ISSN 0376-5156
Geophytology 47(1): 11-26
May 2017

Fluctuations in relative sea level and mangroves in the Coleroon estuary since ~4.6 ka: A palynological study from SE coast of India

Jyoti Srivastava* and Anjum Farooqui

Birbal Sahni Institute of Palaeosciences, 53 University Road,
Lucknow - 226007, U.P., India.
*Corresponding author's e-mail: jyotisri.bsip@gmail.com

Manuscript received: 17 February 2017
Accepted for publication: 9 April 2017

ABSTRACT

Palynological analysis of a 200 cm deep sediment core was carried out to understand the trend in relative sea level (RSL) rise and fall as the Coleroon river delta prograded since middle Holocene. The Radiocarbon age (^{14}C) broadly allowed us to infer climate, vegetation and RSL changes in three phases. The sediment depositional environment and climatic phases identified in the Coleroon estuary are (1) fluvio-marine to estuarine transition phase from 4.6 to 3 ka with silt sand fills along with the dominance of *Avicennia*, upland arboreal/shrub vegetation and few *Rhizophora* pollen indicating deltaic progradation/shoreline regression that continued after ~ 6 ka, the period of transgression; (2) late Holocene muddy tidal estuarine phase from 3 ka with fine sandy clay sediment and presence of back mangroves, low percentage of arboreal taxa indicating a dry period until 0.8 ka with a continuous fall in RSL as the delta prograded and (3) since 0.8 ka, corresponding to Medieval Warm Period (MWP), the evidence of pollen grains of true mangroves and their associates show estuarine sediment deposition although a drastic loss in coastal plant diversity is recorded. Palynological results reveal that the delta prograded continuously since the last transgressive phase when the sea encroached land much beyond the studied core. The rise in RSL observed since MWP is attributed to hydrostatic and configurational changes in the wetland induced by climatic conditions and neo-tectonic activity in the area. Loss in mangrove diversity would have been enhanced by the recent anthropogenic activity.

Key-words: Palynology, Mangroves, Holocene, climate, relative sea level, Coleroon estuary, India.

INTRODUCTION

A regular periodicity of sea level changes has been observed and recorded worldwide through different proxies in sediments deposited during the Quaternary period (Achyuthan et al. 2016, Sivan et al. 2016, Farooqui et al. 2014, Srivastava and Farooqui 2013, Woodroffe et al. 2012, Kemp et al. 2011, Hait and Behling 2009, Kumaran et al. 2005, Lambeck et al. 2004, Sen and Bannerjee 1990). The Holocene transgressive phase ~6- 7 ka was witnessed on global scale that encroached several kilometers of land and subsequently, as the sea-level stabilized the deltas prograded defining the present day coasts. The relative proportion of the sediment brought by rivers/streams coupled with coastal dynamics such as subsidence/ upliftment, geomorphology, configurational changes in tidal inlets, dynamics of fluvial energy from land induced by climatic conditions or anthropogenic pressure have largely defined the estuarine/lagoonal biodiversity. Mangroves and the terrestrial vegetation beyond this zone harbor rich biodiversity and are indispensible for increased demography in coastal areas. Mangroves are sensitive to changes in the duration and frequency of inundation as well as salinity levels that exceed a species-specific physiological threshold of tolerance (Friess et al. 2012). Increase in flooding duration can cause plant death at the seaward margin of mangrove forests (He et al. 2007) as well as shifts in species composition (Gilman et al. 2008), finally leading to a reduction in productivity (Castañeda-Moya et al. 2013) and ecosystem services. Coastal flooding is expected to increase in the future because global sea levels have risen by 3.2 mm/yr over recent decades (Church and White 2011) and is possible to rise by 0.28-0.98 m by 2100 (IPCC 2013). Regional factors also strongly influence local sea level, and resultant SLR rates are highly variable, from 1.9 mm/yr in the Caribbean to 7.5 mm/yr in parts of Indonesia (Nerem et al. 2010), and up to 9 mm/yr in the lower Mississippi River Delta (NOAA 2015).

All the deltas in the east coast of India have low slope gradient through which the rivers/streams flow and are recharged only during monsoon depositing fine grain sediments in estuaries that makes the region best archive for gathering information related to climate and relative sea level rise and fall in the past. In Tamil Nadu, almost the entire coastline was covered with mangroves roughly 100 years back (Venkatesan 1966), but now these mangrove formations are discontinuous in the Cauvery delta, Pennar delta, South Tuticorin and Rameswaram. Near Pichavaram village (latitude-11°25' N), the halophytic formation covers an area of approximately 11 km^2 and these areas are situated at the mouth of Vellar, Coleroon and Uppanar; here temperature ranges between 19°C and 31.5°C. Strong biotic pressure, viz., fire-wood exploitation, cattle grazing in these Tamil Nadu coasts have been reported by Kesavan and Swaminathan (2006), Swaminathan (1999), Kaliraj et al. (2013) and Blasco (1975). The middle Holocene palaeoshoreline recorded on land in vertical sections reveal its position at different depths with respect to present mean sea level. In southern Annamalainagar (Tamil Nadu) it is below (Farooqui 2008) and in Pulicat lagoon (Andhra Pradesh) it is above the mean sea level (Farooqui and Vaz 2000). This indicates of tectonic activity in different parts along the east coast of India.

Sea-level changes in any area are considered as relative sea-level (RSL), as it is recorded against the land based on field evidences such as ancient shoreline, coral reef, wavecut notches, mangroves etc. Studies in coral terraces of Barbados and Papua New Guinea have been used to construct the eustatic sea-level changes of late Quaternary (Bard et al. 1990). Periodicity in the relative sea level changes since the sea level stabilized around 6 ka (Chanda and Hait 2003) is of great concern to human beings. Relict corals exposed along the Saurashtra coast (Somayajulu et al. 1985), oyster beds in Goa coast, as well as data presented by Verma and Mathur (1979) points to a ~2m higher than present sea level along the west coast of India, some 6000 years ago. On the east coast, at a water depth of 120 m ridge-terrace with corals are developed, dated 18,390 yrs BP (Vaz 2000). Banerjee (1993) discusses sea-level changes on the east coast during Late Pleistocene-Holocene. The sea transgressed the land, inland of present shoreline between 7-6 kyrs. In many parts, with high sediment supply the coastline has prograded seaward by several kilometres. Banerjee (2000) argued that sea-level on the east coast of India was 3 m higher than today around 7.3 kyrs, and between 5.2-4.2 kyrs, separated by a period of lowered sea-level. Organic remains in their growth position are reliable criteria to determine sea-level, where mangrove sediment (both mangrove peat and pollens) are very useful indicator of sea-level in tropical climate. Chanda and Hait (2003) reconstructed Holocene sea-level changes using mangrove vegetation and radiocarbon dates in Ganga delta. A review on sea-level changes along the coasts of India (Somayajulu 2002) and coastal evolution of India has been compiled by Rajamanickam (1990) and Rajamanickam and Tooley (2001).

While recent research has rapidly advanced our knowledge of the sediment texture, mineralogy and geochemistry of the Coleroon estuarine system of the Cauvery River (Irudhayanathan et al. 2011, Seralathan 1979) the potential of this estuary as a site of palynomorph preservation has not hitherto been exploited. Palynological signatures in vertical sedimentary sections of the estuaries at the mouth of Coleroon River and its adjoining tributaries have been highlighted in view of other similar records in contemporary areas. Since mangroves have considerable resilience to fluctuations in sea level (Woodroffe and Grindrod 1991) due to their ability to actively modify their environment through surface elevation change processes and to migrate inland over successive generations (Krauss et al. 2014). Mangrove palynology, radiocarbon age and physico-chemical parameters of the sediment together can be known as useful indicators of past sea level in tropical climate. Predicted magnitude and duration of future relative sea level trends as an outcome of such studies would further be important for the formulation of wiser strategies in industrial and agricultural development in Economic Coastal Zones.

STUDY AREA

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 biggest of such in the east coast of Tamil Nadu. The underlying Cauvery Basin is known for its hydrocarbon prospects and the deltaic region has potential aquifer systems particularly along the palaeo-channels and levee deposits (Das 1991). The Cauvery River originates from the Western Ghats in Karnataka and flows towards southeast over the Mysore plateau to the Bay of Bengal through the state of Tamil Nadu with an approximate aerial coverage of 87,900 km^2 (Ramanathan et al.1996, Singh and Rajamani 2001). The upper ~300 km of the river flows through a low-relief landscape, where as in the downstream the river flows in a gorge, inset with terraces and cut in to a succession of older erosion surfaces. This transition of geomorphology is attributed to active faulting (Valdiya 2001), seen together with shift from stable to an uplifting region with the change in crustal rheology from a cold Archaean cratonic region to a hotter crust of Pan-African thermal age (Bridgland and Westaway 2008). The region is chiefly underlain by the Archaean- Proterozoic crystalline rocks which constitute gneisses, charnockites and granites and is covered by Quaternary sediments towards the coast. The river basin falls within two major terrains with its head waters flowing through a greenstone- granite terrain (Dharwar Craton) in the north and a granulite terrain in the south. These two terrains are separated by a transition zone of granitic rocks with inclusions of a schist belt towards the north and charnockites and pyroxene granulites and high grade amphibolites assemblages in the south (Sharma and Rajamani 2001). Towards the east, bound to the Quaternary alluvium in the delta it also features exposures of Cretaceous sediments (Uttatur, Ariyallur and Tiruchirrapalli Formation) and sandstone (Cuddalore Formation) of Mio- Pliocene age. The Quaternary sediments are basically fluvial sediments, middle Holocene beach ridges and late Holocene dune sands (Kunz et al. 2010). The area is crisscrossed by a number of distributaries of the River Cauvery and few manmade channels which bring sediments into the coastal region. The Cauvery Delta is a river dominated delta and is occupied by several of its distributaries. The present delta has developed a triangular pattern with three distinct morphological areas consisting of a marginal denudational unit, a central fluvio-marine depositional unit and a coastal marine depositional unit (Babu 1991). In this fanning delta with its origin located east of Tiruchirappalli, the present day river flows through the northern channel of the delta as the River Coleroon. From the satellite images of the North-eastern part of the delta one can identify a number of palaeo river channels south of this main channel, which includes the former channel of River Cauvery with its mouth located south of Pumpuhar and other tributaries south of this channel. A number of geomorphological features can be identified in the delta region such as palaeo river channels, lagoons, swales, dunes, beach ridges, salt marshes, swamps etc. The Cuddalore Sandstone of Miocene-Pliocene age is seen in the uplands in the western margin of the delta and is outcropped in the north at Jayamkondam region and in the south at the Vallam-Pattukottai-Mannargudi region (Ramasamy et al. 2006). These detached outcrops formerly existed as a continuous unit starting from Pondicherry to Sivaganga in the south west and the present day streams such as Coleroon largely removed this formation (Vaidyanadhan and Ramakrishnan 2008). The Cuddalore Formation generally comprises of gritty, pebbly to conglomerate, coarse to fine grained argillaceous sandstone, ferruginised and laterised towards the top (Vaidyanadhan and Ramakrishnan 2008). In the south, Miocene- Pliocene sandstone of

Text Figure 1. Location map of sediment core (K) in the Coleroon estuary, SE coast of India

Text Figure 2. Vegetation at the core site (K) showing dominance of *Avicennia* and *Rhizophora* fringing the backwater channels.

the Vallam area is largely undissected and that of Pattukottai- Mannargudi is highly dissected with gullies and relict butte landforms (Ramasamy et al. 2006).

Coleroon River is the main distributary channel of the northern part of Cauvery delta and forms an estuarine complex in its lower reach. Since middle Holocene the delta has prograded and shifted northwards gradually (Sambasiva Rao 1982, Meijerink 1971). The shift in the river channel has been probably due to siltation of the channel belt. There are records of differential movement of uplift and subsidence in Cauvery delta during Quaternary (Meijerink 1971). The Coleroon estuary is connected to Pichavaram and Vellar estuary in the north fed by Uppanar and Vellar Rivers, respectively. The estuary receives copious supply of freshwater during the northeast monsoon (October-December) and also during the June-September period, when water is released from the Cauvery River for irrigation purposes. Though the estuary has perennial connection with the sea, the width of the mouth varies with flooding and dry periods. There is tidal influence in the estuary up to a distance of 12 km from the river mouth.

MATERIAL AND METHODS

The core site K (11° 23' 14.34" N, 79° 48' 22.28" E) is located near the margin of the Coleroon estuarine channel close to Mahendrapalli approximately 5 km inland from the coast (Text Figure 1). The site was within an undisturbed protected environment dominated by back mangrove *Avicennia* sp. and *Rhizophora* sp. along the channel margin which act as a guard for the inland areas against wave action and storm. A 200 cm sedimentary soil profile retrieved using manual piston corer (Eijelkamp, Netherlands) in the vicinity of mangrove forest (Text Figure 2) was sub-sampled at 2 cm intervals. Sediment colour, texture, salinity and terrestrial/ marine pollen and non-pollen forms were studied. The soil color was recorded (Munsel color chart 2000) and the texture (percentage of sand, silt and clay) was examined by density method (USDA 1992). Both these parameters were recorded in the core in order to understand the sediment depositional environments in the past. Conventional ^{14}C radiocarbon dates of the organic carbon were obtained from Birbal Sahni (BS) Institute of Palaeosciences, India by following a standard preparation method. Particularly, organic carbon rich silty clay sediments were manually selected to get a good chronological control for reconstructing RSL changes. Samples were cleaned, sieved and digested with hydrochloric acid to remove carbonate component if present. After thorough rinsing for pH stabilization, sediment dried at 95°C was combusted in the continuous flow of oxygen. The resulting carbon dioxide was collected and converted to acetylene and then benzene using standard catalyst and procedures. Counting was carried out in a Liquid Scintillation Counter (Quantulus 1220). Calibrated age (cal. yr BP) is weighted average of 2ó ranges using IntCal13.14c data set (Reimer et al. 2013, Stuiver et al. 1998) and has been given in results.

Salinity was measured in the aqueous soil solution of the sediment core in order to know the salinity of the available water required for the growth of mangroves and its associates. For this 10 g of air dried sample was dissolved in 100 ml of deionized water. The aqueous soil solution was kept overnight and homogenized for 30 minutes prior to measuring salinity (psu) using 'Orion-5 star' (Thermo-Orion, USA) at standardized 25°C temperature.

Palynological study was carried out in 10 g of air dried soil sediment following Erdtman (1943). The samples were seived through 8 μm mesh and the residue was collected for the palynological slides in 1:1 ratio of glycerine and deionized water and a drop of phenol to prevent its microbial degradation. The samples were studied under a high power light microscope (Olympus BX-51) at 400x magnification and the palynomorphs were 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 in palynological slides referring Ogden and Hadley (1980), Patterson and Kumar (2002). The palynological spectrum represents the percentage of the total count i.e. 300 of mangrove taxa, upland tree and herb/shrub, wetland, aquatic taxa, freshwater algal spores, fungal remains, thecamoebians, foraminifera linings and dinoflagellate cysts in homogenized 10 ml acetolysed sample. The relative sea level changes have been recorded through the curve showing the ratio between marine (mangrove taxa pollen, foraminiferal linings, dinoflagellate cysts) and terrestrial (upland arboreal and non arboreal taxa pollen, freshwater algae and thecamoebians) palynomorphs.

RESULTS AND DISCUSSION

Chronology

14C radiocarbon dates (Table 1) from the K core are plotted (Text Figure 3) and a simple age-depth model based on interpolation between radiocarbon-based control points have been used. Estimated net rate of sedimentation (NRS) in zone K-I prior to c. 3150±100 yrs BP is high (0.06 cm/yr). For the period between c. 3150±100 and 1839±140 yrs BP, estimated NRS falls to 0.03 cm/yr. After 1839±140 yrs, estimated NRS increased to 0.05 cm/yr.

On the basis of sediment texture and palynological results the entire 200 cm core has been demarcated into three broad zones in ecological perspective. These are K-I, K-II and K-III.

Sediment color, texture and salinity

The bottom (K-I) deposits of loamy sand sedimentary fill (Text Figure 4) between 200-152 cm are composed of sand (88%), clay (8%) and silt (4%). The greyish brown colour of the sediment falls under 5Y5/2 of Munsell Colour chart. Sediment between 152-90 cm (K-I/II) is silty loam constituting sand (67%), clay (9%) and fine-grained silt (24%). The greyish brown colour of the sediment falls in 5Y4/2 block of the Munsell colour chart. The zone K-II/III (90-0 cm) is sandy clay to clayey loam and constitutes fine-grained sand (69%), clay (16%) sediment and silt (15%) and colour of the sediment is 5Y4/2 (greyish brown).The values of salinity in bottom zone K-I comprising of sand as the main fraction reveal the lowest salinity having an average of 0.7 with a maximum of 0.8 and a minimum of 0.6. Zone K-II constituting silty sand show an average salinity of 2.3, maximum being 3.9 and minimum 0.8. The topmost zone K-III constituting fine clayey sand shows the highest salinity status with an average of 2.4 (maximum 3.3 and minimum 1.6). Predominance of sand and low salinity condition at the base of the sediment profile suggests more fluvial activity in the area which gradually shifted towards an enclosed ecosystem with low fluvial energy condition marked by increased fine sediment deposition and high salinity status. Thus, a homogenous sediment composition with dominance of fine sediment signifies a low fluvial energy estuarine ecosystem with least bioturbation and erosional effects.

Palynology

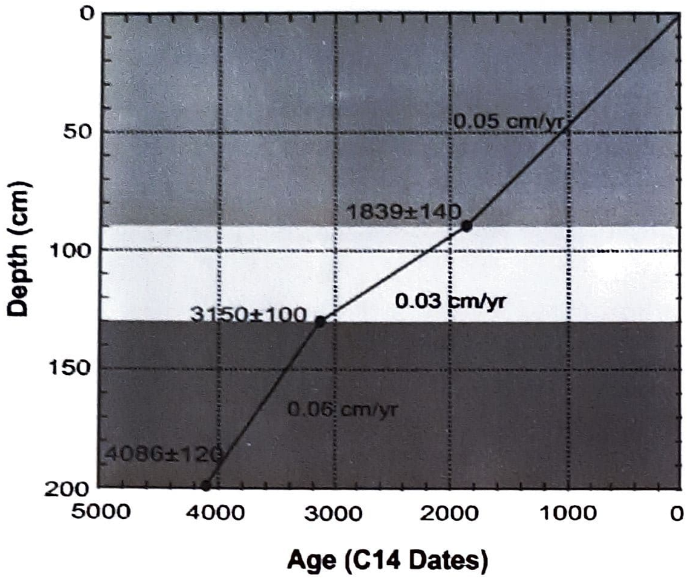
The entire sediment core shows good pollen preservation. The palynological spectrum (Text Figure 5) shows the results in ecological perspective.

K-I: 200-120 cm (4611-3000 cal BP)

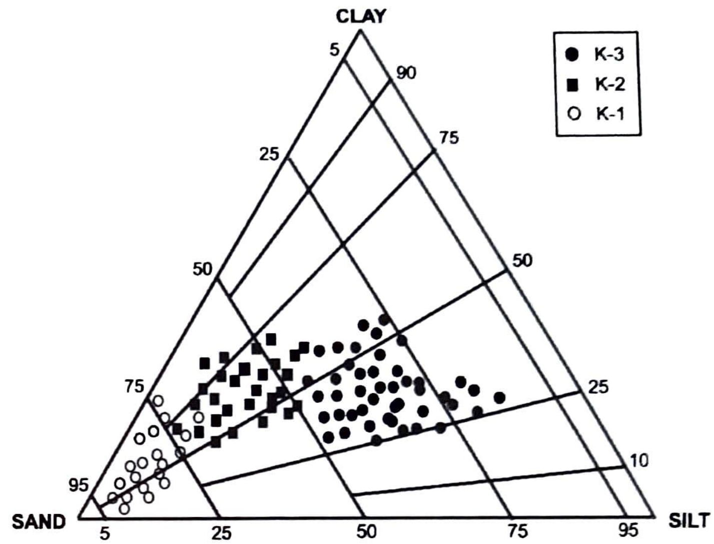
This zone represents high abundance of mangrove pollen. Among these the highest percentage is of *Avicennia officinalis* (> 20) followed by *Ceriops, Bruguiera, Rhizophora, Avicennia marina, Sonneratia apetala, Sonneratia caseolaris, Aegiceras corniculatum, Lumnitzera racemosa, Conocarpus erectus, Acrostichum aureum, Cynometra iripa* and *Acanthus ilicifolius* (5-8%).The upland plants represent moderate to high percentage of tree taxa such as Anacardiaceae (>10), Apocynaceae (~5), *Azadirachta indica* (5-7), Bombacaceae, Moraceae, *Syzygium, Cocos nucifera, Casuarina* and Dipterocarpaceae (~7 each). *Cedrela odorata, Hopea* and Sapotaceae constitute (~1% each). Small trees and tall shrubs belonging to Combretaceae, Malvaceae, *Mallotus, Thespesia* and *Tabernaemontana* constitute 5-7% each along with the herbaceous taxa such as pollen grains of Lamiaceae, Asteraceae, Caryophyllaceae, Euphorbiaceae and Solanaceae (~7% each). Herbaceous plants of salt marsh environment like Chenopodiaceae/ Amaranthaceae, Poaceae/ Cyperaceae and aquatic taxa *Eichhornia* represent 5-8% each. *Selaginella* and Polypodiaceae spores constitute 10%. The non-pollen forms such as freshwater algae *Pediastrum* and thecamoebians along with the cyst of unknown lineage *Pseudoschizaea* show high percentage (> 20%). The average ratio of marine forms and terrestrial forms identified in the assemblage for this zone is 0.5 (Text Figure 6).

Table 1. Radiocarbon dates (14C) for core K from Coleroon estuary, Southeast coast of India

S.No	Depth (cm)	Material	Laboratory Number	^{14}C age (yr BP)	Calendric age (cal BP)	Calendric age (cal BC/AD)
1.	90	Sediment	BS-3359	1839±140	1773	177 cal AD
2.	130	Sediment	BS-3200	3150±100	3362	1412 cal BC
3.	200	Sediment	BS-3191	4086±120	4611	2661 cal BC



Text Figure 3. Age-Depth model showing the rate of sedimentation in the core sediment (K) Solid dots show the median calibrated ages



Text Figure 4. Ternary diagram showing sediment texture in the sediment core (K)

K-II: 120-45 cm (3000-800 cal BP)

A decline in mangrove pollen (>3%) is observed. It comprised of *Rhizophora* sp. and *Lumnitzera racemosa* (~5%) with a continuous curve for *Avicennia officinalis* (~4%) and *Excoecaria agallocha* (~4%). The upland pollen also shows a sparse assemblage with dominance of Euphorbiaceae (~10%) pollen followed by Anacardiaceae, *Cedrela odorata*, Dipterocarpaceae, *Azadirachta indica*, Moraceae, Bombacaceae, *Cocos nucifera*, *Casuarina equisetifolia*, Combretaceae, *Mallotus*, *Thespesia*, *Tabernaemontana* and Lamiaceae (2-5%). Herbaceous taxa include Asteraceae, Caryophyllaceae, Solanaceae and *Derris* (~5%). The wetland group is dominated by peak values of Liliaceae, Cheno/Ams, Poaceae and Cyperaceae (10-12%). Taxa such as *Acrostichum aureum*, *Aegiceras corniculatum*, *Bruguiera*, *Justicia*, *Polygonum* and *Typha* were completely absent from the assemblage. Other microfossils include *Pediastrum* and thecamoebians displaying a declining curve (2-3%) whereas foraminifera linings and dinoflagellate cysts show marked abundance (15%). The average ratio of marine forms and terrestrial forms identified in the assemblage for this zone is 0.2.

K-III: 45 cm (800 cal BP to present)

The Mangrove pollen again show an increase in percentage (>10%) since c. 1000 years back represented by *Rhizophora, Bruguiera, Ceriops, Excoecaria, Avicennia* and *Acanthus*. Dominance of *Avicennia officinalis* pollen (12%) is observed. Mangrove pollen such as *Acrostichum aureum, Aegialitis rotundifolia, Aegiceras corniculatum, Cynometra iripa, Conocarpus erectus, Lumnitzera racemosa, Sonneratia apetala* and *Sonneratia caseolaris* constitute lower percentage (2-5%). The reappearance of upland tree pollen reflect moderate to low peaks of ~5% comprising Anacardiaceae, Apocynaceae, Bignoniaceae, *Azadirachta indica, Casuarina, Cocos nucifera, Syzygium, Cedrela odorata, Hopea* and Moraceae. Herbs and shrubs show moderate values for Combretaceae, Malvaceae, *Tabernaemontana, Acacia* (<5%), *Alternanthera*, Euphorbiaceae (>5%), *Justicia* (~3%), Lamiaceae (8%) and *Mallotus* (~2%). Moderate percentage of Cheno/Ams, Poaceae and Cyperaceae (~5%) along with low values (~2%) of *Typha* and *Eichhornia* was observed. Among the non-pollen forms such as *Pseudoschizaea*, thecamoebians and foraminifera linings show moderate values (~10%) whereas dinoflagellate cysts (~8%) emerge only after c. 600 cal BP in this zone. The average ratio of marine forms and terrestrial forms identified in the assemblage for this zone is 1.1.

The study allowed us to infer sediment depositional environment and coexistence of mangroves and upland plant taxa which remained in equilibrium with the climate and relative sea level changes during the last 4 ka. The bottom Zone K-I shows dominance of greyish brown coarse sand and comparatively low salinity. Zone K-II is characterized by silty sand and shows high salinity in the aqueous soil solution. Similar results were observed in Zone K-III where the sediment texture is again silty sand and high salinity of maximum 3.3 is recorded. The increase in salinity in aqueous soil solution points to the fact that the high percentage of salts are present in the pore water and can move upwards or downwards through capillary action. Silty sediments are prone to hold more salts in their lattices (Farooqui 2010) and therefore, the slow sediment depositional environment coupled with poor water runoff induced by either natural climatic factors or anthropogenic pressure is likely to build up salts in the estuarine sediments. Salt accumulation takes place readily in the surface soil due to the exposure of estuarine highlands subjected to evaporation during low water runoff particularly in tropical areas. High rate of sedimentation also affects the tidal inlet into the coastal wetlands and change in the inlet loci is always possible in short duration time. Zone K-I shows high net rate of sedimentation which may have resulted in the siltation at the tidal inlet restricting the water runoff that lead to a decline in true mangroves and dominance of salt tolerant *Avicennia* species. In both the Zones K-II and K-III the net rate of sedimentation is quite low. Overall results here show good water runoff in Zone K-I with high net rate of sedimentation which also favoured conducive ecology for diverse species of mangroves such as *Ceriops, Bruguiera, Rhizophora, Avicennia marina, Sonneratia apetala, Sonneratia caseolaris, Aegiceras corniculatum, Lumnitzera racemosa, Conocarpus erectus, Acrostichum aureum, Cynometra iripa* and *Acanthus ilicifolius* in high percentage. The palynological results show comparatively high precipitation during 4.6 to 3.0 ka and the vegetation pattern is in equilibrium with the climatic conditions. Presence of dinoflagellate cysts along with a good proportion of freshwater algae and thecamoebians in this zone also characterize the good riverine influx along with the marine influence. The climate of the Middle to Late Holocene has played a chief role in supply of inland water that formed the past landforms and vegetation (Bryson and Swain 1981, Van Campo and Gasse 1993, Van Campo et al. 1996, Bera et al. 1997, Bera and Farooqui 2000, Chauhan and Suneethi 2001).

Later in Zone K-II and K-III the increase in salinity may be largely responsible for the decline in true mangroves as the availability of the physiologically active water required for their survival was restricted. As a result dominance of salt tolerant *Avicennia* and *Suaeda* is common in most part of the estuary. This shift in the vegetation in Coleroon estuary is attributed to the gradual weakening of monsoon during the late Holocene characterized by a drier climate (K-II) as compared to the middle Holocene. During 3.0 to 1.2 ka (K-II) the loss in arboreal pollen along with the core mangrove species such as Rhizophoraceae members indicates a dry/arid phase which could be due to the setting in of a high seasonality climatic regime. After 1.2 ka (K-II/III) *Avicennia* spp. inhabiting the intertidal zones of the estuarine ecosystem rejuvenates along with the other core mangroves and arboreal taxa, suggesting a moderate rise in precipitation displaying a relatively wet condition in the recent past. The upland arboreal and herbaceous vegetation also show a moderate rise in the pollen sum reflecting low seasonality conditions but not as low as around 4.0 ka, which could be emphasized due to the loss in diversity of both mangroves as well as upland taxa. The entire east coast of India as of now is infested by scrubby *Avicennia* and *Suaeda* species. Since the east coast is characterized by low slope gradient and poor drainage pattern enhanced by anthropogenic activity the dominance of silty and clayey sediment deposition is common. Such type of sediment shows good organic matter preservation but are also good salt accumulators.

Salinity is the primary environmental stressor and regulator of plant development in mangrove forests (Medina et al. 1990). Mangrove fern *Acrostichum aureum* disappeared from the region during 3.4-1.0 ka as it generally requires freshwater for its establishment and optimal growth. Several authors (Tomlinson 1956, Walter 1973) reported that *Acrostichum* grows optimally on somewhat elevated grounds in mangrove forests that are well protected from frequent tidal influx and have high rainfall, which tends to desalinate the upper soil layers. *Aegiceras corniculatum* and *Cynometra iripa* which grow luxuriantly in a range of substrates from sandy to compact mud also faced deterioration during this time period due to low freshwater input as they grow specifically near riverine freshwater sources. Likewise, *Lumnitzera racemosa* was absent from the pollen assemblage during 3.1-0.9 ka which also prefers moist, well drained sediment for better performance. Mangrove apple *Sonneratia* species along with *Bruguiera* and *Ceriops* also deteriorated ~3.0 ka but reestablished them in the last millennium while *Rhizophora* sp. survived throughout the time span though with reduced diversity. All these mangroves are considered good pioneering species with high generation potential that colonize well on newly formed mud flats (Terrados et al. 1997) but *Rhizophora* sp. known as facultative halophytes have better ability to thrive even in waterlogged soils which may have salinities ranging from 0-90 ppt. *Excoecaria agallocha*, a back mangrove was continuously found after 3.4 ka due to its ability to exploit open areas. It bears extensive cable roots and multiple stem and can be deciduous in cooler/drier climatic conditions. Similarly, *Avicennia* sp. has a high tolerance to hypersaline condition and also regenerates quickly on newly fomed habitats. It is the colonizing species on newly formed mudflats in most of the Southeast Asia (Terrados et al. 1997).

COASTAL ENVIRONMENT AND RELATIVE SEA LEVEL CHANGES

Most of rivers/streams that join the Bay of Bengal in the east and the Arabian Sea in the west traverse a long distance and are monsoon driven. Therefore, the palynological succession reconstructed from sediments deposited in mangrove wetlands are good indicators of the rise in relative sea level and changes in the marine ecosystems. Mangroves have an important role in protecting coasts during storm and tsunami events, both by frictional reduction of wave energy and by promoting sedimentary resilience to erosion (Kathiresan and Rajendran 2005). Studies following the 2004 tsunami found that, in some places, human deaths and loss of property were reduced by the presence of coastal vegetation shielding coastal villages (Dahdouh-Guebas et al. 2005).

Mid to late Holocene fluvio-marine to estuarine transition (K-I; 4.6-3.0 cal BP)

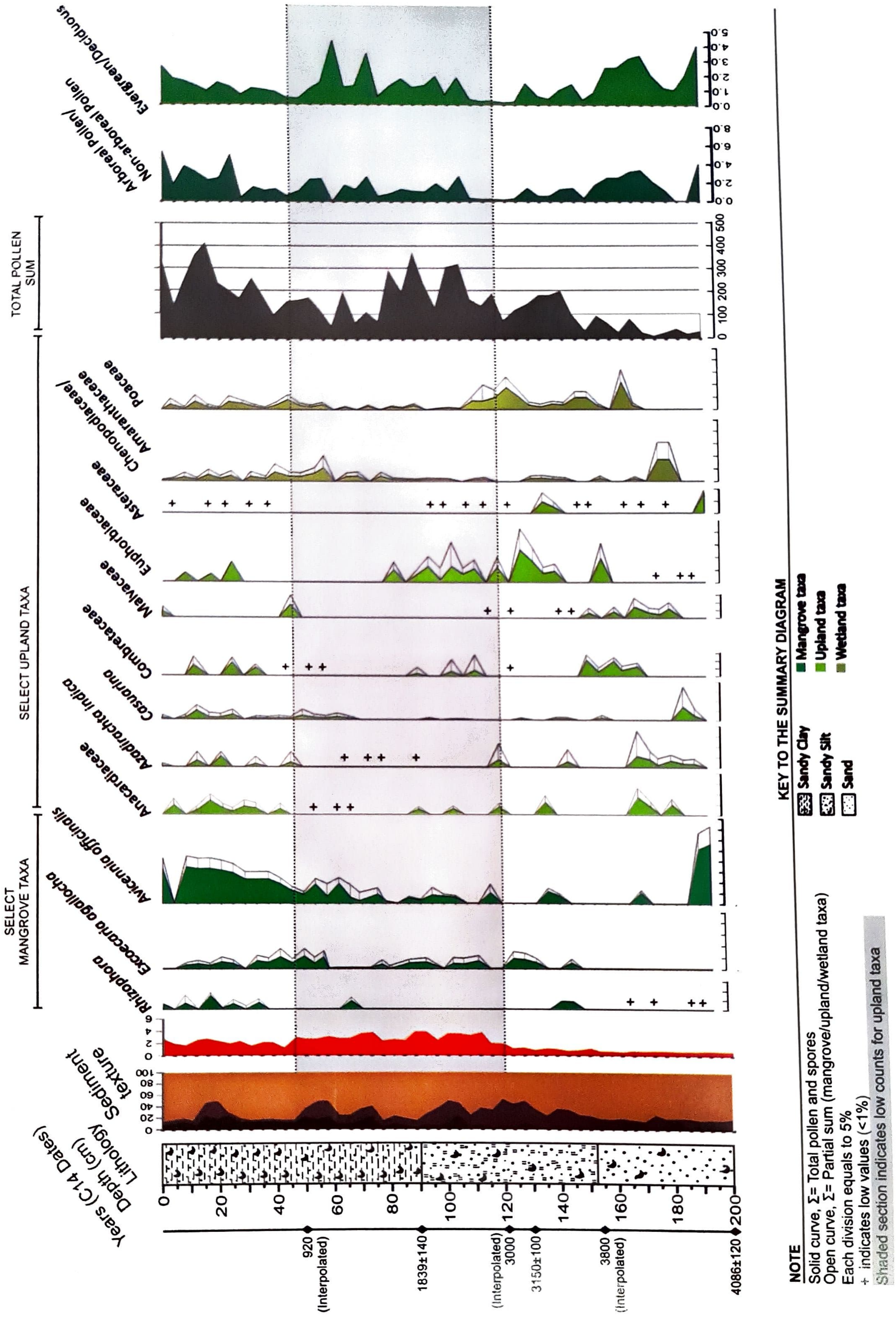
The silty sand fills composed of medium to fine sand and silts reflect the general conditions of a fluvial/estuarine sedimentary environment at the core location. In the basal zone of K-I, high percentage of *Avicennia* and a few other mangrove associates along with the upland arboreal taxa and high percentage of shrub vegetation marks the presence of a fluvio-marine coastal environment during the early part of late Holocene (~ 4.0 ka) due to the influence of moist conditions in the middle Holocene (Bera and Farooqui 2000). The abundance of upland taxa in the lowland areas of the landscape close to the site suggests the presence of a forested basin beyond the mangrove forests during the late Holocene (Farooqui 2008). The on land palynological evidence of increased plant diversity throughout India during this period is also well known (Farooqui and Vaz 2000, Bera and Farooqui 2000, Bera et al. 1997, Banerjee and Sen 1987, Gupta 1981). At 3.6 ka reduction in the *Avicennia* percentage with the emergence of other *Rhizophora* pollen suggests a transformation of fluvio-marine condition to an estuarine environment along with the loss of the nearby upland forest and moderate changes in the lowland vegetation. In terms of non-pollen microfossils, the presence of *Pediastrum* and other freshwater algae along with thecamoebians indicates the dominance of riverine input in relation to the sea incursion which later on ~3.4 ka was affected as deduced by the decline in freshwater algae and concurrent rise in the foraminiferal linings and the dominant estuarine dinoflagellate *Spiniferites* which is abundantly found in the warm and wet climatic condition along with the other freshwater algae, thecamoebians and foraminferal linings, reflecting a well-mixed tidal source of palynomorphs and algal bodies during the wet mid-late Holocene phase of the estuarine infilling. ^{14}C dates from Muttukadu estuary, Tamil Nadu indicate a rapid relative sea-level rise (RSL) after 3500 cal BP and tidal flat sedimentation between 3475 and 3145 cal BP (Achyuthan and Baker 2002). The sea-level on both the west and east coast of India reached the present level at 7.0 ka and continued to rise (Brückner 1987) till it reached its maximum between 6.0 and 4.0 ka, as suggested by the beach ridges of the Krishna-Godavari delta coast (Nageswara Rao et al. 2013). The palynological reconstruction of sediments deposited between 2500-4000 yr BP reveal fluvio-marine deposition and a good percentage of diverse mangrove species, indicating comparatively strengthened monsoon condition along with adequate seawater ingression through tidal inlets which favoured the estuarine ecosystem. During this period the stability of relative sea level is recorded due to the consistency recorded in the mangrove pollen percentage and other terrestrial and marine palynomorphs (Srivastava et al. 2012, 2013, Srivastava and Farooqui 2013). Altogether, the present study suggests a deltaic progradation/shoreline regression that continued after ~ 6.0 ka, the period of transgression along with a wet climate which provides a conducive habitat for the coastal vegetation development.

Late Holocene muddy tidal-flat (K-II; 3.0 ka to 0.8 ka)

The sediments in K-II display evidence of a sheltered mudflat with fine sand and clay representing a shift towards lower energy depositional conditions. The zone is generally poor in organic matter although some detrital plant matter is contained within the fine-grained layers. Low concentration of all pollen types suggests a sparsely vegetated or non-vegetated sediment surface, i.e. a mud-flat environment. The greater evidence of marine influence (dinoflagellate cysts) at 0.9 ka as compared to the basal phase suggests the intrusion of the marine-estuarine domain inland as a result of weaker monsoon condition during the last millennium in comparison to the period around 4.0 ka. Similar trends in climate induced relative sea level changes were recorded from the Pichavaram eatuary, Tamil Nadu. Palynological and sediment analysis results reveal a climate shift from warm and humid with strengthened monsoon condition to dry and arid at ~ 2750 yrs BP (Srivastava et al. 2013). Sea water intrusion and loss of deltaic land have also been reported in Krishna-Godavari delta (Nageshwara Rao et al. 2013). The consequences of climate change and land subsidence are often related to sea level rise/fall. Mangroves extinction and migration through time has been assessed through palynological studies in the Krishna delta (Farooqui et al. 2016) also where the results reveal that the sea level rise has not been continuous but fluctuated with intermittent short duration before the weakening of monsoon began during the late Holocene (~3000-2500 yrs BP).

Last millennium estuarine ecosystem (K-III; 0.8 ka to present)

Since the last millennium, corresponding to Medieval Warm Period (MWP), the evidence of true mangroves and their associates show an estuarine sediment deposition although a drastic loss in coastal plant diversity is observed. The mangroves rejuvenated since ~0.8 ka but abandoned most of the central and southern part of the study area, shifting in the direction of the fresh water thrust and sea inlet which is in the north-east of the present estuary. At present, mangroves are confined to the north-east fringe of the Coleroon estuary between a number of criss-crossed backwater channels. The mangrove diversity was perhaps affected by a variety of factors, including the size of the estuary, nutrient supply (Farooqui 2000, Farooqui et al. 2009) and retention, the complexity of water circulation, the variety and extent of sediment types on the bottom, the range of habitats available and the tidal range. The palynofloral aggregates suggest an increase in salinity in the ecosystem and reduction in the diversity of true mangroves during the late Holocene as compared to middle Holocene. This loss in mangrove diversity would also have been enhanced by the recent anthropogenic activity. The rise in relative sea level observed since



Text Figure 5. Pollen percentage diagram for selected taxa from Coleroon estuary, Southeast coast of India.

MWP is attributed to hydrostatic and configurational changes in the wetland induced by climatic conditions and neo-tectonic activity in the area.

ANTHROPOGENIC PRESSURE ON COASTAL VEGETATION

The diversification of shrublands and open ground vegetation accompanied by the loss of both Dipterocarpaceae and Meliaceae forests since 4.0 ka, along with the destruction of woodlands and thickets of Anacardiaceae and *Syzygium* in the present study not only suggests a competitive readjustment to a drying trend, but also human impact through clearance, fire and pastoral activities across the upland and lowland environments. Finally, since ~1.5 ka, declines of both the shrub taxa and riparian woodlands demonstrate the ultimate reduction of all arboreal taxa, regardless of climatic preferences, and suggest the extension of cutting and clearance activities into both the driest and wettest areas of the region. While climatic aridity may have exacerbated the impact of human activities, the view here is that anthropogenic influence is also one of the factors underlying the distinct changes in the pollen record after 4.0 ka. Between 4.0 and 1.5 ka, anthropogenic pressure due to vegetation clearing in adjacent catchments, urban runoff and the influx of waste water increased. All of these flows containing excessive nutrient loadings may have triggered ecological imbalances that changed the distribution and structure of mangrove community and reduced its complexity. The mangroves were reduced but comparatively covered more area than present. The present estuarine area is now a wave-dominated estuary characterized by sand barrier development. The mangrove line followed the receding shoreline and faced deterioration in the east coast of India during the Late Holocene due to increased aridity in the climate that resulted in gradual/ rapid geomorphological changes affecting the wetland configuration. The overall results show that mangroves existed continuously since the Middle Holocene in the estuary with a seaward and northeastward shifting of relative sea level/shoreline. However, in Pichavaram mangroves have continuously existed since ~ 4.0 ka (Srivastava et al. 2012, Srivastava and Farooqui 2013) which suggests that either there was no change in the relative sea level or the area experienced land upliftment/ subsidence. Several factors like vertical land movements, sediment input (marine and fresh water sediment) and biomass production, local rate of compaction, river flow and related salinity changes which depend on climatic changes leading to rainfall variations in the catchment basin of the Cauvery River and its tributaries/rainfed streams may have played a vital role in the development/ downfall of the vegetation.

CONCLUSIONS

Palynological record of core K from Coleroon river estuary reveals coastal environment, relative sea level and vegetation changes since 4.6 ka. From 4.6 to 3.3 ka a transitional phase from fluvio-marine to estuarine condition is reflected by coarse- to fine-grained sedimentation and dominance of mangroves and their associates along with upland taxa indicating high precipitation, low seasonality and good freshwater runoff causing delta progradation/shoreline regression. A low energy sedimentary environment with low precipitation, high seasonality, low freshwater input and continuous fall in relative sea level from 3.3 to 0.8 ka is inferred from the presence of back mangrove *Avicennia*, low percentage of arboreal taxa. During the last millennium with the onset of Medieval warm period, estuarine ecosystem stabilized with the deposition of silty clay sediments and rejuvenation of true mangroves and associates. However, the total percentage of mangroves and their associates steadily declined accompanied by a decline in the diversity of plants due to local extinction of several mangrove species which is attributed to the anthropogenic activity in the region enhanced by climatic changes and restriction of fresh water input in the estuary. The observed rise in RSL since Medieval warm period is also attributed to hydrostatic and configurational changes in the wetland induced by climatic conditions and neo-tectonic activity in the area.

ACKNOWLEDGEMENTS

The authors are grateful to Prof. Sunil Bajpai, Director BSIP for providing all necessary facilities and permission to publish the manuscript (BSIP/RDCC/76/ 2014-2015). One of the authors Jyoti Srivastava thanks the Department of Science Technology (SR/S4/ES-264/2007) for financial support as JRF.

REFERENCES

Achyuthan, H., Farooqui, A., Gopal, V., Phartiyal, B. & Lone A. 2016. Late Quaternary to Holocene Southwest Monsoon Reconstruction: A review based on Lake and Wetland systems (Studies carried out during 2011-2016). Proceedings of Indian National Science Academy 82(3) July Spl Issue: 847–868.

Babu, P.V.L.P. 1991. Cauvery delta-Its Past and Present. Memoirs Geological Society of India 22: 91–101.

Banerjee, M. & Sen, P.K. 1987. Paleobiology in understanding the change of sea level and coast line in Bengal basin during Holocene period. Indian Journal of Earth Sciences 14: 307–320.

Banerjee, P.K. 1993. Imprints of late Quaternary climatic and sea level changes on East and South Indian Coasts. Geo-Marine Letters 13: 56–60.

Banerjee, P.K. 2000. Holocene and Late Pleistocene relative sea level fluctuations along the east coast of India. Marine Geology 167: 243–260.

Bard, E., Hamelin, B., Fairbanks, R.G & Zindler, A. 1990. Calibration of the 14C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals. Nature 345: 405–410.

Bera, S.K. & Farooqui, A. 2000. Mid-Holocene vegetation and climate of South Indian Montane. Journal Paleontological Society of India 45: 49–56.

Bera, S.K., Farooqui, A. & Gupta, H.P. 1997. Late Pleistocene-Holocene vegetation and environment in and around Marian Shola, Palni Hills, Tamil Nadu. Palaeobotanist 46: 191–195.

Blasco, F. 1975. Mangroves of India. French Institute of Pondicherry. Trav. Sect. Sci. Tech. 14: 1–18.

Bridgland, D.R. & Westaway, R. 2008. Preservation patterns of Late Cenozoic fluvial deposits and their implications: results from IGCP 449. Quaternary International 189(1): 5-38, DOI 10.1016/j.quaint.2007.08.036.

Brückner, H. 1987. Miliolite occurrences off Kathiawar Peninsular (Gujarat), India. Berliner Geographische Studien 25: 135–145.

Bryson, R.A. & Swain, A.M. 1981. Holocene variations of monsoon rainfall in Rajasthan. Quaternary Research 16: 135–145.

Castañeda-Moya, E., Twilley, R. & Rivera-Monroy, V. 2013. Allocation of biomass and net primary productivity of mangrove forests. Forest Ecology and Management 307: 226–241.

Chanda, S. & Hait, A.K. 2003. The floral and faunal evolution in the Bengal basin with reference to Paleoclimate during Late Quaternary. Proc. GEOSAS-IV, Geological Survey of India: 275–292.

Chauhan, O.S. & Suneethi, J. 2001. 18 ka BP records of climatic changes, Bay of Bengal: Isotopic and sedimentological evidences. Current Science 81: 1231–1234.

Church, J. & White, N. 2011. Sea-level rise from the late 19th to the early 21st century. Surveys in Geophysics 32: 585–602.

Dahdouh-Guebas, F., Jayatissa, L.P., Di Nitto, D., Bosire, J.O., Lo Seen, D. & Koedam, N. 2005. How effective were mangroves as a defence against the recent tsunami? Current Biology 15: R443–R447.

Das, S.K. 1991. Hydrogeological features of deltas and estuarine tracts of India. In: Quaternary Deltas of India (ed. Vaidyanadhan, R) Memoirs of Geological Society of India 22: 183–226.

Erdtman, G. 1943. An Introduction to pollen analysis. Chronica Botanica Co., Waltham Mass, US.

Farooqui A. 2010. Salt water intrusion, metal accumulation and mangroves along the Pednapatnam, Machlipatnam coastline, Andhra Pradesh, India. Journal of Applied Geochemistry 12: 126–138.

Farooqui, A. 2000. Leaf cuticular and epidermal traits and elemental status in Rhizophora species in a coastal wetland ecosystem. Phytomorphology 50 (3&4): 317–325.

Farooqui, A. 2008. The evolution of Pichavaram mangrove and its environment since Middle Holocene. Proceedings Volume of Workshop on IGCP 464, Continental shelves during the Last Glacial cycle: Knowledge and Applications. Special Publication 96: 40–54.

Farooqui, A., Pattan, J.N., Parthiban, G., Srivastava, J. & Ranjana. 2014. Palynological record of tropical rain forest vegetation and sea level fluctuations since 140 ka from sediment core, south-eastern Arabian Sea. Palaeogeography, Palaeoclimatology, Palaeoecology 411: 95–109.

Farooqui, A., Ranjana. & Nautiyal, C.M. 2016. Deltaic land subsidence and sea level fluctuations along the east coast of India since 8 ka: A palynological study. Holocene 26(9): 1426–1437.

Farooqui, A., Srivastava, J. & Hussain, S.M. 2009. Comparative Leaf Epidermal Morphology and Foliar Na:K Accumulation in *Suaeda* species: A Case Study from Coastal Ecosystem, East Coast, India. International Journal of Plant Morphologists (Phytomorphology) 59 (3&4): 102–111.

Farooqui, A. & Vaz, G.G. 2000. Holocene sea- level and climate fluctuations: Pulicat lagoon- A case study. Current Science 79(10): 1484–1488.

Friess D.A., Krauss, K.W., Horstman, E.M., Balke, T., Bouma, T.J., Galli, D. & Webb, E.L. 2012. Are all intertidal wetlands naturally created equal? Bottlenecks, thresholds and knowledge gaps to mangrove and saltmarsh ecosystems. Biological Reviews 87: 346–366.

Gilman, E., Ellison, J., Duke, N. & Field, C. 2008. Threats to mangroves from climate change and adaptation options: a review. Aquatic Botany 89: 237–250.

Gupta, H.P. 1981. Palaeoenvironments during Holocene time in Bengal Basin, India as reflected by palynostratigraphy. Palaeobotanist 27(2): 138–160.

Hait, A.K. & Behling, H. 2009. Holocene mangrove and coastal environmental changes in the western Ganga-Brahmaputra Delta, India. Vegetation History and Archaeobotany 18: 159–169.

He, B., Lai, T., Fan, H., Wang, W. & Zheng, H. 2007. Comparison of flooding-tolerance in four mangrove species in a diurnal tidal zone in the Beibu Gulf. Estuarine, Coastal and Shelf Science 74: 254–262.

IPCC. 2013. Climate change 2013: the physical science basis. Cambridge University Press, New York, New York, USA.

Irudhayanathan, A., Thirunavukkarasu, R. & Senapathi, V. 2011. Grain size characteristics of the Coleroon estuary sediments, Tamilnadu, east coast of India. Carpathian Journal of Earth and Environmental Sciences 6(2): 151–157.

Kaliraj, S., Chandrasekar, N. & Magesh, N.S. 2013. Evaluation of coastal erosion and accretion processes along the Southwest coast of Kanyakumari, Tamil Nadu using geospatial techniques. Arabian Journal of Geosciences DOI 10.1007/s12517-013-1216-7.

Kathiresan, K. & Rajendran, N. 2005. Coastal mangrove forests mitigated tsunami. Estuarine, Coastal and Shelf Science 65: 601–606.

Kemp, A.C., Horton, B.P. & Donnelly, J.P. et al. 2011. Climate related sea-level variations over the past two millennia. Proceedings of the National Academy of Sciences 108(27): 11,017–11,022, doi:10.1073/pnas.1015619108.

Kesavan, P.C. & Swaminathan, M.S. 2006. Managing extreme natural disasters in coastal areas, Phil. Trans. R. Soc. A 364: 2191-2216.

Krauss, K., McKee, K., Lovelock, C., Cahoon, D., Saintilan, N., Reef, R. & Chen, L. 2014. How mangrove forests adjust to rising sea level. New Phytologist 202: 19–34.

Kumaran, K.P.N., Nair, K.M., Shindikar, Limaye, R.B. & Padmalal, D. 2005. Stratigraphical and palynological appraisal of the late Quaternary mangrove deposits of the west coast of India. Quaternary Research 64: 418–431.

Kunz, A., Frechen, M., Ramesh, R. & Urban, B. 2010. Luminescence dating of Late Holocene dunes showing remnants of early settlement in Cuddalore and evidence of monsoon activity in south east India. Quaternary International 222: 194-208, DOI 10.1016/j.quaint.2009.10.042.

Lambeck, K., Anzidei, M., Antonioli, F., Benini, A. & Esposito, A. 2004. Sea level in Roman time in the Central Mediterranean and implications for recent change. Earth Planet. Sci. Lett. 224: 563–575, doi:10.1016/j.epsl.2004.05.031.

Medina, E., Cuevas, E., Popp, M., Lugo, A.E., 1990. Soil salinity, sun exposure, and growth of *Acrostichum aureum*, the mangrove fern. Botanical Gazette Chicago 151(1): 41–49.

Meijrink, A.M.J. 1971. Reconnaissance of Quaternary geology of Cauvery delta. Journal of Geological Society of India 2: 113–124.

Munsel Color Charts 2000. Munsell Soil Color Charts Year 2000 Revised Edition. Greta G. Macbeth. New York.

Nageswara Rao, K., Subraelu, P., Nagakumar, Ch. V., Demudu, B., Malini, Hema. B., Rajawat, A.S. & Ajai. 2013. Geomorphological implications of the basement structure in the Krishna-Godavari deltas, India. Zeitchrift für Geomorphologie 57(1): 25–44.

Nerem, R., Chamber, D., Choe, C. & Mitchum, G. 2010. Estimating mean sea level change from the TOPEX and Jason Altimeter Missions. Marine Geodesy 33: 435–446.

NOAA. 2015. National Oceanic and Atmospheric Administration, National Ocean Service, Center for Operational Oceanographic Products and Services, Tides and Currents. http://tidesandcurrents.noaa.gov/

Ogden, C.G. & Hadley, R.H. 1980. An Atlas of freshwater Testate Amoeba. British Museum of Natural History and Oxford University Press, London and Oxford, UK.

Patterson, R.T. & Kumar, A. 2002. A review of current testate rhizopod (thecamoebian) research in Canada. Palaeogeography, Palaeoclimatology, Palaeoecology 180: 225–251.

Rajamanickam, G.V. (Ed.) 1990. Sea level variations and its Impact on Coastal Environment. Tamil University Publication, Thanjavur 131: 452 pp.

Rajamanickam, G.V., Tolley, M.J. (Eds.) 2001. Quaternary Sea level Variation, Shoreline Displacement and Coastal Environments. New Academic Law Serial Publication, New Delhi 259.

Ramanathan, A.L., Subramanian, V. & Das, B.K. 1996. Sediment and Heavy metal accumulation in the Cauvery Basin. Environmental Geology 27 (3): 155–163.

Ramasamy, S.M., Saravanavel, J. & Selvakumar, R. 2006. Late Holocene geomorphic Evolution of Cauvery delta, Tamil Nadu, India. Journal of Geological Society of India 67(5): 649–657.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilerson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Bronk Ramsey, C., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J. & Weyhenmeyer, C.E. 2004. IntCal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. Radiocarbon 46(3): 1029–1058.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatt•, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southen, J.R., Staff, R.A., Turney, C.S.M. & van der Plicht, J. 2013. IntCal13 and Marine 13 radiocarbon age calibration curves 0–50,000 years Cal BP. Radiocarbon 55(4): 1869–1887.

Sambasiva Rao, M. 1982. Morphology and evolution of modern Cauvery delta. Transactions on Indian Institute of Geographers 4: 67–78.

Sen, P.K. & Bannerjee, M. 1990. Playno-plankton stratigraphy and environment changes during the Holocene in the Bengal basin, India. Review of Palaeobotany and Palynology 65: 25–35.

Seralathan, P. 1979. Studies on texture, mineralogy and geochemistry of the modern deltaic sediments of the Cauvery river India. Unpublished thesis, Andhra University.

Sharma, A. & Rajamani, V. 2001. Weathering of charnockites and sediment production in the catchment area of the Cauvery River, southern India. Sedimentary Geology 143: 169-184. DOI 10.1016/S0037-0738(01)00102-6.

Singh, P. & Rajamani, V. 2001. REE Geochemistry of recent clastic sediments from the Kaveri floodplains, southern India: Implications to source area weathering and sedimentary processes. Geochimca et Cosmochimica Acta 65: 3093–3108.

Sivan, D., Sisma-Ventura, G., Greenbaum, N., Bialik, O.M., Williams, F.H., Tamisiea, M.E., Rohling, E.J., Frumkin, A., Avnaim-Katav, S., Shtienberg, G. & Stein, M. 2016. Eastern Mediterranean sea levels through the last interglacial from a coastal-marine sequence in northern Israel. Quat. Sci. Rev. 145: 204–225.

Somayajulu, B.L.K. 2002. Present and past (Late Quaternary) sea level e available new information from Indian coastal regions. Memoir Geological Society of India 49: 1–16.

Somayajulu, B.L.K., Broecker, W.S. & Goddard, J. 1985. Dating Indian corals by U–decay–series methods. Quaternary Research 24: 235–239.

Southon, J., Kashgarian, M., Fontugne, M., Metivier, B. & Yim, W.W.S. 2002. Marine reservoir corrections for the Indian Ocean and Southeast Asia. Radiocarbon 44: 167–180.

Srivastava, J. & Farooqui, A. 2013. Late Holocene mangrove dynamics and coastal environmental changes in the Northeastern Cauvery River Delta, India. Quaternary International 298: 45–56.

Srivastava, J., Farooqui, A. & Hussain, S.M., 2012. Vegetation history and salinity gradient during the last 3700 years in Pichavaram estuary, India. Journal of Earth System Sciences 121 (5): 1229–1237.

Srivastava, J., Farooqui, A. & Hussain, S.M. 2013. Climate-induced Late-Holocene ecological changes in Pichavaram estuary, India. Marine Ecology 34: 474–483.

Stuiver, M., Reimer, P.J. & Braziunas, T.F. 1998. High precision radiocarbon age calibration for terrestrial and marine samples. Radiocarbon 40: 1127–1151.

Swaminathan, M.S. 1999. A century of Hope: Towards an era of harmony with nature and freedom from hunger. Chennai, India: East West Books (Madras) Pvt. Ltd.

Terrados, J., Thampanya, U., Srichai, N., Kheowvongsri, P., Geertz-Hansen, O., Boromthanarath, S., Panapitukkul, N. & Duarte, C.M.1997. The effect of increased sediment accretion on the survival and growth of *Rhizophora apiculata* seedlings. Estuarine, Coastal and Shelf Science 45: 697–701.

Thanikaimoni, G. 1966. Contribution a l'etude palynologique des Palmiers. Inst. Fr. Pondichery, Tray. Sect. Sci. Tech. (2): 1–92.

Thanikaimoni, G., Caratini, C. & Blasco, F. 1973. Relation between the pollen spectra and the vegetation of a south Indian mangrove. Pollen Spores 15: 281–292.

Tissot, C., Chikhi, H. & Nayar, T.S. 1994. Pollen of Wet Evergreen Forests of the Western Ghats, India. Institute français, Pondicherry, India.

Tomlinson, P.B. 1986. The Botany of mangroves. Cambridge University Press, Cambridge, U.K. 413.

USDA, 1992. Soil Conservation Service. Soil Survey Laboratory Methods Manual. United States Dept. of Agriculture, Soil Surv. Invest. Report. No. 42. Washington DC.

Vaidyanathan, R. & Ramakrishnan, M. 2008. Geology of India. Geological Society of India, Bangalore 2: 557–994.

Valdiya, K.S. 2001. Tectonic resurgence of the Mysore plateau and surrounding regions in cratonic southern India. Current Science 81: 1068–1089.

Van Campo, E., Cour, P. & Hang, S. 1996. Holocene environmental changes in Bangong Co Basin (Western Tibet). Part 2. The pollen record. Palaeogeography, Palaeoclimatology, Palaeoecology 120: 49–63.

Van Campo, E. & Gasse, F. 1993. Pollen- and diatom-inferred climatic and hydrological change in Sumxi Co Basin (Western Tibet) since 13,000 yr B.P. Quaternary Research 39: 300–313.

Vaz, G.G. 2000. Age of relict coral reef off Karaikal, Bay of Bengal: evidence of Last Glacial Maxima. Current Science 79: 228-230.

Venkatesan, K.R. 1966. The mangroves of Madras state. Indian Forester 92: 27–34.

Verma, K.K. & Mathur, U.B. 1979. Quaternary sea-level changes along west coast of India, Geological Survey of India Miscellaneous Publication 45: 263–272.

Walter, H. 1973. Vegetation of the Earth. Springer, NewYork. 237 pp.

Woodroffe, C.D., Cowell, P.J., Callaghan, D.P., Ranasinghe, R., Jongejan R., Wainwright, D.J., Barry, S.J., Rogers, K. & Dougherty, A.J. 2012. Approaches to risk assessment on Australian coasts: A model framework for assessing risk and adaptation to climate change on Australian coasts. NCCAR.

Woodroffe, C.D. & Grindrod, J. 1991. Mangrove biogeography: the role of Quaternary environmental and sea-level change. Journal of Biogeography 18: 479–492.