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HOLOCENE CLIMATE AND RELATIVE SEA LEVEL CHANGES IN CAUVERY RIVER DELTA, INDIA BASED ON POLLEN AND SEDIMENTARY RECORDS

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ABSTRACT

Climate induced minor relative sea level oscillations, brought by either natural or anthropogenic factors involves serious impact on the economy of coastal habitation that largely sustains millions of people living along the vast stretch of coastal areas in tropics. Relative sea level changes that occurred during the last 7000 cal BP affecting the coastal vegetation have been documented through palynology in sedimentary cores/trenches retrieved from the Vellar estuary (VE) and Thillaividangan village (TVG) which are 3 km and 10 km away from the coast, respectively in the northeastern Cauvery river delta. Around 6000-7000 cal BP both sites show marine palynomorphs thereby indicating palaeoshoreline extending inland to about 10 km. Retreat in shoreline post 5700 cal BP from TVG and stray presence of salt tolerant *Avicennia* species from Vellar was recorded. Around 2440 cal BP true mangroves rejuvenated in Vellar indicating approximately 2-3 km ingression of sea water due to configurational changes in the coastal wetland likely induced by geomorphological changes influenced by weakened monsoon that is evidenced by the low percentage of terrestrial and mangrove pollen. At 4000 cal BP, evidences of marine palynomorphs in Vellar, Pichavaram and Coleroon is at present mean sea level but in TS Pettai the marine signatures are about 4m below present mean sea level suggesting ~2-3 m subsidence in TS Pettai i.e. the middle part of North-eastern Cauvery delta which facilitated more diverse mangroves in this part of delta.

Keywords: Pollen, Mangroves, sea-level change, Holocene, Cauvery delta, India.

INTRODUCTION

The coastal wetlands having high biodiversity are of economic importance in several ways (EEA, 2006; Patterson *et al*., 2011). Estuaries are exceptionally vulnerable to degradation in response to anthropogenic activities and probable sea-level rise due to global climate change (Watson and Byrne, 2009). Relative -sea -levels may be affected by a number of factors, including climatically induced global/eustatic variations in ocean water volume, tectonic subsidence or uplift of the crust and glacio- and hydro-isostatic adjustments (Church *et al*., 2001) and changes in the tidal range (Shennan and Horton, 2002; Vink *et al*., 2007; Smith *et al*., 2011). Holocene relative sea-level history has spatial and temporal variation for which researchers around the globe have contentious views. Some researchers have reported a gradual sea-level rise in the early Holocene followed by a steady fall from a mid-Holocene highstand (Bird *et al*., 2007, 2010). During the Holocene regionally synchronous phases of expansion and contraction of estuaries appear to have taken place in the coastal wetlands of India (Kumaran *et al*., 2005; Farooqui and Achyuthan, 2006; Khandelwal *et al*., 2008; Farooqui, 2008; Hait and Behling, 2009; Srivastava and Farooqui, 2013 and Pandey *et al*., 2014).

Majority of the research in the Cauvery River delta is confined to remote sensing imageries (Ramasamy *et al*., 2006), geochemical studies on surface sediments (Sharma and Rajamani, 2001), tectonics and geodynamics (Valdiya, 2001) and sedimentological studies on deeper sediments for hydrocarbon potential (Chandra *et al*., 1991). The rivers which flow into the Bay of Bengal are monsoon driven and are considered as excellent sedimentary repositories of palaeomonsoon records. Except for a few records (Farooqui, 2008) the comprehensive and sequential history of the northern part of the Cauvery River Delta based on numerical ages and palynology is scarce. The Holocene vegetation and climate variability has been characterized by mangrove establishment and expansion/contraction phases in the northern Brazilian coast (Cohen *et al*., 2012; Guimarães *et al*., 2012), the lowland swamps of Singapore (Taylor *et al*., 2001), NW Africa (Bouimetarhan *et al*., 2009) and the Carribean mangroves (Vegas-Vilarrúbia and Rull, 2002; Peros *et al*., 2007; Ellison, 2008). The present study aims to reconstruct the chronological palaeoecology in sedimentary archives of the Cauvery River Delta using sedimentological, physico-chemical and palynological parameters with special emphasis to mangrove succession, migration and local extinction of species in response to climate and geomorphologically induced sea level fluctuations to assess the net rate of sea level rise/fall in this sector of Indian coastline.

REGIONAL SETTING

Geographic setting and climate

The Cauvery River originates from the Western Ghats in Karnataka and flows towards east before merging into the Bay of Bengal (Ramanathan *et al*., 1996; Singh and Rajamani, 2001). The Quaternary sediments are basically fluvial sediments, middle Holocene beach ridges and late Holocene dune sands (Kunz *et al*., 2010). The river dominated Cauvery Delta has developed a triangular shape with three distinct morphological areas consisting of a marginal denudational unit, a central fluvio-marine depositional unit and a coastal marine depositional unit. A number of geomorphological features can be identified in the delta region such as palaeo river channels, lagoons, swales, dunes, beach ridges, salt marshes, and swamps etc. (Babu, 1991). The Cauvery River delta (10°16' to 11°30'N; 78°45' to 79°51' E) is one of the major sediment repositories in peninsular India and the biggest in the east coast of Tamil Nadu. Sadakata (1980) based on borehole data and a radiocarbon date of basal peat recovered from about 20m depth suggested that

the Holocene sediments were 3m thick, about 50 km inland and about 30 m thick near the present shoreline.

About 75-90% of the total rainfall is recorded during the north-east monsoon (October-December); it is accompanied by frequent depressions in the Bay of Bengal while low rainfall is registered during the south-west monsoon (April-June) (Kathiresan *et al*., 1996). The surge of water from the tributaries to the main course of Cauvery during the south west monsoon brings sediment into the deltaic region. The region experiences a semi-arid tropical climate with the maximum mean annual temperature of 25°C (March to May) reaching up to 43°C occasionally. An average sediment accumulation rate between 0.4 and 4 mm/yr for the recent past has been reported in the Cauvery River basin with less sedimentation rates in the tributaries (Ramanathan *et al*., 1996). The mean relative humidity is high during the monsoon period and comparatively low during the post monsoon period.

Mangroves and associated flora

Deltaic regions of the Cauvery River harbors the major mangrove wetlands of Tamil Nadu. A large patch of healthy mangroves comprising of 13 mangrove species is present in the Pichavaram and Muthupet regions (Selvam *et al*., 2002). The common dominant mangroves are *Rhizophora apiculata, R. mucronata* which attain 5-7m height and the occasional mangroves are *Sonneratia apetala* (rare), *Avicennia marina, A. officinalis, Bruguiera cylindrica, Ceriops decandra, Aegiceras corniculatum* and *Lumnitzera racemosa*. The back mangroves included *Dalbergia spinosa, Derris trifoliata, Dendrophthoe falcata, Suaeda maritima, S. monoica, Sesuvium portulacastrum, Heliotropium curassavicum, Salicornia brachiata, Excoecaria agallocha, Acanthus ilicifolius, Clerodendrum inerme, Solanum trilobatum, Azima tetracantha, Cyperus arenarium, Fimbristylis cymosa, Zoysia matrella, Aeluropus lagopoides* and *Geniosporum tenuifolium.*

MATERIALS AND METHODS

Two sediment cores from Vellar (VE -3.8 m long; 11º29’ 27.72”N, 79º45’58.92”E; altitude +2.1 m) and Thillaividangan (TVG -6.0 m long; 11º26’24.32”N,79º44.25.67”E; altitude +5.2 m) were retrieved in 2010 and selected for the study in order to assess the palynological data generated from the previous work carried out in the Pichavaram estuary that falls in the coastal wetland formed by the tributaries of the Cauvery river (Figure 1). While the core TVG is located 10 kms inland, the VE core is located in the floodplain of the Vellar River which is 3 km inland from the river mouth. The village surrounding the TVG site has been ravaged by many floods and cyclones over the years.

Sedimentary cores were retrieved by hand operated piston corer (Eijkelkamp, Netherlands).The cores were sub-sampled at 2 cm intervals and stored in polythene bags. In the laboratory sediment colour was recognized using the Munsell color chart (2000) and texture was examined on the basis of the percentage of sand in the sediment following the soil density method (USDA, 1992). In total 7 radiocarbon (^{14}C) dates were obtained from the VE and TVG (Table 2) through which sample ages were estimated by the linear interpolation between the radiocarbon data. Salinity was measured in the aqueous soil solution of 10 g of air dried sediment sample dissolved in 100 ml of deionized water using ‘Orion-5 star’ (Thermo-Orion,

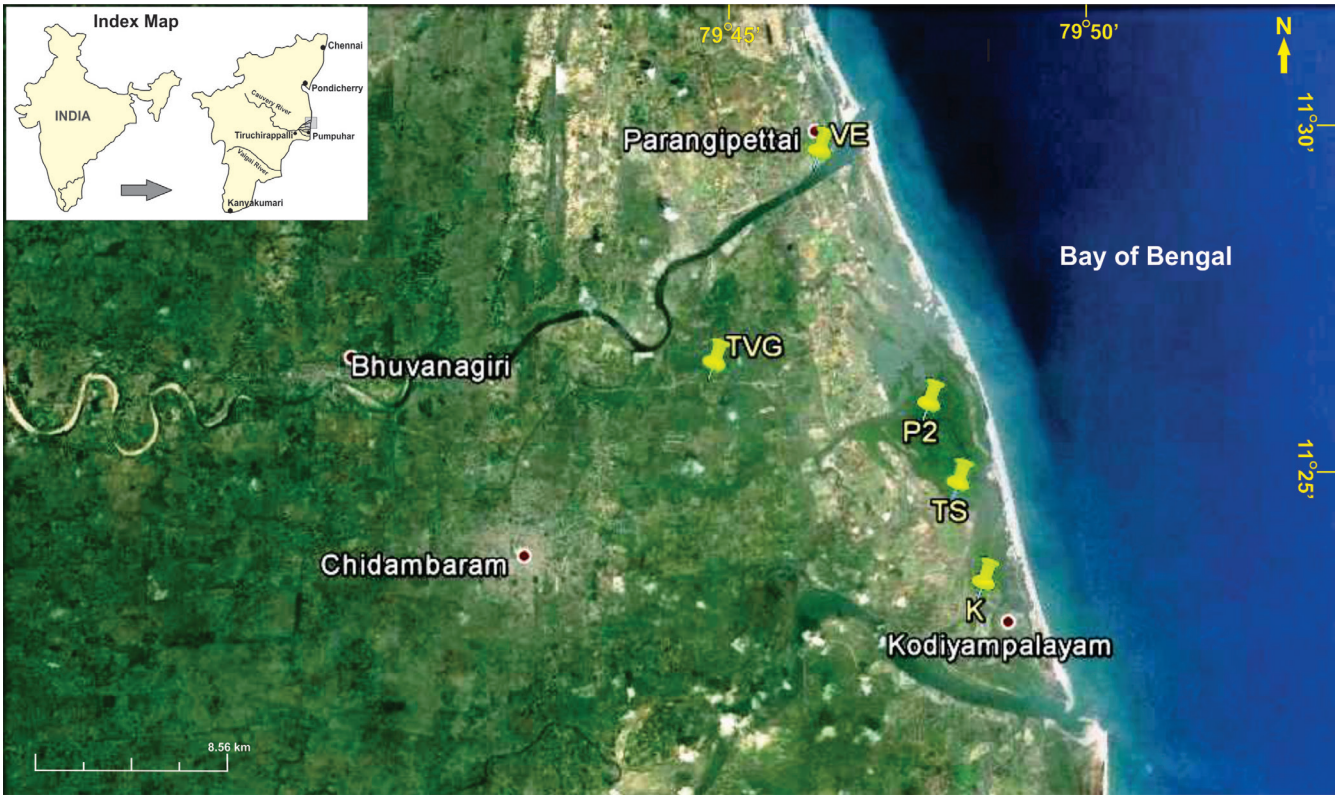

Fig. 1. Geographical location of the core sites Vellar (VE) and Thillaividangan (TVG) on the northeastern Cauvery River Delta, SE coast of India (Present Study). Pichavaram (P2), TSpettai (TS) and Coleroon (K) core sites from previous studies (Srivastava *et al*., 2012, Srivastava and Farooqui, 2013 and Srivastava, 2013).

Scientific Equipment, USA) at standardized 25ºC temperature. For the palynological study 10 g of air dried sediment sample was treated with 10% potassium hydroxide (KOH) on sand bath (for 5-8 minutes and sieved using 150 mesh size (105 µm). The filtrate was then acetolysed following Erdtman (1943). The samples were then passed through a 600 mesh size sieve and the residue (>10 µm) was collected for palynological slides. The palynomorphs were analysed under Olympus BX-51microscope and identified by referring to pollen atlases of Thanikaimoni (1966), Thanikaimoni *et al.* (1973), Tissot *et al.* (1994) and reference pollen slides from the Herbarium of Birbal Sahni Institute of Palaeosciences. Thecamoebians were also identified with the aid of standard literature (Ogden and Hadley 1980; Patterson and Kumar, 2002; Farooqui *et al* 2012). The palynological diagram represents the percentage of selected mangrove taxa, upland tree and herb/shrubs, wetland, aquatic taxa, freshwater algal spores, fungal remains, thecamoebians, foraminifera and dinoflagellate cysts in a homogenized 10 ml acetolysed sample. A dual calculation of pollen percentages on the basis of both the total sum of pollen and spores and separate partial sums, as described by Rybníèková and Rybníèek (1971), provides an effective and intuitive way to deal with the overrepresentation of local pollen elements in organogenic peat deposits (Srivastava, 2013). Percentage values are calculated for each taxon in two ways: on the basis of 1) the total sum of all pollen and spores, and 2) separate sums totaling 100% for mangrove, upland and wetland taxa (partial sums). The two percentage values for each taxon can then be shown as a dual curve on the pollen diagrams, permitting the proportion of any taxon with respect to both the entire assemblage and appropriate ecological group to be viewed easily. The percentage values for upland taxa based on the partial sum (of upland taxa only) are comparable to those shown in the diagrams based on restricted main sums of regional pollen types (Mateus, 1992). These values should provide the best indication of the vegetation composition in the wider landscape. The percentage values for wetland taxa based on the partial sum (of wetland taxa only) should provide the best indication of changes in wetland habitats, especially those in the vicinity of the coring site. Change in the estuarine ecosystem has been observed through the Marine index showing the ratio between marine (mangrove pollen, foraminiferal linings, dinoflagellate cysts) and terrestrial (upland arboreal and non arboreal taxa pollen, freshwater algae and thecamoebians) palynomorphs.

RESULTS

On the basis of sedimentology, salinity trend and pollen/spore analysis, three phases of depositional environment and vegetation changes since the last maximum marine transgression around 6000 cal BP were recorded showing: Unit I- Well developed estuarine ecosystem, Unit II- Retreating estuarine condition and Unit III- Fluctuating estuarine condition (Figure 2).

Radiocarbon chronology and rate of sedimentation

In general, the estuarine environment is characterized by complex patterns of sedimentation and highly variable deposition rates (Colman *et al*., 1992). At the VE site, the sedimentation rate (SR) from 7440-6630 cal BP is 0.14 cm/yr followed by a steady decline in SR to 0.03 cm/yr from 6630-4217 cal BP.

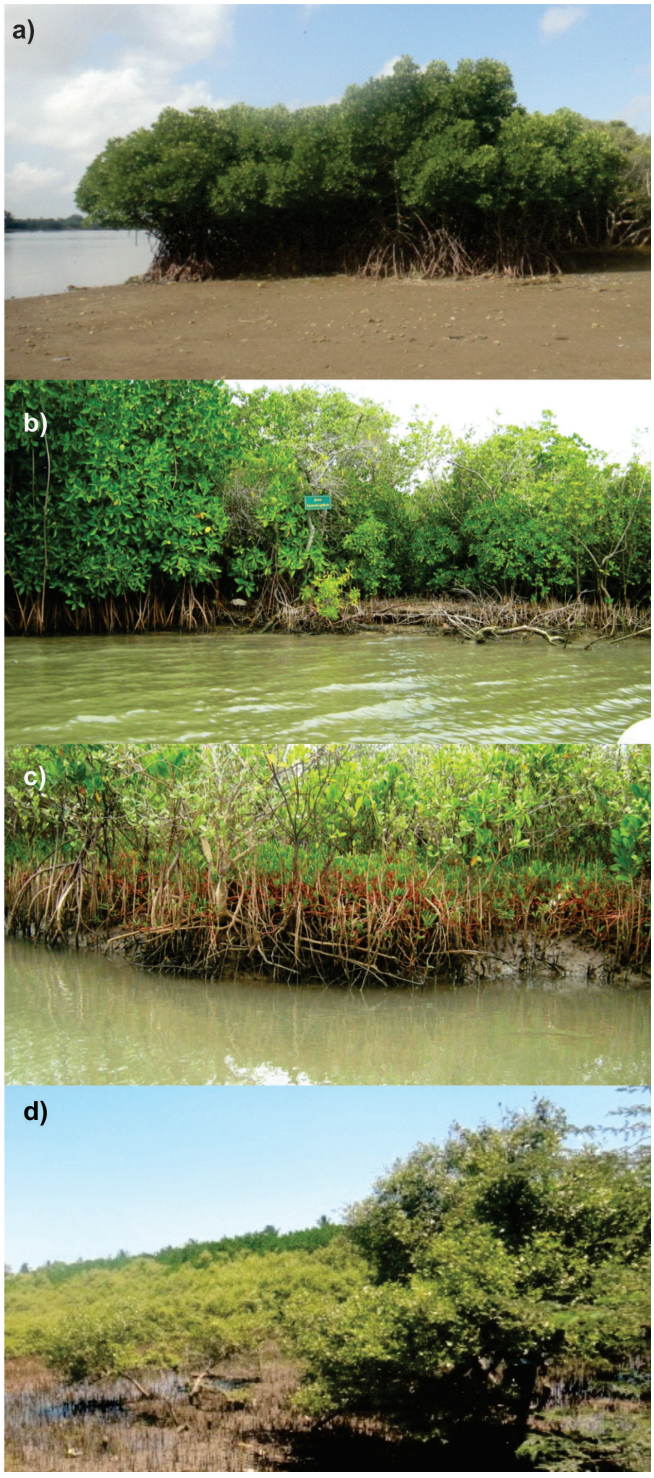

Fig. 2. Mangrove vegetation status at: a) Retreating mangroves in Vellar estuary, b) Well developed true and back mangroves in Pichavaram estuary, c) Salt tolerant and back mangroves in TSpettai mangrove wetland, d) Back mangroves in Coleroon estuary.

Since 4217 cal BP till present the rate of sedimentation at Vellar shows a minor increase to 0.04 cm/yr. At Thillaividangan SR from 6184-5919 cal BP was 0.23 cm/yr; then it increased to 0.33 cm/yr from 5919-5141 cal BP. Sedimentation rate subsequently declined to 0.09 cm/yr from 5141-3257 cal BP and further to 0.03 cm/yr from 3257 cal BP till present (Figure 3).

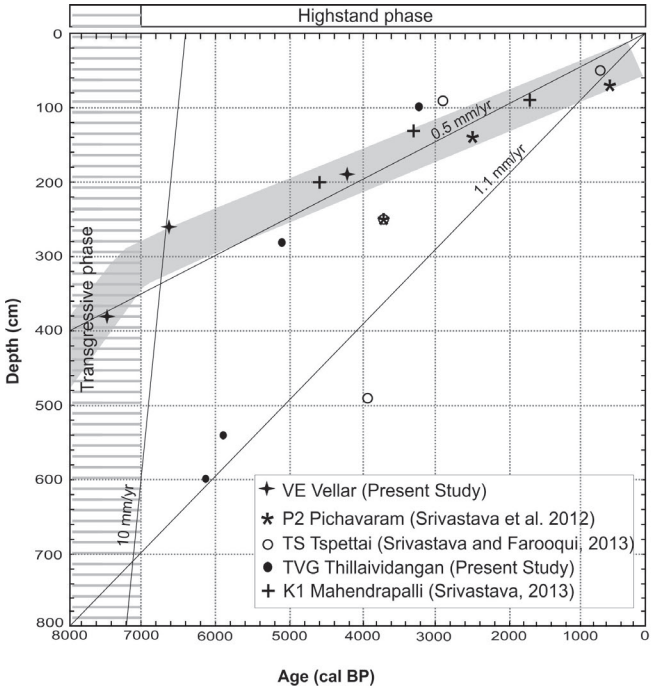

Fig. 3. General sedimentation trend in the Cauvery river delta, India. Lines showing sedimentation rates of 10, 0.5 and 1.1 mm/yr are plotted for reference.

Sediment colour, texture and salinity

At the base of the Vellar core (VE) is a unit of sand and silt (5Y5/4). Unit I (7440-5700 cal BP) is most coarse at the base (380-360 cm) with less percentage of silt (Table 1). Above 360 cm the fill comprises medium to coarse sand and a higher percentage of silt fractions. From 285-220 cm the sequence contains predominantly fine-grained sediment (silts) with clay (5Y4/2). Salinity of the aqueous soil solution shows marked variation with the sediment texture in Unit I. The silty sand sediment fraction shows an average salinity of 1.1 with a maximum of 2.1 and a minimum of 0.4 whereas the silty clay fraction displays higher average salinity of 2.1 with a maximum of 2.6 and a minimum of 1.8. In Unit II (5700-2441 cal BP) from 220 to 160 cm the sequence is defined by more fine silty clay to clay sediments (5Y4/2) with less percentage of sand while above 160 cm till 80 cm (Unit III- 2441 cal BP to present) the fill comprises of sand with a higher percentage of silt fractions (5Y5/4). Salinity of the aqueous soil solution is the highest in the part dominated by fine clay sediment fraction of Unit II with a maximum salinity of 6.0 and a minimum of 2.1 (average= 3.2) whereas the silty sand fraction displays lower average salinity of 2.4 with a maximum of 2.8 and a minimum of 1.8. Unit III comprises of a long silty clay (5Y4/2) segment from 80-20 cm sandwiched between two silty sand (5Y5/4) fractions; one from 160 cm to 80 cm and the other topmost 20 cm sand dominant fraction has been observed. Salinity of the aqueous soil solution shows an average of 2.1 with a maximum of 2.8 in the silty clay segment of Unit III and a minimum of 1.2.

The basal part (Unit I: 6184-5700 cal BP) of TVG sedimentary fill (600-520 cm) is composed of fine clayey silt sediment (5Y4/2) with low proportion of coarse sand and salinity ranging from 1.5 to 1.3 having average of 1.4. The top layers (Unit II: 5700 cal BP to present) contain predominantly fine-grained sandy silt sediments (5Y4/4) with a high proportion of medium to fine sandy soil. Minor fluctuations in the salinity gradient having an average of 0.4 with a maximum of 1.2 and minimum of 0.3 have been recorded in this Unit.

Palynology

Pollen, fern spores, thecamoebians, freshwater algae, dinoflagellate cysts and foraminiferal linings were identified and grouped as shown in Figures 4 and 5. In the Vellar site Unit I shows 17.3% of mangroves and associates, 18.8% herbaceous taxa along with 7.0% hinterland evergreen to semi evergreen trees, 5.9% shrubs and 6.2% aquatic taxa. The non pollen palynomorphs recorded in the unit includes 11.7% freshwater algae, 5.3% fungal remains, 9.0% thecamoebians, 13.1% foraminiferal linings and 5.7% dinoflagellate cysts. The average marine/terrestrial ratio for Unit I is 0.4. Thereafter,

Table 1. Location of the cores, elevation, depth and their lithological characteristics inferred from sediment texture and color examination.

S.No.	Sampling site	Geographical distribution	Elevation	Depth (cm)	Lithological Characteristics
1.	Vellar estuary	11° 29'27.72" N 79° 45'58.92" E	2.1 m	0-20 cm 20-80 cm 80-160 cm 160-285 cm 285-380 cm	Greyish silty sand (5Y5/4) sediment with less organic material in the topmost layer. Blackish brown compact silts with clay rich sediment. Thick zone of greyish compact silty sand sediment. Greyish brown fine-grained sediments (silts) with clay. Layer of blackish grey fine clay is noted at depth 190-220 cm, resting in continuity with the underlying silty clay layer. The upper part of the zone (160-190 cm) is predominantly fine grained with a less proportion of silt and fine sand, enriched in parts with organic material. Greyish brown sand and silt with the coarsest sediment at the base (380-360 cm) with less percentage of silt. Above 360 cm, the fill comprises medium to coarse sands and a higher percentage of silt fractions.
2.	Thillaividangan	11° 26'24.32" N 79° 44'25.67" E	5.2 m	0-476 cm 476-600 cm	Greyish brown fine-grained sandy silt sediments with a high proportion of medium to fine sandy soil. Blackish grey fine clayey silt sediment (5Y4/2) with low proportion of coarse sand.

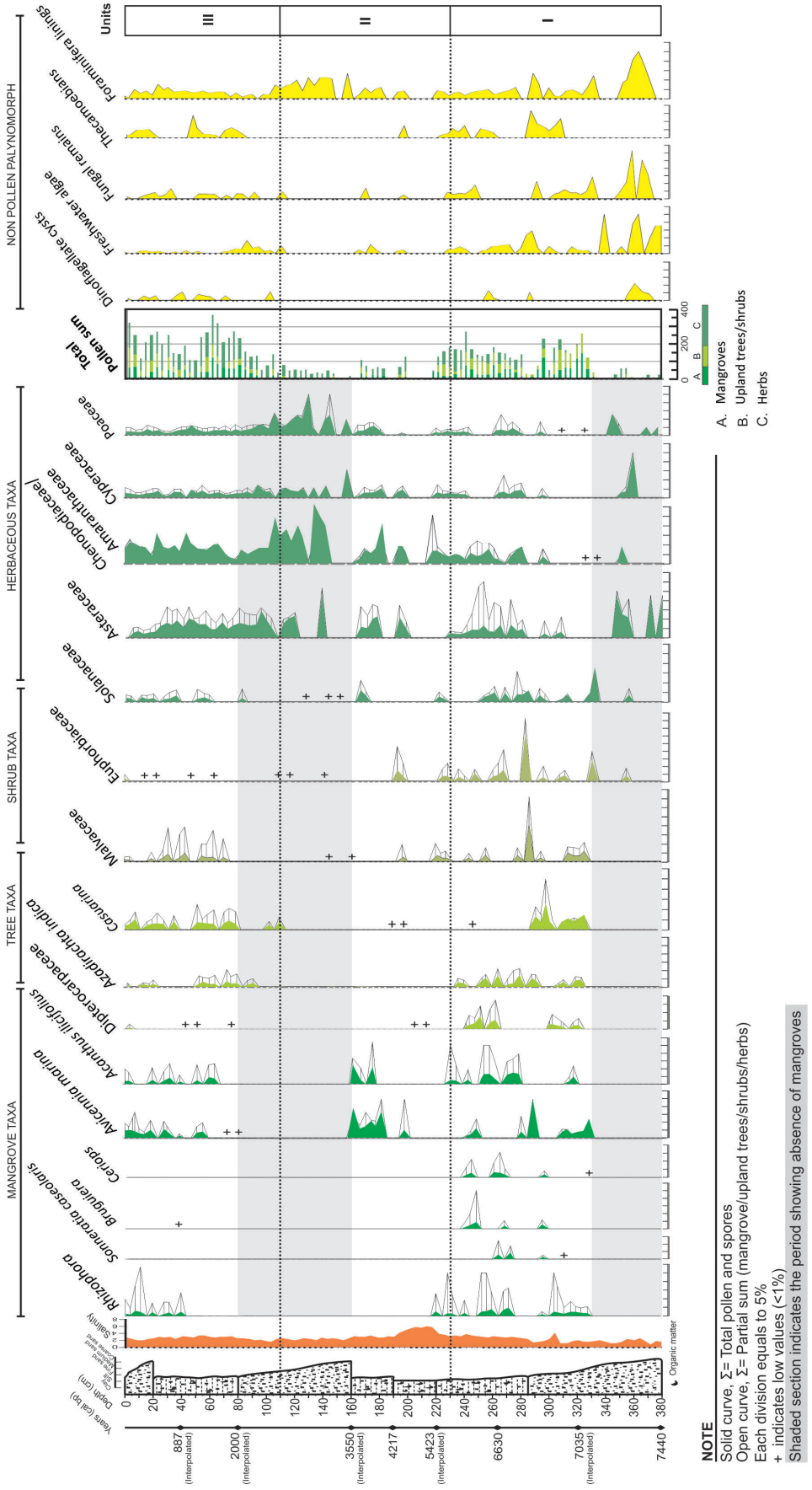

Fig. 4. Summary palynomorph percentage diagram of core VE from Vellar estuary, southeast coast of India

there was a decline in true mangroves, trees and shrubs with a dominance of back mangroves (14.1%) in Unit II along with 32.2% herbaceous and 1.5% aquatic taxa. 9.5% Freshwater algae, 4.8% fungal remains, 8.8% thecamoebians and 26.0% foraminiferal linings were also recovered from Unit II with a marine/terrestrial ratio of 0.3. Unit III marks the recolonization of true mangroves along with back mangroves (10.5%), 12.4% trees, 16.8%,shrubs, 37%, herbaceous taxa and 2.9% aquatic plants have also been recorded from the unit. Marine/terrestrial ratio for Unit III increases to 0.4.

In the TVG core Unit I was marked with 9.3% mangroves, 22.0% trees, 28.4% herbaceous plants and 5.4% aquatic taxa along with 30.2% freshwater algae and 4.7% fungal remains. Average marine/terrestrial ratio was estimated to be 0.3 However, only herbaceous taxa (82.5%) and low abundance of other terrestrial plants was recorded in Unit II with no mangrove taxa hence the average marine/terrestrial ratio was 0.1.

DISCUSSION

Dominance of sandy sediment in VE suggests high fluvial energy conditions whereas the other contemporary sites at Pichavaram (Srivastava *et al*., 2012a), TSpettai (Srivastava and Farooqui, 2013) and Coleroon estuary (Srivastava, 2013; Srivastava and Farooqui, 2017) show dominance of sandy-silt or silt sediment which indicates low fluvial energy conditions. In calm settings (e.g. saltmarsh, closed estuary) sediment deposition consists of aggregates from the suspended particles in the water column resulting in deposition of fine grained sediments. In transitional sub-environments (e.g. tidal flats, channel margin) such as in Thillaividangan sediments comprise of a mixture of fine suspended particles and coarse grained bedload material.

Unit-I: Well developed estuarine ecosystem (7440-5700 cal BP; VE-380 cm to 230 cm; TVG-600 cm-520 cm)

A good representation of mangrove taxa including *Rhizophora, Avicennia, Ceriops, Bruguiera, Sonneratia, Excoecaria* along with mangrove associates such as *Acanthus, Aegiceras, Aegialitis, Cynometra, Acrostichum aureum* in both VE and TVG suggests a significant pollen contribution from a stabilized estuarine condition (Figure 6). Higher Marine Index and salinity status during 7440-5700 cal BP in Vellar estuary shows that the palaeoshoreline first reached there as it was closer to the river's mouth then to Thillaividangan which was 10 km inland from the sea. High percentage of upland arboreal taxa *Azadirachta*, *Cedrela odorata, Syzygium*, Dipterocarpaceae, Moraceae, Myrtaceae, Sapotaceae members and emergence of *Casuarina equisetifolia* is considered to represent areas of evergreen woodland and thickets which in turn indicates high precipitation in the region. The concomitant expansion of evergreen types probably reflects a forest expansion structured by microclimatic and edaphic conditions, with *Hopea* and *Cedrela* growing on the deeper, moister soils in the valleys and evergreen thickets occurring on thinner soils on slopes and other xeric locations. The consistent presence of *Azadirachta*, *Cedrela* and *Hopea* in this domain demonstrates the status of these taxa as a constituent member of the natural vegetation cover in association with other evergreen taxa whereas shrub taxa are not strongly represented. Altogether the middle Holocene period (~5000-7000 cal BP) marks a vegetation response to warmer and wetter conditions (Fuller and Korisettar, 2004). Stable isotope ($\delta^{13}C$ on organic matter) investigations on peat deposits based on the differences in the ecological preferences of C3 (higher precipitation) and C4 (lower precipitation) type of plants from Nilgiris, South India, (Sukumar *et al*., 1993) show evidence of an early Holocene moist phase followed by the onset of present day conditions ~5400 cal BP (Rajagopalan *et al*., 1997). This indicates a low lying depositional environment surrounded by marsh vegetation dominated by grasses such as *Polygonum* sp. rather than Cheno/Ams. Presence of dinoflagellate cysts in VE suggests a stronger tidal influence in the area with the transport of dinoflagellate cysts from more open coastal waters at the estuary's mouth. *Spiniferites* sp. is of typical estuarine type tolerant to low salinities and their dominance is typical of the estuarine environment (Morzadec-Kerfourn, 2005). *Pediastrum*, considered an indicator of freshwater conditions, (Round, 1965) is fairly abundant in VE which corresponds to lowest values for dinoflagellates suggesting high precipitation conditions forming a low salinity wetland. Presence of fungal remains along with spores and pollen of terrestrial vegetation in sediments provide evidence of relative humidity, atmospheric pressure and heavy precipitation rates (Medeanic *et al*., 2008). Presence of thecamoebian species such as *Cyclopyxis* and *Arcella* in both VE and TVG indicates a lacustrine environment (Patterson and Kumar, 2002; Farooqui *et al*., 2014). High peaks of foraminiferal linings in both cores are exclusive to intertidal and shallow waters in coastal areas.

Unit-II: Retreating estuarine ecosystem (5700-2441 cal BP; VE- 230 cm to 110 cm; TVG- 520 cm to 0 cm)

Overall percentage values suggest a significant decline in mangroves and arboreal taxa both in Vellar and Thillaividangan indicating a progressive reduction in the regional forest cover. Reduced Marine Index along with low salinity status indicates a retreat in shoreline and contraction of estuary which first left TVG and then reached VE showing presence of only back mangroves. According to Tomlinson (1986), true mangrove plants are found exclusively within the mangrove habitat, whereas associated species are often found at the landward edge of mangrove ecosystems known as the "back mangroves". Accompanying the first reduction in true mangroves such as *Rhizophora* and *Sonneratia* along with *Azadirachta* and Dipterocarpaceae percentages is an increase in percentages of *Avicennia* type mangroves and *Acacia*, Euphorbiaceae and Solanaceae. This reflects a major impact on lowland and coastal woodlands at this time. The contrast between the abundance values of Euphorbiaceae and Solanaceae members, open ground herbaceous taxa *Derris*, *Justicia* and absence of Dipterocarpaceae and Meliaceae types suggest that this domain does not reflect woodland trees but rather shrub vegetation. The decline in mangroves and upland taxa suggest the destruction of natural woodland and tall shrub communities across the full range of edaphic and micro-climatic environments. These declines are accompanied by the maximum expansion of open ground indicators (Solanaceae types). The taller shrubs of Malvaceae types decline with smaller species represented by Rosaceae and Asteraceae becoming more important. These changes are considered to reflect an intensification of human pressure through cutting, burning and pastoral activity. In terms of wetland vegetation the cores present evidence for a transitional phase from floodplain to saltmarsh vegetation. High values for Liliaceae, Asteraceae, Poaceae, Cyperaceae and Cheno/Ams suggest open conditions around the core sites and a transition in the wetland environment towards the development of halophytic

Table 2. Radiocarbon dates of selected intervals of cores from the coastal wetlands of Pichavaram mangrove ecosystem

S.No	Core	Depth (cm)	Material	Laboratory Number	14C age (yr BP)	ó range (cal BP)	Calibrated age (cal BP)
1.	VE	190	Sediment	BS-3368	3790±410	3680 - 4754	4217
2.	VE	265	Sediment	BS-3369	5810±135	6316 - 7020	6630
3.	VE	380	Sediment	BS-3370	6520±40	7408 - 7471	7440
4.	TVG	100	Sediment	BS-3363	3080±140	3081 - 3433	3257
5.	TVG	280	Sediment	BS-3364	4520±300	4760 - 5521	5141
6.	TVG	540	Sediment	BS-3365	5140±210	5684 - 6153	5919
7.	TVG	600	Sediment	BS-3366	5400±260	5906 - 6461	6184

communities. High values of Cheno/Ams are considered an indicator of arid climatic conditions representing scrubby vegetation. In a coastal setting it may be difficult to distinguish between climatic aridity and hydrographic salinity signals in the pollen record as the two pose a similar effective pressure on the plant life. Aridity and salinity may surely be related in a coastal environment, for example, decreased freshwater supply and increased evaporation promote the salinization of marginal areas and encourage the development of salt crusts. *Artemisia* is included with the herbaceous group of pollen types because of its increased importance during the late-Holocene representing widespread arid environments during this period (Zhao *et al*., 2012). The Coleroon estuary (Core K) towards the south of Pichavaram also shows a moderate abundance of *Rhizophora, Avicennia, Excoecaria* and other mangrove associates marking the gradual retreat of a stabilized estuarine ecosystem during the early part of late Holocene (~4000 cal BP) period. These observations along with earlier records from Pichavaram Estuary (Srivastava *et al*. 2012b) and TSpettai mangrove wetland (Srivastava and Farooqui, 2013) suggest a regional signal reflecting a wider development of arid or saline environments within the estuarine complex encompassing the northeastern Cauvery River Delta. Two major climatic events are noteworthy: (i) weakening of monsoon suggested ~3800 cal BP from pollen (Caratini *et al*., 1994) and geochemistry (Lückage *et al*., 2001) records which are probably associated with weaker monsoon winds (Bhattacharya *et al*., 2011); (ii) arid event ~2000 cal BP (Lückage *et al*., 2001) characterized by the weakest monsoon winds (Gupta *et al*., 2003; Chauhan *et al*., 2010).

Unit-III: Fluctuating estuarine ecosystem (2441cal BP-present; VE 110 cm to 0 cm)

After 2441 cal BP a rise in mangroves and main arboreal taxa was detected at Vellar but not at Thillaividangan which indicates progressing shoreline and rejuvenation of true mangroves at VE . The salinity status and marine Index at TVG indicates that the shoreline did not reach TVG site due to its inland position from the river's mouth. Pollen percentage values for *Azadirachta*, Sapotaceae and *Casuarina* are slightly increased along with a range of shrub and open ground indicators. A reduction in the diversity of arboreal taxa perhaps associated with human activity is detected parallel to fairly well represented evergreen thickets and scrub communities. These changes suggest an episode of reduced forest cover with an expansion of Malvaceae scrub and *Acacia* vegetation. A peak in Chenopodiaceae pollen suggests a flourishing of halophytic vegetation associated with a phase of marsh development. Certain freshwater indicators (*Typha*, *Eichhornia*, and *Myriophyllum*) reappear during this domain indicating a wet climate as compared to Unit II. Increase in dinoflagellate diversity noted in VE with taxa of probable neritic origin (*Operculodinium centrocarpum*) indicates the near shoreline condition (Debenay *et al*., 2003). However, high values of *Pediastrum* also occur in VE associated with peak dinoflagellate abundance and diversity. This juxtaposition of freshwater and salinity indicators is considered to reflect a well-mixed tidal source of palynomorphs and algal bodies. Higher frequency of fungal remains in this unit also suggests freshwater marsh/flood-plain environment with high organic input and heavy rainfall (Limaye, 2004) but not higher than in unit I. Along with that reappearance of thecamoebians indicates freshwater to slightly brackish environments in the estuary (Reinhardt *et al*., 2005).

DELTA EVOLUTION AND RELATIVE SEA LEVEL CHANGES

The climatic fluctuations during middle Holocene correspond to the relative sea level transgression in three phases (Pirazzoli *et al*., 1993). During this time period three successive transgressive phases have been encountered but the intensity of the last relative sea level rise between 7500-6000 cal BP was much higher than the other two during which the sea level rose from below -12.8m to 1.2m above present sea level encroaching the lowland areas. The end of the transgressive phase (~7000 cal BP) saw a diversification of estuarine geomorphologies. The evidence of which are recorded at 4.2m above present sea level several kilometers on land in the east coast of India (Farooqui and Vaz, 2000). The present study also records the relative sea level around Thillaividangan (10 km inland) at 6000 cal BP which was approximately 50 cm below the present sea level. Thenafter since 5700 cal BP mangroves disappeared from both VE and TVG showing a retreat in the relative sea level. Although the earlier studies (Islam and Tooley, 1999; Banerjee, 2000) reveal that the stabilization of the relative sea level (RSL) in the deltaic areas took place around 6000 cal BP. The deltas prograded with short-term rise and fall in RSL in the beginning of Late Holocene which was attributed to neo-tectonic activities along the east coast of India (Farooqui and Vaz, 2000; Nageshwara Rao *et al*., 2012).

Mangrove vegetation and adjacent terrestrial pollen were abundant around 6000 cal BP that suggest near shore paralic coastal environment 10 km inland till Thillaividangan (TVG) from the present shoreline. The climate was warm and humid with good water runoff in the estuary favorable for true mangroves and inland taxa. Relative sea level also stabilized which provided a conducive habitat for forest development beyond the mangrove zone. The middle Holocene palaeoshoreline was 18 km inland in Annamalainagar (Farooqui, 2008) similar to records in Sulurpet (Pulicat Lagoon, Andhra Pradesh) in the North (Farooqui

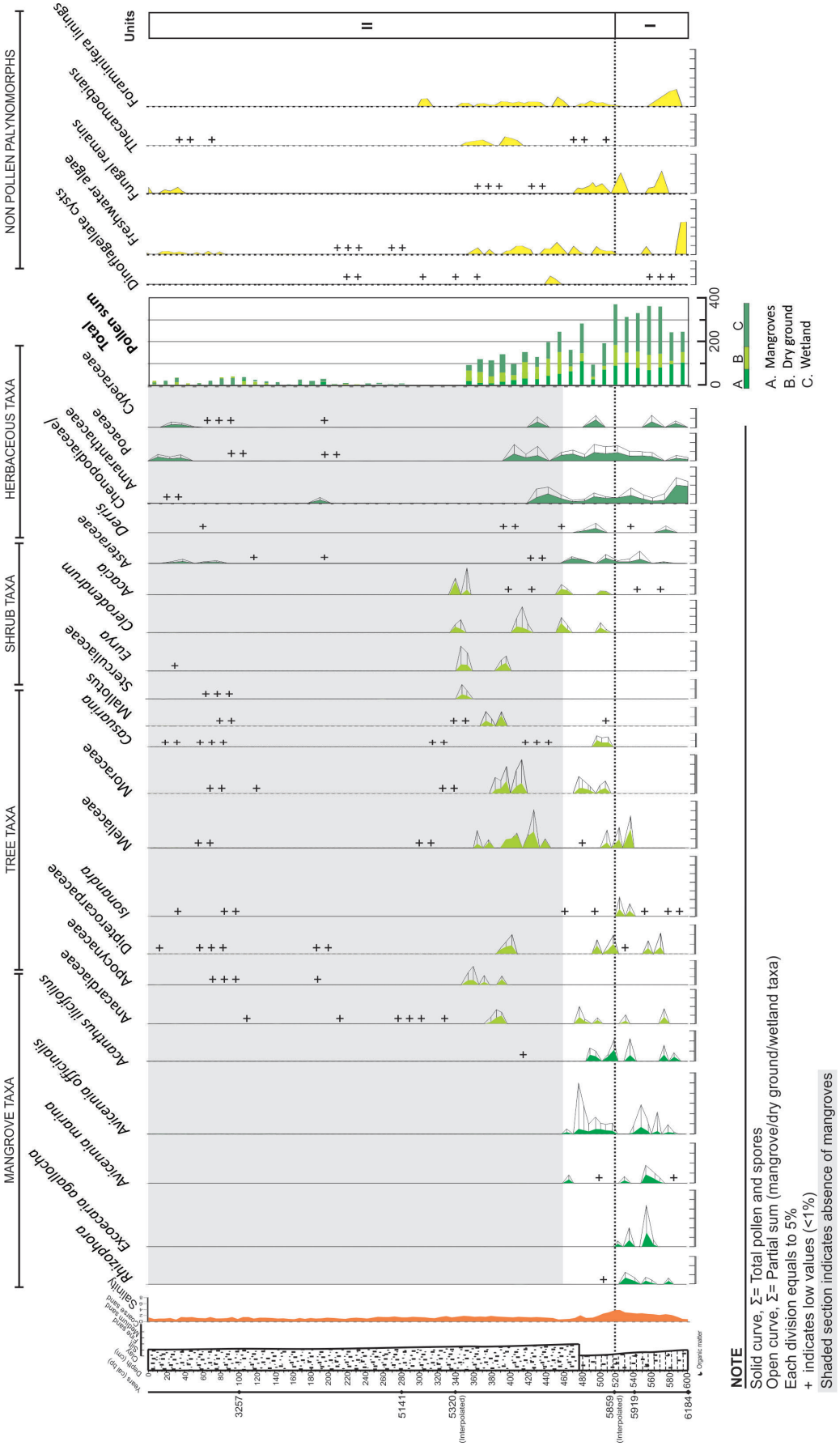

Fig. 5. Summary palynomorph percentage diagram of core TVG from Thillaividangan, southeast coast of India.

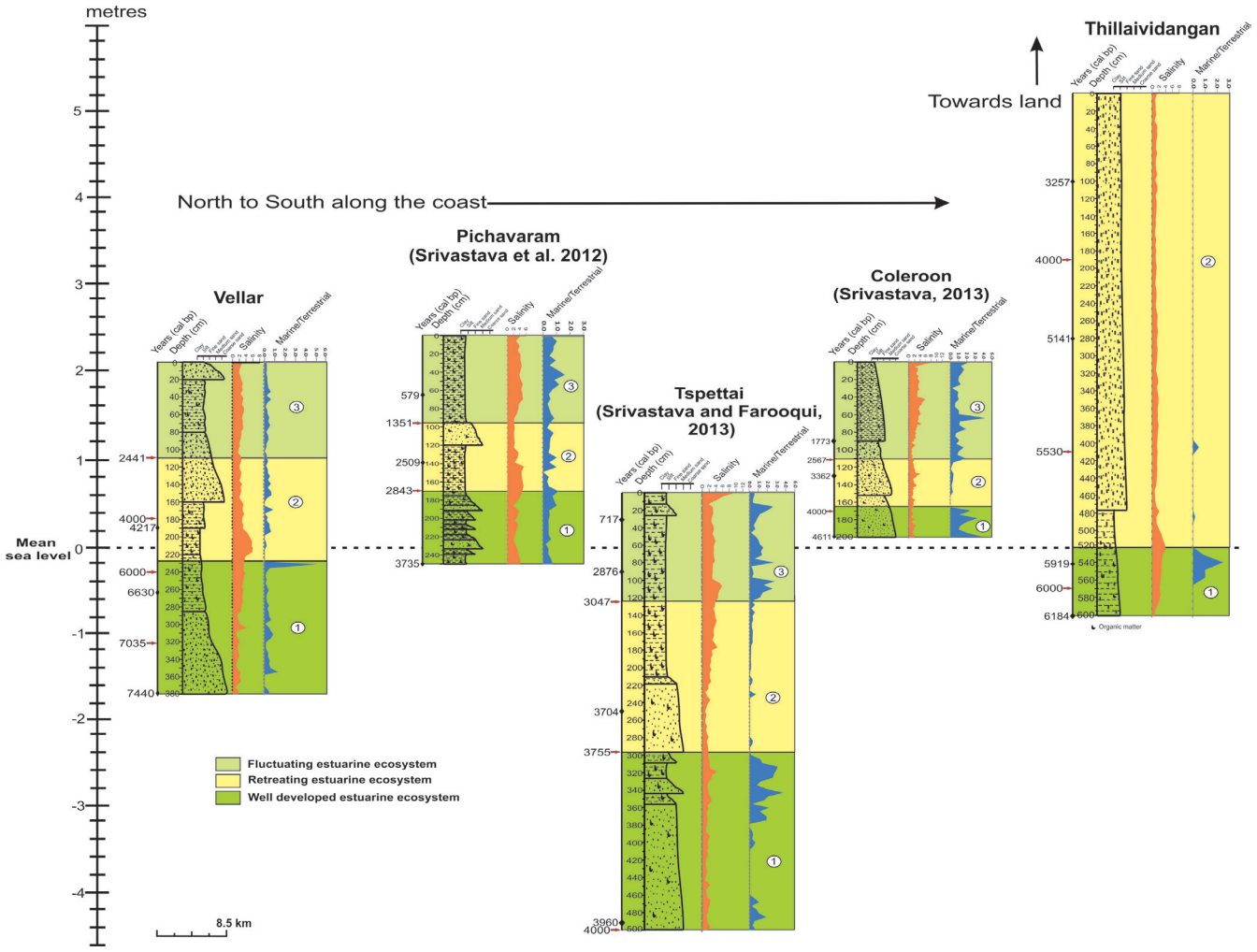

Fig. 6. Holocene tectonic setting and relative sea level changes in southeast coast of India.

and Vaz, 2000). After 5700 cal BP the shoreline receded and the mangroves followed the receding shoreline abandoning landward sites (Figure 7). Mangroves rejuvenated in Vellar as it was only 3 km away from the shoreline and configurational changes caused sea water ingression in this region. In the contemporary cores studied from Pichavaram, TS pettai and Coleroon estuaries in the Cauvery Delta mangroves existed between 4000 to 2800 cal BP. Although this was recorded at different levels from the present mean sea level indicating subsidence/upliftment in the vertical stack of the sediment. Such geomorphological changes may have triggered the ingression of sea water in the subsided area (Farooqui *et al*., 2016). Therefore the luxuriant growth of mangroves is present in Pichavaram and TS pettai wetlands during the late Holocene (~4000 cal BP). It is estimated that a 6 km shift in shoreline took place in a span of about 2000 yrs. Finally the mangroves rejuvenated since 2441 cal BP at Vellar due to sea water ingression but abandoned the Thillaividangan region as it was far from the shoreline.

HOLOCENE TECTONIC SETTING OF SOUTHEAST COAST OF INDIA

Since the evidence for late Holocene estuary (~ 4000 cal BP) in Vellar and Coleroon estuary is 0.3m above mean sea level in contrast to other contemporary areas (Figure 6) along the east coast land upliftment/subsidence in the vertical stack of Holocene sediment is suggested in these locations which is comparable to the coastal wetlands from Kolkata, West Bengal (Banerjee, 2003). In the central region of the study area other sites like Pichavaram and TSpettai estuarine complex mark the late Holocene (4000 cal BP) estuary at 0.2m and 4.4m below the present mean sea level indicating land subsidence in the area with a maximum subsidence observed in the TSpettai mangrove wetland. An overall subsidence of ~1.3-2.2 cm/year has been recorded from Sundarbans, Bangladesh and the Krishna river delta which led to a RSL rise of 2.3cm/year (Brammer, 2014; Farooqui *et al*., 2016). Previous studies conform to the records of mangrove habitat loss and neotectonic activity in the middle of late Holocene from the contemporary Pulicat lagoon on the east coast that was located 18 km inland from the present shoreline during middle Holocene (Farooqui and Vaz, 2000). Here, the mangrove evidence suggesting middle Holocene palaeoshoreline is at 4.2m above present mean sea level. This indicates that the land upliftment and subsidence all along the east coast, perhaps took place in the middle of late Holocene inducing major deltaic configurational changes and habitat loss for mangroves. It indicates strong tectonic control leading to vertical displacement of sediments in different parts giving a

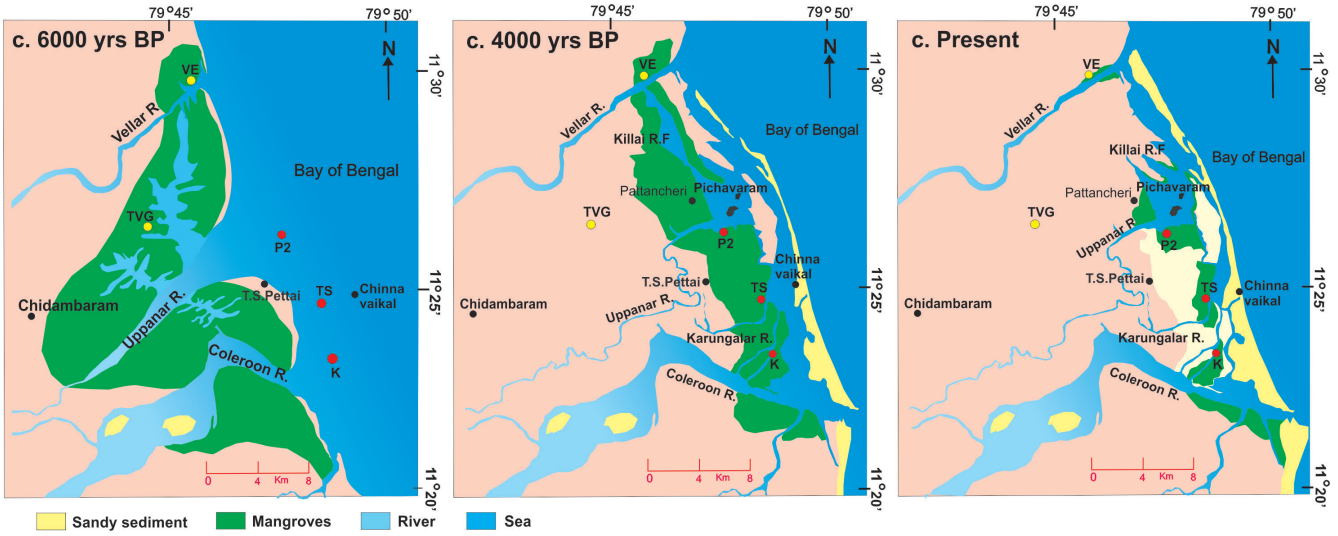

Fig. 7. A schematic representation of estuarine evolution and shoreline progradation in the northeastern Cauvery River Delta since Holocene marine transgression.

complex RSL (Relative Sea Level) for Holocene in the east coast of India. However, an average rise in sea level of ~1.2 to 1.5m during 5000-6000 cal BP has already been reported along the east coast of India (Bannerjee, 2000). A study on the Holocene tectonics of the Tamil Nadu deltas of India suggests that the Proto-Cauvery delta of Chennai region is witnessing ongoing NE – SW sinistral, NW–SE dextral and E–W vertical tectonic activities (Ramasamy, 2006). The sudden right angle turn of the Karungalar River south of the study site TS supports the role of neo-tectonic activities for the observed geomorphological changes (Ghosh and Mistri, 2012). In the present study the region between latitudes 11°25'54.37"N- 11°23'16.12"N and longitudes 79°47'37.84"E- 79°48'24.36"E experienced land subsidence with the maximum depression around latitude 11°24'41.21"N longitude 79°47'59.88"E. The historical record of mangroves along the east coast including the present study area suggests overall progradation of the Cauvery River delta but with sea water ingression probably induced by tectonically controlled vertical stack of unstable loosely packed Holocene sediment.

CONCLUSIONS

This study reveals the relative sea level changes that occurred during the last 7000 cal BP in the Northeastern Cauvery Delta. The study is based on sediment texture and color, salinity and palynological analysis of sedimentary cores/ trenches retrieved from Vellar and Thillaividangan locations which are at 3 km and 10 km respectively, from the coastline. As the delta prograded to about 10 km during 7000-6000 cal BP the net rate of sedimentation in TVG was 0.3 cm/year while in VE (3km from the mouth) the net rate of sedimentation is 0.08 cm/year. Sediment color and texture showed marked variation from blackish grey (5Y4/2) fine clayey silt to greyish brown (5Y4/4) sandy silt sediment in TVG and VE. Evidence of marine palynomorphs at both sites during 6000-7000 cal BP indicate palaeoshoreline extending inland to about 10 km. Since 5700 cal BP the shoreline retreated from TVG whereas salt tolerant *Avicennia* species were recorded from VE. Mangroves followed the receding shoreline and faced deterioration in the east coast of India during the late Holocene induced by increased aridity in the climate that consequently led to gradual/rapid geomorphological changes affecting the wetland configuration. At 2441 cal BP true mangroves rejuvenated in Vellar but with a lower diversity indicating sea water ingression in the wetland following an arid phase. The overall results show that mangroves existed since 4000 cal BP in the Pichavaram estuary (south of Vellar) but at different levels in the core from the present mean sea level. During this period evidence of marine palynomorphs have been recorded at present mean sea level in Vellar, Pichavaram and the Coleroon estuary but in TS Pettai this is about 4 m below present mean sea level indicating land subsidence of about 2-3 m in TS Pettai, the central part of North-eastern Cauvery delta providing a conducive environment for the growth and diversity of mangroves in this part of delta.

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