment delivery to the inner topset and, subsequently, to the outer topset. The physical character of interlaminated sands and muds down core suggests rapid deposition, however, these events are likely sporadic and timing of the anchor stations may have missed them. The most significant changes in the seabed occur on the seasonal timescale. The outer topset (~15 m water depth) experienced significant erosion following the trade wind season of 2003. Calm conditions throughout the monsoon season favored deposition on the inner topset. At the same time, persistent tidal currents on the outer topset combined with limited sediment delivery promoted erosion there.

Though seasonal and tidal variation drive sediment transport processes along the outer topset, spatial differences exist between Umuda Valley, the NE Fly outer topset, and the central gulf outer topset. Umuda Valley acts as a conduit for suspended sediment, due to its proximity to the Fly River mouth and by enhancing tidal currents and concentrating gravity-driven flows. The central gulf outer topset is influenced less by the Fly River discharge, placing a more prominent role on the regional circulation [see Slingerland et al., 2008] in delivering and concentrating sediment there. On the broad NE Fly outer topset, seabed evidence for gravity-driven flows exists, but they were not observed, highlighting the spatial and temporal heterogeneity of the processes operating on the outer topset.

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