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COASTAL RESPONSE TO CHANGES IN SEA LEVEL SINCE THE LAST 4500 BP ON THE EAST COAST OF TAMIL NADU, INDIA

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ABSTRACT. Geomorphology, clay mineral composition, and radiocarbon dates from Muttukadu to Marakkanam estuaries and the tidal zone along the east coast of Tamil Nadu, India, have been used to reconstruct coastal evolution between approximately 4500 and 1100 BP. Formation of alternate oyster beds with intervening tidal clay units indicate fluctuation in the sea level may be a consequence of changes in the Mid-Holocene sedimentation pattern and coastal configuration. ^{14}C dates from Muttukadu indicate a rapid relative sea-level rise (RSL) subsequent to 3500 BP and tidal flat sedimentation between 3475 and 3145 BP. Marine conditions along the east coast area returned around 1900 BP. Comparison of dates with other sites, e.g. Muttukadu, Mammallapuram, and Marakkanam, points toward short removal of marine conditions, ample sediment supplies in the tidal zones, and neotectonic activity. Reactivation of the north–south trending fault line occurred not earlier than approximately 1050 BP. Our study indicates that Middle to Late Holocene coastal sedimentation and the chronology of the tidal zone formation have been strongly influenced by local factors. These have provided considerable scope for internal reorganization with changing coastal processes.

INTRODUCTION

During the Holocene, the coastal environment experienced active cyclones and climate change, and the intensity of these processes varied in diverse coastal geomorphologic settings (Belknap et al. 1989). Sea level changed rapidly throughout the world. The effects of the relative sea-level change imprinted signatures in coasts, tidal zones, and estuaries. These signatures can be determined by the application of the radiocarbon dating method and geomorphology of the coasts. ^{14}C dating of shells, corals and organic carbon-rich clay occurring in the tidal flat zones and estuaries has often been used to determine the age of formation and processes of deposition (Katupotha 1994).

Along the east coast of India (Vaz 2000), Mid-Holocene coastal changes have not been studied in great detail as compared to the work carried out in the west coast of India (Nigam and Khare 1994; Badve et al. 1997). A study was carried out to understand sedimentological pattern in the tidal flat occurring along the east coast of Tamil Nadu between Muttukadu and Marakkanam. This study was based on geomorphology, ^{14}C dating of oyster beds, shell fragments, and organic carbon-rich clays. The purpose of this paper is to present ^{14}C data available for the east coast tidal zone and estuary associated sediments.

Geology of the Study Area

The east coast, Tamil Nadu is a narrow, sandy coastal belt extending from Chennai, Muttukadu to Mammallapuram and Marakkanam near Pondicherry. It covers an aerial extent of approximately 150 km^2, and was studied for delineating various geomorphic units. The area was mapped using satellite data IRS –1A LISS II and ground checked for the various geomorphic units (Figure 1). Geomorphology of the tidal flats and estuary along the east coast of Tamil Nadu between Muttukadu (12°49′N, 80°16′E), Mammallapuram (12°37′N, 80°14′E), and Marakkanam (12°13′N, 79°56′E) (Figure 1), reveal beach dunes running parallel to the present coastline and beach ridges inland. The dunes are stabilized at their base but are mobile on their crests. The coastal dune field, which is stabilized by vegetation, occurs in a very high-energy wind regime. At a height of 10–15 m, irregular dune forms gradually replace the dune ridges slightly inland. The geology of the study area is represented by the Archaean charnockite rocks which are overlain by a thick mantle of Quaternary allu-

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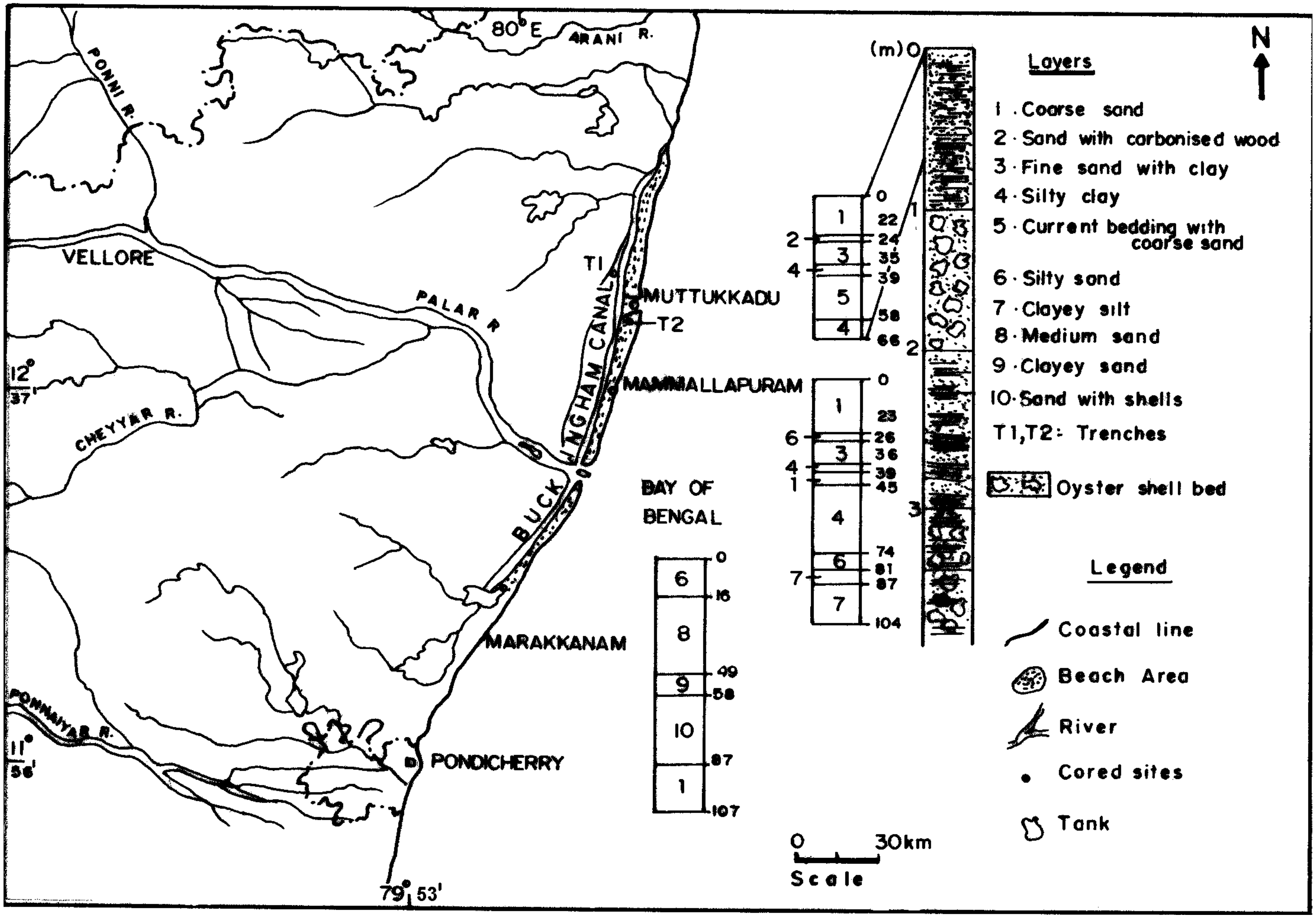

Figure 1 Location map of the study area

vium and these are in turn overlain by the Holocene tidal flat deposits and dunes (Achyuthan 1997). Isolated pockets of charnockite rock exposures occur at Muttukadu and Mammallapuram. A north–south trending boundary fault projects into the sea at Mammallapuram. The site around Marakkanam exposes Cuddalore sandstone of Mio-Pliocene age resting over the charnockites and in turn is overlain by the Quaternary sediments. The Adyar and the Palar rivers drain the coastal strip. The rocks of the Adyar drainage basin are predominately charnockites of the Precambrian age. By contrast, the Palar river basin near the coastline is carved into the sedimentary rocks of the Upper Jurassic to Middle Cretaceous age. The hinterland for the basins is fairly hilly, ranging in height from 200 to 250 m within 30 km of the sea.

The study area receives both summer and winter rains, the latter being dominant during October to December receiving an average rainfall of 1200 mm per year. The area experiences a subtropical climate with mean annual average temperature of 28–30 °C. The wind velocity is also stronger during the same period. The climate of the narrow coastline belt is tropical and humid. The local fishing community is presently exploiting oyster beds (*Crassostrea madrasensis*) occurring at Muttukadu for lime burning.

Linear dunes along the shoreline, which are stabilized to a large extent, represent the major geomorphology of the area. A spit of sand protects the low-lying marshy land at Muttukadu. The coast has a meso-tidal range and the current altitude of mean high water from spring tides at Mammallapuram is 1.5 m OD MHWST.

Four major zones within the tidal flat were recognized at Mammallapuram, Muttukadu, and Marakkanam: 1) an outer sand flat merging with the beach dune complex and rock exposures, 2) middle sand flat, 3) sandy to silty inner flats (mixed flats of Reineck and Singh 1980), and 4) salt marsh. The salt marsh is separated from the inner flat by a narrow spit built of shell and shell debris. Variation in carbonate percentage of the spit is largely a function of shell content. Grain size decreases from the outer flat zone to the inner flat. The channel is also characterized by relatively poor sediment sorting.

The outer sandy flat and the beach dune complex are characterized by sand waves (wave length approximately 5–8 m), in which amplitude (maximum approximately 0.5–1.0 m) decreases land ward. The east coastline is bordered by beach dunes oriented NNE-SSW or N-S running parallel to the coastline.

The inner sand flat consists of elevated grounds (fine sand mixed with algal material) surrounded by shallow (2–5 m) pools of water with soft substrate. Shell mounds are at or above mean high water level (MHWL) and are scattered at the points of small headlands.

A trench (2 × 2.1 Mts.) (T1) was dug in the sandy flat to 2.1 m depth in the shallow low intertidal zone. Observations made in the surrounding well sections and the trenches revealed a 1-m organic and carbon-rich tidal clay unit (Unit I), with alternate laminae of grey to black fine silty clay 3–4 mm, and dark grey to grey silty sand 2–3 mm. Figure 1 shows the detailed lithology. Sedimentary structures are dominated by horizontal layering and flat-topped ripple marks. Ripple crests are oriented at a slight angle to the shoreline. This unit is underlain by an oyster bed unit I nearly 1.1 m thick with a sharp contact. The size and the dimension of the oysters identified as *Crassostrea madrasensis* (2–3 cm across) increases downward with depth. The diameters vary from 10 to 12 cm. This is an open-estuarine mollusk that has grown in saline conditions (6–20 ppt). The oyster bed unit I is subsequently underlain by a tidal clay unit II (0.8–1.0 m thick) which is largely similar to the tidal clay unit I but varied in color, compactness, and laminated. Tidal clay unit II is nearly 1.5 m thick and is underlain by an oyster bed unit II with a sharp demarcation. Tidal clay unit II reveals sedimentary structures that are dominated by horizontal layering with ripple marks that are often flat-topped, alternating with laminations of very fine silt and clay. Mottled colors range from rusty red and brown to greyish green. Sediments range from sand to silty sand to clayey silt. The sand and coarse silt usually occur as well-sorted layers interlaminated with silty clay and clay silt layers.

Oyster bed unit I thrived well on the tidal clay unit II, which formed a hard muddy bottom (Achyuthan 1997). Tidal units II and I are devoid of oysters and shell content, although the top layers of these units contain shell fragments such as those of lamellibranchs, gastropods, oysters, and foraminifera.

Geomorphic observations around Muttukadu, natural exposures, and a trench (T2) dug 3 m deep in the leeward side of the dune reveal that the beach dunes can be divided into a lower unit that drapes over the buried oyster beds units I and II with the intervening tidal unit II. The upper dune unit drapes over the top tidal clay unit I. The lower dune unit locally is composed of two depositional sub-units separated by immature soils. It is difficult to correlate the sand surges deposited to form the dunes and the tidal layers.

MATERIALS AND METHODS

Three sediment cores (nearly 1–2 m long) from Muttukadu, Mammallapuram, and Marakkanam (Figure 1) were retrieved from a water depth range of 0.30 m using 2-inch wide PVC liners. The sediments were analyzed for mineral composition and texture. Figure 1 shows the core litho logs.

Samples for clay mineral composition were air-dried and the organic material was digested in H_2O_2. The sediments were then washed and dispersed in calgon. The sediment fractions coarser than 6 Ø were separated and the clay fractions were identified for mineral composition. Clay mineral composition was identified using X-ray diffraction at the Indian Institute of Technology, Chennai. Table 1 lists the results.

Stratigraphic data from the study area were derived from unpublished borehole logs. Samples from the cores collected from the three sites were ^{14}C dated by Beta Analytic. The results are presented in ^{14}C years before present (BP) with uncertainty of 1 σ. ^{14}C dates were calibrated using the program of Stuiver and Braziunas (1993) and are quoted in calibrated years before present (cal BP) with 2-σ age (Table 1). The samples were dated at the University of Arizona's radiocarbon laboratory (Department of Geosciences) and its NSF-Arizona AMS lab (Department of Physics), as well as at the Birbal Sahani Institute of Palaeobotany in Lucknow, India.

RESULTS AND DISCUSSION

The tidal sediments are multicolored and compact with fragments of charnockite rocks at Muttukadu and Mammallapuram, whereas at Marakkanam the sediments contain fragments of sandstone. At Muttukadu and Mammallapuram, the coarser sediments are mainly quartz with small amount of feldspar, sillimanite, hypersthene, garnet, and traces of mica, rock fragments, including carbonized material. Admixed with these are molluscan shell debris, plant and root fragments, foraminifer tests, and various aggregates including fecal pellets and other minor components. Pyrite is commonly found developing within the sediment. This assemblage differs slightly from that found in sediments from the beaches and dunes at the neighboring Marakkanam coast. These variations are largely the result of differences in grain size and also in source. The clays consist of kaolinite, dehydrated illite, and montmorillonite (Table 1). Because these clays are very similar in composition to

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Table 1 Radiocarbon ages determined on organic carbon-rich tidal clay samples and shells from different depths and mineralogy of the clays and coarse fractions

Site and lab code	Depth (cm) sample type	^{14}C age	Calibrated age range[a]	$\delta^{13}C$ (‰)	Clay mineral by XRD	Coarse mineral fraction >80 µm
Marakkanam						
BS-1605	38–40 cm shell[b]	1153 ± 132	612–1082 AD	—	Kaolinite, illite, vermiculite, aragonite	Quartz, K feldspar, rutile (>2%), garnet, quartzite grain
BS-1608	86–88 cm shell[b]	1563 ± 132	136–680 AD	—	Kaolinite, illite, aragonite	Quartz, K feldspar, rutile (<2%), garnet, quartzite grain
Mammallapuram						
AA-30022	24–39 cm organic matter	1085 ± 60 BP	780–1033 AD	–19.6	Kaolinite, dehydrated illite, montmorillonite	Quartz, K feldspar, rutile (<2%), garnet, quartzite grain
AA-30024	45–56 cm organic matter	1620 ± 110 BP	145–648AD	–21.2	Kaolinite, dehydrated illite, montmorillonite	Quartz, K feldspar, rutile (<2%), garnet, silimanite, hypersthene, augite
AA-30027	88–98 cm organic matter	1900 ± 45 BP	22–231AD	–22.5	Kaolinite, illite, montmoril-lonite	Quartz, K feldspar, rutile (<2%), garnet, silimanite, hypersthene, augite
Muttukadu						
AA-18459	50 cm organic matter	3145 ± 55 BP	1520–1267 BC	–18.5	Kaolinite, dehydrated illite, vermiculite, montmorillonite	Quartz, K feldspar, garnet, silimanite, hypersthene, augite
AA-18458	70 cm organic matter	3475 ± 55 BP	1935–1639 BC	–18.5	Kaolinite, dehydrated illite, vermiculite, montmorillonite	Quartz, K feldspar, garnet, silimanite, hypersthene, plagioclase
A-8374	185 cm oyster shell[b]	5000 ± 70 BP	3436–2997 BC	–2.50	Kaolinite, montmorillonite, aragonite	Quartz, K feldspar, garnet, silimanite, hypersthene, plagioclase

[a]Calculated with the University of Washington Calibration 4.1 program.
[b]Reservoir-corrected

those supplied by the rivers draining into the area and to those being eroded from the neighboring coasts and adjacent seafloor, it is difficult to assign a definite source to them.

The nine ^{14}C dates pertain to organic material and shells sampled from the cores (Table1). The ^{14}C dates indicate a more rapid relative sea level rise (RSL) subsequent to 2500–3500 BP. The ^{14}C dates indicate tidal flat sedimentation between 3475 and 3145 BP. At Muttukadu, ^{14}C dates of oyster shells in the tidal zone associated with the lower litho unit I (depth 1.85 m) is dated to 4473 ± 72 BP. The layer at the depth of 50 cm is dated to 3145 ± 55 BP.

The dates at Mammallapuram range from 1900 ± 45 to 1085 ± 60 BP at 98–39 cm from the surface. Shell fragments at 50 cm depth from cores collected at Marakkanam yield ^{14}C dates of >1153 BP, whereas shell fragments analyzed from the same depth from the core collected at Muttukadu yielded an age of 3145 ± 55 BP. The discrepancies in the age between Muttukadu and the other two sites indicate probable neotectonic activity or coastal configuration shift. The likely cause is the reactivation of the fault line east of Muttukadu trending north-south, and projecting into the sea near Mammallapuram, consequently drowning the beach system south of Muttukadu. This resulted in the short removal of marine conditions and ample supply of sediments in the tidal zones. The approximately 2000-year discrepancy between the ages of sediments at 50 cm at Marakkanam and Muttukadu suggest that the faulting of these sediments occurred no earlier than approximately 1050 BP. ^{14}C dates of organic carbon-rich silty clay units between 0.50 and 0.70 m at Muttukadu indicate a 0.9 mm yr^{-1} rate of sedimentation while at Mammallapuram and Marakkanam the rate of sedimentation is approximately 1.1 mm yr^{-1}. The occurrence of two buried oyster beds with intervening clay units perhaps points towards a local fluctuation of the RSL due to the uplift rather than global sea-level change during the Middle-Late Holocene period. Our data show a complex tidal zone response to the storms between 4473 ± 73 BP and 3145 ± 55 BP.

Foraminifera (*Ammonia beccarii, Elphidium crispum, Quinqueloculina seminulum,* and *Triloculina trigonula*), identified from the core samples collected from these three sites at various depths, indicate their deposition in the shallow inner shelf littoral zone. Rao et al. (1999) identified similar foraminifer species at the Karikkattukuppam site near Muttukadu. Occurrence of *Glandulina spinata* Cushman—a typical foraminifer species from the inner shelf sediments off Karikkattukuppam, near Muttukadu—indicates a tropical inner shelf dwelling taxon, associated with muddy substrates. On the other hand, dark gray fine silty units rich in small foraminifers indicate their deposition in a brackish intertidal environment. Their small size is attributed to the mixing of fresh water probably from the landscape (Phleger 1960). The symmetrical morphogroup probably points to their deposition in the proximal part of the tidal mouth under a turbulent environment (Nigam and Khare 1994).

The microfaunal data reveal that the clay unit (depth of 88–98 cm) marks the advance of the sea at the beginning 1900 ± 45 BP, whereas the silty sand unit points to the seaward migration of the shoreline. The overlying organic-rich clay unit represents a new phase of the advance/transgression, thereby increasing the marine influence. This suggests that the position of the tidal and estuary zones did not alter drastically, but the amplitude of the shoreline moved horizontally as revealed by the occurrence of the foraminifers. Microfauna and ^{14}C dates of our study point towards a repeated shift from open-estuarine to brackish conditions with average salinity decrease (<6 ppt). The clay units are devoid of oysters. Short periods of decreased storminess are recorded by the occurrence of immature soil formation in the bordering beach dunes. Litho units in the tidal zone point to a local fluctuation of the sea level. Probably, the Terminal Pleistocene–Early Holocene period was characterized by an overall strong climate and relative low sea level with high-saline conditions (Achyuthan 1997). This resulted in an increased availability of sand in the shore zone. Large pulses of sand were supplied to the beaches by southward-running coastal currents with returning monsoons. The low sea level partly eroded and drowned the Terminal Pleistocene and Early Holocene coastal tract. It is important to note that reworking of the innershelf sediments as a result of the dropping sea level provided the ultimate sediment source for the progradation of the present coastline. Similar observations at the Mahi estuary on the west coast of India (4000–1700 BP) have been made by Kusumgar et al. (1998) based on ^{14}C dates and foraminifer assemblage (Raj and Chamyal 1998).

The lack of lengthy Holocene tidal and estuarine sequences from different parts of the eastern coastline makes it difficult to recognize intersite correlation and the abrupt changes in coastal stratigraphy. Although it is possible to offer a first-order interpretation of the data in terms of the sedimentation rate, the interplay among the elements of tectonism, sea-level change, and sedimentation makes such inferences all the more difficult. We emphasize that the sea-level change described is found in a temporally limited area. Our data suggest storm signatures that varied markedly within the tidal zones and that the sea-level behavior since the Middle to Late Holocene has been the dominant factor in determining the general sedimentary framework of the modern east coastal region.

CONCLUSION

The east coast of Tamil Nadu reveals shell beds, beach dunes, and tidal deposits, indicating rapid transgression of the sea and uplift no later than approximately 1050 BP. We conclude the following:

1. ^{14}C dates of organic carbon rich silty clay units between 0.50 and 0.70 m at Muttukadu indicate 0.9 mm yr^{-1} sedimentation rate, while at Mammallapuram and Marakkanam the rate of sedimentation is approximately 1.1 mm yr^{-1}.
2. Oyster bed unit I ceased to form after approximately 4000 BP, with probable reduction in saline condition. ^{14}C dates and lithology of the estuary and tidal zones indicate that the marine conditions were set approximately 1900 years ago along the east coast, south of Chennai.
3. Geomorphology of the area between Muttukadu and Marakkanam, and the ^{14}C dates obtained from the three sites, indicate neotectonic activity that occurred no later than 1050 BP. The recent faulting has been the dominant factor in determining the general sedimentary framework of the modern east-coastal region.

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