Selective Sorting, Storage and Progressive Dilution of Sediment in Two Tropical Deltas, Veracruz, Mexico

Zhongyuan Chen†, Daniel Jean Stanley‡, and Eric E. Wright§

†State Key Laboratory for Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China P.R.
‡Deltas-Global Change Program, E-206 NMMNH Paleobiology, Smithsonian Institution, Washington, D.C. 20560, U.S.A.
§Marine Science Department, Coastal Carolina University, Conway, SC 29528, U.S.A.

ABSTRACT


Compositional and textural attributes of the surficial sediment in deltaic settings typically differ from the sediment load carried by their source rivers. This phenomenon is evaluated here by semiquantitative study of the variability of petrologic characteristics in different delta subenvironments of the Nautla and Tecolutla deltas along Mexico’s Veracruz coast. Sediment composition and texture in the different environments of both deltas are related to processes that involve selective sorting during seasonal flooding and temporary storage after deposition. Displacement of particles of different size, density and shape onto the two tropical delta plains is controlled by fluctuating fluvial discharge that responds to a highly variable seasonal rainfall pattern. These discharge variations induce changes in hydraulic equivalence and, consequently, the release of substantially different proportions of volcanic, mica, heavy mineral and grain-size fractions in the Veracruz delta settings. These phenomena, together with progressive dilution of sediment upon reaching the coast, result in significant modifications to the original petrologic attributes of fluvial loads as they are transported seaward.

Comparable variations of composition and texture in subsurface Holocene sections would likely record former large-scale climate, rainfall and fluvial discharge fluctuations. Petrologic analysis of core sections recovered at Prehispanic sites on the two deltas could be used to detect past long-term flooding pulses and droughts, natural events that archaeologists suggest caused deterioration of subsistence resources, stratigraphic hiatuses, cultural discontinuities and human migrations in this region.

ADDITIONAL INDEX WORDS: Archaeological sites, delta sedimentation, fluvial discharge, Gulf of Mexico, Holocene, particle composition, rain pattern, sediment load, texture, transport processes.

INTRODUCTION

A river’s unidirectional flow carries a sediment load that is generally representative of materials transported from upslope source terrains. However, petrologic analyses of modern deposits positioned in deltas and contiguous coasts indicate that the proportions of compositional components accumulated in such coastal settings usually differ substantially from those of their major fluvial channels in more landward and upslope sectors. Several petrologic investigations, such as that of the Burdekin delta in Australia (*ETHRIDGE et al.*, 1975), have detailed the compositional and textural variability in delta systems that are proximal to source terrains. Most such studies of modern deltaic deposits, however, have been made in settings that are at a considerable distance from terrigenous source areas. Examples include the Nile (*STANLEY and CHEN, 1991; STANLEY et al., 1992*) and Yangtze (*YAN and XI, 1987*) where composition and texture of the sediment released in various deltaic subenvironments differ markedly from that of the sediment load carried by their main river channels.

The southwestern Gulf of Mexico coastal margin, flanked by the high Sierra Madre Oriental chain of eastern Mexico, provides an appropriate setting to gain further insight on the nature of depositional variability in deltas. Preliminary surveys were made of two small tropical deltas, Nautla (*SELF, 1971, 1975*) and Tecolutla (*LENTELL, 1975*), positioned ~35 km apart on the tropical Veracruz margin of the Gulf of Mexico (Figure 1). Building upon these earlier studies, the current investigation focuses specifically on the semiquantitative changes of composition and texture in these two deltas to determine the relation that may exist among petrology, delta subenvironment and sedimentation process. Also considered are depositional processes that modify the fluvial loads of the Nautla and Tecolutla rivers as they reach deltaic and contiguous coastal environments. Definition of petrologic variability in the two lower river systems in this investigation provides a means to interpret the past geological and human history of this region.

DESCRIPTION OF STUDY AREA

The Nautla and Tecolutla rivers are short (~160 km and ~220 km, respectively) torrential rivers, with headwaters in the proximal Sierra Madre Oriental mountain chain (Figures 1, 2). Tributaries of these two rivers reach elevations in ex-
Sediments in Tropical Deltas

cess of 3000 m, and channels flow down steep eastern mountain flanks toward the northeast. Beyond the base of mountain slopes, the rivers traverse piedmont hills, alluvial fans and terraces (Figures 3, 4A) and extend across the lower, narrow (~15 km), near-horizontal coastal plain. Sediment source areas for the Nautla and Tecolutla deltas are primarily volcanic terrains widely exposed in the Neovolcanic Cordillera of the Sierra. Peaks include the Cofre de Perote (4282 m) and Pico de Orizaba (5747 m), andesitic cones active during the Cenozoic (GARFIAS and CHAPIN, 1949; TAMAYO, 1962; MEXICO, DIRECCION GENERAL DE GEOGRAFIA, 1984; MORAN-ZENTENO and Collaborators, 1994).

Sediment in both drainage basins is transported to the sea by rivers that are directly subject to seasonal rainfall and flooding. Mean annual rainfall ranges regionally from ~1500 mm on the coastal plain to as much as 3000 mm in high-elevation headlands (TAMAYO, 1962; SELF, 1971). Rain falls primarily in summer and early fall, and is heaviest during August and September. Differences in transport regime and sediment supply to the two deltas are mainly a result of dissimilarities in fluvial basin area and consequent amounts of discharge (TAMAYO, 1962). The area of the Nautla drainage basin is approximately 2270 km²; the average river flow is 1,086,000 m³ per km² of basin area, accounting for a mean annual discharge of 2465 million m³. In contrast, the Tecolutla drainage basin area (8080 km²) is about 3.5 times larger, while the average river flow per basin area (931,800 m³ per km²) is nearly the same as the Nautla. This accounts for a mean total annual river discharge of the Tecolutla that is at least 3 times larger (7529 million m³) than in the Nautla. During dry periods, flow in the lower Nautla is reduced to ~20 m³/sec, while in the lower Tecolutla it is at least 30 m³/sec.

Figure 1. Map (modified from several sources) showing the two delta study areas on the Veracruz coastal margin, southwestern Gulf of Mexico.
The Nautla and Tecolutla Holocene deltas are among several wave-dominated and sharply truncated depocenters along the NW-SE trending Veracruz margin (Figure 5D-F). The distance between apex and coast is ~9 km in the Nautla delta and ~7 km in the Tecolutla delta, and both have a coastal margin length of ~14 km. The trapezoidal Nautla delta area is ~115 km², and that of the triangular Tecolutla is ~50 km². Delta margins and distributary channel patterns are constrained by adjacent higher terrains formed by Tertiary and Quaternary deposits (Figure 6A). This coastal region, characterized by few, low magnitude, shallow earthquake epicenters, has remained relatively stable during the Holocene. Some faulting and neotectonic deformation (Lentell, 1975), however, appear to control the configuration of the two depocenters, including angular paths of their fluvial channels and distributaries (Figures 2, 3). The savannah veg-
station that now prevails over large parts of this coastal area (Figure 4A–D) results primarily from recent human activity, including deforestation of tropical stands, cattle ranching and plantation agriculture (Wilker son, 1976, 1983; HEBDA et al., 1991).

Fluvial discharge reaches the Veracruz coast where the mean air temperature ranges from -21°C to 29.5°C annually (Leipper, 1954a), mean annual surface temperature of Gulf water ranges from 21°C to >25.5°C, and mean tidal range approximates 1.3 m (Tamayo, 1962). Most pertinent in this study are wind and surface current patterns that vary seasonally. In winter (January), wind velocity (10 to 12 knots) and direction are variable, most from easterly directions, with fewer southerlies but more northerlies, and surface ocean currents are oriented primarily toward the southeast (as part of a Gulf counter eddy), with flow approximating 4 nautical miles per day (Leipper, 1954b). Conditions differ in summer (July), when wind velocities diminish (6 to 8 knots) and directions are less variable, primarily from the southwest (following the major Gulf circulation pattern), with flow ranging from 6 to 12 nautical miles per day. As a response to these seasonally variable physical conditions, fluvial sediment from the Nautla and Tecolutla rivers is dispersed along the coast by wave-driven currents toward the SE in winter (Figures 3, 5D–F), and NW in summer.

METHODS

A total of 122 surficial sediment samples on and adjacent to the Nautla (62 samples) and Tecolutla (60 samples) deltas were collected in February 1996 (Figure 2). These samples were recovered in the following 11 environments (using numerical codes 1–11), from land to sea: river (1), natural levee (2), delta plain (3), marsh (4), red mangrove (Rhizophora mangle) thicket (5), upper estuary (tidal creeks in Nautla, tidal ponds in Tecolutla) (6), lower estuary (where channels widen markedly and are affected by the sea) (7), dune (8), beach (9), breaker zone (10), and inner shelf (11). At least five to eight samples were collected in each of the above environments in the two deltas.
The amount of organic matter (by weight percentage) was determined for a representative cut of each sample by combustion at 450°C for 4 hours. A separate sample fraction was selected to determine grain size and identify sand-size compositional components; in this cut, plant fragments and other particles of coarse size (>1 mm) were separated by sieving, and organic matter was removed by using bleach. More than 300 grains in the sand-size residue (63 to 1000 μm) were identified and counted in each sample. The following 14 components were recorded: volcanic (rock fragments, glass), mica,
light minerals, lithic aggregate, calcareous fragment (limestone fragment, unidentified biogenic material), heavy minerals (opaque, transparent), iron nodule, foraminifera, ostracod, pelecypod, gastropod, echinoderm, diatom, and ‘other’.

Grain size was determined for the fraction ranging from 0.4 to 1000 µm, using a Coulter laser diffraction particle analyzer (LS 200). Moment measures and percentages of clay (<4 µm), silt (4–63 µm), and sand (>63 µm) were obtained for each sample.

Averaged percentages of sand-size compositional components, organic matter and textural parameters for each environment in the Nautla and Tecolutla deltas are listed in
Figures 7 and 8. Complete petrologic database listings that record non-averaged numerical information for each individual sample are available from the authors.

OBSERVATIONS

Petrologic data of our Nautla delta study are compared to those of SELF (1971, 1975) who examined sediment samples collected between headwaters and coast in the Nautla drainage basin. Compositional components are dominated by volcanic (rock fragment, glass), quartz, feldspar, limestone fragment, and a heavy mineral suite comprising largely magnetite, pyroxene, and amphibole. These are derived from exposures in the eastern and southeast flank of the Sierra Madre Oriental (Figure 6A): Cenozoic volcanics, including andesite,
Sediments in Tropical Deltas

Compositional Component (% Sand)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1=River (8)</td>
<td>21.8</td>
<td>1.1</td>
<td>8.6</td>
<td>61.3</td>
<td>6.6</td>
<td>0.4</td>
<td>0.5</td>
<td>398.8</td>
<td>3.7</td>
<td>8.4</td>
<td>89.0</td>
</tr>
<tr>
<td>2=Natural Levee (5)</td>
<td>32.6</td>
<td>0.5</td>
<td>2.5</td>
<td>59.4</td>
<td>4.6</td>
<td>0.3</td>
<td>1.1</td>
<td>71.5</td>
<td>22.5</td>
<td>43.7</td>
<td>34.2</td>
</tr>
<tr>
<td>3=Flood Plain (5)</td>
<td>32.4</td>
<td>0.8</td>
<td>1.8</td>
<td>58.9</td>
<td>5.6</td>
<td>0.5</td>
<td>1.4</td>
<td>42.6</td>
<td>29.0</td>
<td>51.1</td>
<td>19.2</td>
</tr>
<tr>
<td>4=Marsh (5)</td>
<td>13.7</td>
<td>1.5</td>
<td>4.5</td>
<td>70.5</td>
<td>9.6</td>
<td>0.2</td>
<td>15.0</td>
<td>96.1</td>
<td>26.3</td>
<td>39.1</td>
<td>34.3</td>
</tr>
<tr>
<td>5=Mangrove (6)</td>
<td>56.5</td>
<td>0.8</td>
<td>0.0</td>
<td>40.9</td>
<td>1.6</td>
<td>0.2</td>
<td>5.1</td>
<td>49.1</td>
<td>26.7</td>
<td>50.3</td>
<td>23.0</td>
</tr>
<tr>
<td>6=Upper Estuary (5)</td>
<td>54.8</td>
<td>1.0</td>
<td>3.0</td>
<td>31.1</td>
<td>3.8</td>
<td>6.3</td>
<td>6.9</td>
<td>30.2</td>
<td>30.2</td>
<td>52.9</td>
<td>16.9</td>
</tr>
<tr>
<td>7=Lower Estuary (7)</td>
<td>11.3</td>
<td>0.4</td>
<td>13.9</td>
<td>62.6</td>
<td>11.0</td>
<td>1.1</td>
<td>2.0</td>
<td>281.9</td>
<td>9.9</td>
<td>19.0</td>
<td>71.1</td>
</tr>
<tr>
<td>8=Dune (5)</td>
<td>5.8</td>
<td>0.1</td>
<td>24.7</td>
<td>38.6</td>
<td>29.6</td>
<td>1.2</td>
<td>0.2</td>
<td>263.0</td>
<td>0.4</td>
<td>0.7</td>
<td>98.9</td>
</tr>
<tr>
<td>9=Beach (5)</td>
<td>6.6</td>
<td>0.0</td>
<td>30.9</td>
<td>48.3</td>
<td>12.8</td>
<td>1.3</td>
<td>0.1</td>
<td>279.6</td>
<td>0.1</td>
<td>0.2</td>
<td>99.7</td>
</tr>
<tr>
<td>10=Breaker Zone (5)</td>
<td>6.5</td>
<td>0.0</td>
<td>36.9</td>
<td>48.3</td>
<td>6.6</td>
<td>1.7</td>
<td>0.1</td>
<td>323.8</td>
<td>0.0</td>
<td>0.1</td>
<td>99.8</td>
</tr>
<tr>
<td>11=Inner Shelf (5)</td>
<td>12.2</td>
<td>0.2</td>
<td>16.5</td>
<td>65.1</td>
<td>4.3</td>
<td>1.8</td>
<td>0.7</td>
<td>149.3</td>
<td>3.0</td>
<td>9.6</td>
<td>87.4</td>
</tr>
</tbody>
</table>

Figure 7. Table listing averaged sand-size compositional components, organic matter (% by weight), and sediment texture from 62 surficial samples in 11 environments of the Nautla delta. Compositional data are depicted in graph below.

ash and tuff; granite of undetermined age; Cretaceous limestone; and Tertiary and Quaternary clastics in piedmont, alluvial fan and terrace deposits at the base of the steep Sierra Madre slope.

SELF (1971, 1975) defined three fluvial segments of the Nautla (Figure 6A,B): headwater (from ~3750 m, on the flanks of the Cofre de Perote volcano, where slope exceeds 50 m/km), intermediate (where slope decreases to ~5 m/km), and coastal (where the Nautla flows on a slope of <1 m/km). That author recorded a sharp decrease in percent gravel, mean grain size, and some heavy mineral species at the base of the intermediate segment, and interpreted these changes as a response to the altered fluvial regime where slope decreases on the lower part of alluvial fans (SELF, 1975, his Figure 3). The simplified, downslope-trending mineralogical pattern that he compiled shows a general seaward increase in volcanic and limestone rock fragments, and somewhat decreased proportion of light minerals (quartz, feldspar) toward the coast (Figure 6B). His findings indicate that Nautla sediment reaching the Gulf coastal margin comprises to 48% volcanic material (33% rock fragments, 15% ash), 34% light minerals (22% quartz, 12% feldspar), 7% calcareous fragments, and to 11% heavy minerals plus 'other' components (SELF, 1975).
Using sample data obtained in the current study, we compile a similar graph for the ~15 km wide base of slope-Nautla delta-coastal sector (Figure 6C). Shown is the percentage of compositional components for each of the 11 Nautla subenvironments (1-7, deltaic, 8-11, contiguous coastal). Of note are particularly high proportions of volcanic fragments in the mangrove and upper estuary, and very low values of these components in coastal environments. Reworked carbonate fragments and shells are present in the lower estuary, but scarce in the marsh and mangrove. Light mineral suites are particularly abundant along the river channel, on delta natural levees and flood plain surfaces along the river channel, while smaller proportions are present in mangrove, lower estuary and coastal environments. Recent whole shells of marine origin accounts for high values of 'other' in coastal samples; mica and heavy minerals, also in the 'other' category, occur in marsh, river channel and lower estuary, but are scarce in mangrove. High proportions of marine shells characterize dune, beach, and offshore environments. It is apparent that there is as much, and in some cases more, compositional variation along the ~15 km wide lower Nautla-coastal plain sector (Figure 6C) as there is along the entire ~160 km-long fluvial stretch between Sierra Madre headwaters and the shore (Figure 6B).
Table 1. Ranking of compositional parameters by decreasing order of importance for the top 4 parameters for each delta environment (percentage of total sediment as calculated from Figures 7 and 8).

<table>
<thead>
<tr>
<th>Components</th>
<th>1 = Natural Flood</th>
<th>2 = River Levee</th>
<th>3 = Marsh Plain</th>
<th>4 = Upper Marsh</th>
<th>5 = Estuary Mangrove</th>
<th>6 = Lower Estuary</th>
<th>7 = Dune</th>
<th>8 = Beach</th>
<th>9 = Breaker Zone</th>
<th>10 = Offshore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volcanic Mica</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Calcareous Frags</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Light &amp; Lith. Agg.</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Heavy Min. &amp; Iron</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Biogenic Shell</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Organic Matter</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Inorganic Mud</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**NAUTLA DELTA**

**TECOLUTLA DELTA**

To better define the relationship between petrology and delta subenvironment, it is useful to consider a somewhat different and larger number of components. Thus, for each of the 11 Nautla environments, the numerical data in Figure 7 is listed within 6 compositional groups (these incorporate all 14 components described in the above Methods section), plus average organic matter and textural data. Our database (Figure 7) shows that composition of sand-size components in river channel, levee, and adjacent flood plain is similar to that of the Nautla above the piedmont base of slope. In contrast, the other environments record a much greater variation.

The 11 Nautla environments can be readily differentiated by using the various proportions of volcanics, mica, carbonate fragment and biogenic shell, and heavy minerals (Figure 7). Noted is the high content of sand-size volcanics in mangrove and upper estuary, mica in marsh, heavy minerals in dune, and biogenic shell in estuarine and coastal environments. Also of significance are high proportions of organic matter in the marsh, mangrove and upper estuary, and considerably coarser mean grain-size in the lower estuary and coastal environments. Mud-rich sediment prevails on all delta plain environments.

Considering the Nautla delta sediment as a whole, we identify the 4 most important parameters in each of the subenvironments (Table 1). Assessment of the dominant 2 parameters shows that inorganic mud-size sediment prevails in delta flood plain and estuarine environments, while lights and lithic aggregates are the dominant components in river, lower estuary and coastal environments. Volcanics are also important in river, mangrove and upper estuary, calcareous fragments in marine settings, and heavy minerals in dune.

The dataset for the Tecolutla delta system (Figure 8) is strikingly similar to that of the Nautla. Among significant differences recorded (Table 1) are the much lower volcanics in upper estuary, and relatively high mica only in marsh and mangrove. An evaluation of the Tecolutla sediment as a whole provides a higher ranking for organic matter in the marsh, mangrove and upper estuary, and calcareous fragment in the river channel. Also in contrast with the Nautla is the lower ranking of volcanics in river, mangrove and upper estuary.

**DISCUSSION**

The database presented here indicates that (1) the proportion of compositional components, amount of organic matter and texture all vary extensively from environment-to-environment in each delta, and (2) these parameters vary similarly in the comparable settings of the two deltas. Both Nautla and Tecolutla rivers carry large sediment loads, with concentration of suspended solids to >1.0 part/1000 (Tamayo, 1962) and, as noted earlier, drain similar geological terrains. Moreover, both deltas contain large proportions of volcanic material in mangroves, and high amounts of organic matter and finer grain size in marsh, mangrove and upper estuary. However, an important clue to understanding the dynamics of sediment transport is provided by the major difference that exists between the two deltas: there is a much lower proportion of volcanic material in the upper estuary (tidal ponds) of the Tecolutla (10%) than in the upper estuary (tidal creeks) of the Nautla (55%). Although the Nautla river carries only a somewhat higher proportion of volcanic material (~22%) as compared to the Tecolutla (~16%), there is more than five times the amount of volcanics in the upper estuary of the Nautla (Figure 7) than that in the Tecolutla (Figure 8). While Tecolutla ponds may serve as more effective traps (Figure 4E,F) for mud-size material, organic matter and volcanic particles, their markedly increased proportions in the Nautla is a function of smaller drainage basin area and lower overall discharge, as well as of input from more local flood plain runoff.

Overbank flow prevails in both rivers at times of flood, providing large contributions of smaller particles (silt, clay), high
proportions of volcanic, and some organic matter; these components become selectively trapped in mangroves, particularly by tidal forces. Flooding also flushes clay and silt fractions seaward from the estuaries of both delta systems. The environment-to-environment variations of composition (such as proportion of volcanic particles) and texture and differences between Nautla and Tecolutla recorded here can best be interpreted in light of different hydrologic attributes of the two fluvial systems. The larger Tecolutla discharge results in more efficient flushing of its upper estuary and marshes, and reduced temporary storage of sediment therein (cf. LEOPOLD et al., 1964; MEADE, 1988). This decreased retention accounts for lower amounts of volcanic particles and mica in these two environments than in the Tecolutla river system, and is also lower than in comparable settings of the Nautla.

We attribute some petrologic differences between subenvironments in the two deltas to effects of selective sorting (cf. STANLEY, 1978) that occur primarily at times of seasonal flooding and overflow onto the delta plain. In settings of variable energy levels beyond the base of slope, particles released from fluvial flow are segregated on the basis of size, specific gravity and particle shape (FREUNDT and ROSI, 1998). This is a function of mineral grains of different composition and/or texture and/or shape that are hydraulically equivalent, i.e. although displaying different attributes, these grains have similar fall velocities and are deposited together (PETTIJOHN, 1957; PETTIJOHN et al., 1973). The phenomenon of hydraulic equivalence plays a determinant role in the segregation of sediment particles by variable energy levels of flow across a delta plain. This is recorded by the distribution of less dense volcanic material (specific gravity ranging from 1.0 to 2.0), relative to that of light minerals and denser andesite and rhyolite fragments (specific gravities from ~2.0 to 2.8), heavy mineral suites (>2.9), and basalt (~3.1). The distribution pattern of volcanic particles, especially glass, is controlled by shape, i.e. grains are less spherical (values of ~0.5–0.7) than most light and heavy mineral particles with which they are associated. In similar fashion, mica serves as a distinct marker of transport conditions. This component, with typical flake shape and densities ranging from ~2.8 to 3.1, is often associated with elongate and less dense plant fragments; mica also commonly occurs with light minerals and lithic aggregates of somewhat smaller size in the wetlands and on the flood plain of the delta. The above and other transport-related petrologic associations are determined from Table 1 and Figures 7 and 8.

Upon reaching the coast, composition and texture of the fluvial sediment is laterally displaced by moderate to high-energy marine processes (Figures 5D–F). The higher discharge of Tecolutla fluvial runoff and sediment has caused a greater seaward progradation, and a consequent gentle cuspatate shape, of its coastal delta margin (Figures 2, 3). In contrast, the Nautla’s smaller discharge has resulted in a truncated and coast-parallel delta shoreline (Figures 2, 5F). Lag-concentrate sands rich in heavy minerals accumulate in response to the winnowing and selective removal of less dense (such as volcanics) and fine-grained particles. Wave-driven coastal currents that prevail along the shoreline and inner shelf (Figure 2) completely modify any remaining fluvial load attributes of sediment reaching the sea. In these high-energy settings, selected components are removed, and proportions of original particles are masked by introduction of both modern and relict terrestrial particles from other coastal areas and in situ carbonate shell material. The progressive dilution effect (cf. PETTIJOHN, 1957) results in a surficial sediment cover on the inner shelf that comprises a mix of reworked modern and relict components, one that bears little resemblance to the Nautla and Tecolutla terrigenous material carried to the coast.

The Veracruz margin and ecologically rich environments of the Nautla and Tecolutla deltas have long served as breadbaskets for human occupants. Both delta surfaces include important vestiges of Prehispanic cultural and agricultural complexes. There is, for example, evidence of pre-16th Century patterned wetlands, such as raised planting platforms, canals and drainage systems (Figure 4D) developed to enhance agricultural utilization of marginal soils (WILKERSON, 1976, 1983; HERBA et al., 1991). Human centers, including Santa Luisa in the Tecolutla and El Pital in the Nautla (Figures 2, 4B), waxed and waned as populations shifted at different times during the Holocene (WILKERSON, 1983, 1994b). Correlation of compositional and textural characteristics with fluvial regimes and specific depositional environments in the two deltas can help archaeologists understand causes for suggested changes of human occupation in this region since at least 6000 years before present.

In other deltas, such as the Yangtze, it has been shown that long-term floods and droughts cause stratigraphic hiatuses and environmental change that induce cultural disruption and human relocation (cf. STANLEY et al., 1999). In subsurface sections of the Nautla and Tecolutla, changes in proportions of grain size, volcanics, mica, and heavy mineral suites, as determined semi-quantitatively in this study, would signal modified fluvial discharge induced by altered climate-rain pattern. It is anticipated that the record of petrologic variations in radiocarbon-dated sediment borings obtained in and adjacent to archaeological sites in the Veracruz deltaic areas will provide new insight on the timing and nature of altered climate fluctuation. Marked changes in fluvial discharge regimes and deterioration in local subsistence resources likely had a direct impact on Prehispanic Veracruz cultural centers (WILKERSON, 1976, 1994a,b). It is also possible that the petrologic approach used in this study can help determine if such climatic and hydrologic fluctuations occurred randomly or cyclically, and perhaps if they were related to largescale phenomena such as El Niño events (cf. MEGGERS, 1994a,b).

CONCLUSIONS

There is close correlation between petrologic attributes and delta subenvironments in the Nautla and Tecolutla deltas on the southwestern Gulf of Mexico margin. Although positioned close to the base of highlands and receiving sediment directly from adjacent mountain sources, we show that composition and texture of surficial deposits in some deltaic subenvironments differ markedly from those of fluvial loads derived further upslope. Findings here indicate that transport processes,
responsible for distributing sediment onto the two Veracruz deltas, induce more than the simple, seaward, grain-size fining expected in a unidirectional flow system.

Important and consistent variations of compositional and textural characteristics in specific deltaic and contiguous coastal settings are largely a response to the different energy conditions that prevail in such geographic environments. Major controls of sediment displacement and deposition on delta plains include selective sorting and temporary storage of particles on deltas as related to flood discharge. In addition, progressive sediment dilution occurs as downslope transported river material reaches the sea and is dispersed by high-energy wind and coastal current conditions. We expect that these processes, causing significant modifications in the petrology of the original fluvial load, prevail in most deltas. As exemplified in other delta investigations, definition of petrologic attributes in the surficial cover is essential to interpret subsurface Holocene facies recovered in sediment borings, and reconstruct a delta's paleogeographic evolution through time and space.

Major compositional and textural variations of the type recorded in this study, if identified and correlated laterally in dated subsurface sections in the Nautla and Tecolutla, would help detect significant phases of Holocene flooding and droughts in the past. Such events inevitably affected the evolution of Prehispanic cultural centers on the two delta plains in this Veracruz region by altering essential subsistence resources and inducing human migrations.

ACKNOWLEDGEMENTS

We thank Dr. S.J.K. Wilkerson, director of The Institute for Cultural Ecology of the Tropics, Veracruz, Mexico for encouraging this study, providing logistical support and kindly hosting us at his Institute during our fieldwork. Laboratory assistance was provided by Messrs. W. Boykins and J. Winserath, and technical assistance with manuscript preparation by Mr. N. Tandon, all with the Department of Paleobiology, NMNH. Our appreciation is also expressed to Drs. S. Soter and A.G. Warne for their useful reviews. The project was funded by grants from the National Geographic Society, Smithsonian Institution (Scholarly Studies Program, Office of the Fellowships and Grants, National Museum of Natural History Walcott Fund), TCTPF-China, and China NSF (Grant No. 49971011).

LITERATURE CITED


MEXICO, DIRECCION GENERAL DE GEOGRAFIA, 1984. Carta de Terrenos y Conjuntos Estratotectonicos de la Republica Mexicana. Scale, 1: 2,000,000. Instituto Mexicanos del Petroleo and Instituto Nacional de Estadistica Geografia y Informatica (Geological map, in 2 sheets).


