Sea level oscillations, climate change and landform evolution in the western coastal lowlands of Trivandrum block in Peninsular India

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The coastal areas of Kerala falling within the Trivandrum block, in the southern side of the Achankovil Shear Zone (ASZ) of the Peninsular India, host a series of coast perpendicular estuarine basins. These estuarine basins entrenched over the Neogene sediments enfold a nearly complete record of Holocene transgressive-regressive events. Borehole cores retrieved from the fluvial end of these basins show a coarsening upward sequence with sand dominant sediments at the top and clay dominant sediments at the bottom. The high terrestrial inputs resulted from torrential rains in river catchments coupled with the sea level rise during Early – Middle Holocene was instrumental in the development of bay head deltas in the fluvial end and flood tide deltas/islands in the marine end of these estuaries. The faster sea-ward growth than lateral spread of these deltas was responsible for the cut-off of some of the prominent arms of the pre-Holocene estuaries into separate freshwater bodies. The Sasthamkotta kayal, Chelupola and Chittumala chira in the Ashtamudi basin, Kotta kayaal and Pola chira in the Paravur basin and Poovankal wetland in the Nadayara basin were evolved by this way. The Pallikkal river debouching into the Kayamkulam lagoon also responded significantly to the Early Holocene climate change and sea level oscillations. The river once debouched into the Kayamkulam estuary at its middle presumably through the Krishnapuram Ar, was later took a southerly course linking the Late Pleistocene (confirmed from C\textsuperscript{14} age of sediments) wetland bodies like Chunakkara Punja, Komallur Punja, Vatta kayaal and Valummel Punja, and finally debouched into the southern arm of the estuary near Vatta kayaal. Heavy rainfall and beach barrier build up under the rising spells of the sea in the Early – Middle Holocene was responsible for the wetland capturing and diversion of river flow. The Karunagapalli borehole core gave an age of 7270±250 yrs BP for an organic rich sediment sample at a depth of 6.9 m. The Holocene sequence here is 9m thick and rests uncomfortably over the Neogene sediments. This clearly indicates that the river received the present channel configuration only in the second half of Early Holocene.

[Keywords: Southwest coast of India, Holocene sea level changes, Sediment texture, Coastal evolution]

Introduction

The present coastal geomorphology of the world has been evolved largely in the background of the post-glacial transgression and subsequent regression of the sea in Holocene. This process has left out significant imprints in the sedimentary archives which can throw light on the evolution of the coast\textsuperscript{1-5}. The sea level and climate changes have strongly influenced the coastal marine process and much of the coastal land and associated land forms around the world have been carved out during the Late Quaternary period. The west coast of India which are characterised by cliffs and bays has been subjected to several episodes of sea level oscillations and climate change during the Late Quaternary period. The largest coast-perpendicular estuary along the southwest coast, the Ashtamudi estuary (locally known as Ashtamudi kayaal), is situated in the uplifted part of the Trivandrum block\textsuperscript{6}. In addition to this, the Sasthamkotta Lake - the largest natural freshwater lake of Kerala and several other wetland bodies like Chelupola, Cherayattu kayaal, Chittumala chira, Paravur estuary, Pola chira, Kotta kayaal, Nadayara estuary etc., are also located in this block. Among these wetland bodies, the Ashtamudi estuary and the Sasthamkotta fresh water lake are recently declared as Ramsar sites of international importance. In view of the immense ecological and environmental importance, a study has been undertaken to unfold the Late Quaternary evolutionary events as well as coastal processes that are responsible for the development of these wetland basins in the south western coast of India.

Materials and Methods

Regional settings

The study area forms a part of the coastal land of Kerala state in the SW India (Fig. 1).
Geomorphologically, the area comprises hillocks, valleys and gently sloping plains. Hillocks adjacent to the lake basins show moderate to steep slopes. The Quaternary sediments occur close to the mouths of the Kallada, Ithikkara and Pallikkal rivers. Stratigraphically, the area is made up of Pre-cambrian crystalline basement, Neogene sedimentary formations and Quaternary deposits. The Pre-cambrian crystalline basement, represented by garnet- biotite gneisses, khondalites and charnockites, is dominant in the eastern and southeastern parts of the study area. The Neogene sediments are represented by Quilon and Warkalli Formations of Lower Miocene age[^7]. The Warkalli Formation is composed of sandstones and clays, exposed on the laterite hillocks surrounding the wetlands of Sasthamkotta, Chelupola and Paravur lakes. The Quilon Formation, occurring stratigraphically below the Warkalli Formation, is represented by fossiliferous limestones and sandy carbonateous clays. The Pre-cambrian crystalline basement and the Neogene sedimentary sequences are blanketed by laterites. The Quaternary deposits are represented by alluvial clays, sandy clays, peat and sand.

Systematic fieldwork was carried out in study area to collect primary and secondary data on various landform features. A total of 22 surface sediments (16 river and 6 estuarine samples) and 11 borehole cores (4 from Ashtamudi basin, 3 from Paravur basin and 4 from Nadayara basin) were collected from the study area. Sampling locations are shown in Fig. 1. Sub-samples from selected depths were subjected to textural analysis following standard procedures[^9,10]. Organic matter rich sub-samples from selected depths were subjected to palynological examinations following standard procedures[^11-13]. A few selected sub-samples were subjected to stable isotopic estimations of carbon ($\delta^{13}$C) and nitrogen ($\delta^{15}$N) at Centre for Tropical Marine Ecology (ZMT), Bremen (Germany) following standard procedures[^14,15]. Radiocarbon ($^{14}$C) dates of a few samples of sub fossil wood and organic matter rich sediments at specific levels were determined at Birbal Sahni Institute of Palaeobotany, Lucknow, India.

### Results

#### Textural attributes

**Surface sediments**

The upper reaches of the river are characterised generally by high amount of pebbles which transcend to lower values towards the river mouth areas. Tributary that joins the mainstream at 35 km upstream

<table>
<thead>
<tr>
<th>Pebble (%)</th>
<th>Granule (%)</th>
<th>Sand Very coarse (%)</th>
<th>Coarse (%)</th>
<th>Medium (%)</th>
<th>Fine (%)</th>
<th>Very Fine (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tributaries</td>
<td>25.4 (2.6 - 49.5)</td>
<td>8.0 (3.0 - 15.9)</td>
<td>7.4 (3.3 - 11.9)</td>
<td>12.58 (7.59 - 27.8)</td>
<td>21.3 (12.3 - 36.7)</td>
<td>17.2 (5.2 - 41.6)</td>
</tr>
<tr>
<td>Main stream</td>
<td>29.5 (0.9 - 64.4)</td>
<td>9.3 (0.7 - 23.0)</td>
<td>6.7 (1.2 - 57.9)</td>
<td>17.45 (2.19 - 35.27)</td>
<td>26.8 (1.3 - 47.5)</td>
<td>18.5 (2.3 - 39.1)</td>
</tr>
<tr>
<td>Estuary</td>
<td>-</td>
<td>-</td>
<td>0.9 (0.2 - 1.5)</td>
<td>4.6 (0.8 - 7.1)</td>
<td>28.56 (7.2 - 40.0)</td>
<td>34.0 (13.6 - 47.7)</td>
</tr>
</tbody>
</table>

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[^9]: Reference 9
[^10]: Reference 10
[^11]: Reference 11
[^12]: Reference 12
[^13]: Reference 13
[^14]: Reference 14
[^15]: Reference 15
of the estuarine mouth accounts for higher granule contents (15.9%); (Table 1). Higher concentration of coarse sand is reported from the midstream portion of the river. Medium and fine sand show an increase in contents towards river mouth. However, the content of very fine sand is negligible in mainstream and tributaries. Unlike the river, estuarine hydrodynamics are characterised by flow pattern controlled by semidiurnal ebb and flood tides. The coarser entities are totally missing or present only in subtle quantities in the estuarine environment. Higher proportions of very fine, fine and medium sands are seen in the immediate vicinity of river and estuarine mouth (EM). So the samples taken from the centre of Kayakulam lake and estuarine mouth accounts for the maximum content of very fine, fine and medium sands.

Near the river influenced regions of the Kayamkulam estuary (15 to 10 km with respect to the estuarine mouth), the phi mean exhibits a sharp decline due to the influx of medium and fine sand. The phi mean attains peak value (3.18) in the station around 6 km from the estuarine mouth. The standard deviation of the river sediments varies between 0.7ϕ and 2.13ϕ (moderately to poorly sorted). Skewness varies widely in river compared to estuarine environment. In riverine environment, about 50% of the sediment samples exhibit symmetrical to coarse skewed, 20% each are very coarse skewed and very fine skewed and the remaining samples fall within the fine skewed category. About 90% of the samples collected from the estuary are symmetrically skewed and the remaining coarse skewed. The river sediments very platykurtic to very leptokurtic (0.56 to 1.90) while the estuarine sediments are platykurtic to leptokurtic (0.87 to 1.16).

Core sediments

Four shallow borehole cores were collected from the floodplains of the Ayroor river near its confluence with the Nadayar estuary. The core Nadayar core 1 (C1) is 8 m long and composed mainly of mud dominated sediments with intercalation of thick sand layers. The second core Nadayar core 2 (C2) is 10 m long and is composed of sand and clay dominated sequence. The top layer is characterised by mud/clay dominated sediments followed by a sand dominated layer which rests over a clay dominated layer. The borehole core Nadayar core 3 (C3), is 9.5 m long and is composed of sand, clay and mud dominated layers. The top layer is dominated by mud and clay followed by thick sand layer. The bottom layer is dominated by clayey mud-silty clay association. The Nadayara core 4 (C4) core is 10 m long and is retrieved from the bank of the Poovankal wetland. The core is composed essentially of greyish black, silty clay with occasional presence of shell dusts. The Pozhikkara core (C5) collected from the Paravur basin is 30 m long and is composed mainly of three major lithounits: 1) top sand dominated unit, 2) middle greyish green silt and clay dominated unit and 3) bottom sand dominated unit. The Nedungolam core (C6) is 32 m long and is composed mainly of clay dominated sediments, bounded on the top by coarse to fine grained sand and the bottom by yellowish brown coarse grained sand. It is followed downward by thick organic matter rich clay dominated sediments. The entire sequence rests over a gravelly sand layer. The Adichanalloor core (C7) is 10m long; out of which the upper 7.5 m layer is made up of Late Quaternary sediments and the remaining is of laterite. The Late Quaternary deposit is generally mud dominated which is intervened by sand dominant sediments.

The Puthenthuruth core (C8) is 33 m long and is composed of two major litho units. The top layer is composed of medium to fine sand with occasional presence of shell layers. It is followed by a greyish green, silty clay layer with broken and unbroken shells and interlayer's of mud and silt dominated sediments. The entire sequence is coarsening upward and indicates rapid filling of sediments from the nearshore marine environments during high tide phase. The Munrothuruthu core (C9) is composed of a silt and clay dominated sequence inter layered by sand layers. The sand lies over thick mud-clay interlayered sequence with low content of sand fraction and fairly high contents of silt and clay fractions. The West Kallada borehole core is about 27m long, which is retrieved from a wetland close to the confluence of Kallada river with Ashtamudi estuary. The West Kallada core (C10) comprises three major lithounits, 1) top, light grey to greyish green, sand, 2) greyish black, organic matter rich, clayey silt, with small amount of sand fraction which is interbedded by thick silty mud with almost same megascopic properties, 3) greyish white, clayey sand derived from lateritised Tertiary hillocks. Pangod core (C11) is located in the incure of an incised meander loop of the Kallada River. The borehole core shows three major lithological units: the top yellowish brown, muddy sediments; middle greyish black, organic matter rich sediments with highly varied
textural associations; and bottom light grey, medium to fine grained sands. The borehole is terminated at 8.25 m below the ground level.

The sands in the borehole core sediments in the upper estuarine regions of Ashtamudi (Pangod, Kadapuzha, West Kallada and Munrothuruthu borehole cores) and Paravur (Adichanalloor and Nedungolam borehole cores) estuaries are angular to sub-angular. Whereas, the borehole cores in the mouth of Ashtamudi (Puthenthuruthu) and Paravur (Pozhikkara) estuaries are sub-rounded to rounded. The 10 m thick top sand layer of the Pozhikkara core shows the dominance of medium to fine sands whose mean size varies from of 1.657φ to 5.586φ. Sands are poorly to very poorly sorted (1.258φ to 3.046φ), fine to very fine skewed (0.207 to 0.690) and leptokurtic (1.125 to 3.928). Whereas in the Puthenthuruthu core, the top 11.5 m thick sand deposit, comprises mainly of very fine sand with a mean value swinging between 2φ and 3.5φ. Sand is poorly sorted (1.229φ to 1.922φ), symmetrical to very fine skewed (-0.182 to 0.372) and leptokurtic (1.243 to 4.567) indicating deposition of sediments under a comparatively low energy regime. The borehole cores collected from the alluvial deposit at the river confluence zone shows a coarsening upward cycle with dominance of sand towards the top of the core. Sand is composed generally of coarse, medium, and fine grades with the mode confined mainly to medium sand. The grains are angular to sub angular, quartz felspathic and poorly sorted.

**Palynology of the core sediments**

At Pozhikkara, the bottom sediments (i.e., subsampled from the level 23.8-23.9 m bgl) were deposited under fresh water environment as indicated by the abundance of fungal spores and absence of marine elements. All the other samples gave indications of marine influence. The samples collected from 20-23 m levels are marked by slightly complex palynological/NPP suite characterized by foraminiferal linings, fungal and pteridophytic spores, and cyanobacteria. At 13-20 m bgl, diatoms and foram tests are seen, apart from a few pteridophytic spores. The diatoms and foram tests indicate the prevalence of shallow marine/intertidal environment during the deposition of sediments at this level. Shallow marine facies continue up to 7 m bgl. The sediment samples contain foram tests, a few foraminiferal linings and dinoflagellates. Tests of amoeba are recorded at 12.4-12.5 m level, indicating exposure of the sedimentary environment to dryness and pollution. The 3-7 m level though marked by poor organic matter recovery, a few foram tests and ostracods are noticed among the palynological preparations. The palynological contents of the Munrothuruthu borehole reveal highly fluctuating environmental conditions during the deposition of sediments. A few pollens of *Cullenia* are identified at 1.4-4 m level of the Munrothuruthu borehole site. The sediments at 4-6 m level are marked by the presence of pteridophytic spores and *Botryococcus* algae. The level between 6-10 m bgl shows high organic recovery compared to the rest of the borehole core sediments. However, the sample does not yield signals of terrestrial influence; rather tidal influence as indicated by the presence of foraminiferal linings. The sediments at 10-14 m level record poor recovery of organic matter. Interestingly, sediments at this level neither show signals of freshwater nor tidal influence. The sediments at 14.4-14.5 m bgl show abundance of amorphous organic matter, mainly micro-organic spherules. No evidence of fresh or marine water influence is observed at this level. Perhaps the site was subjected to a dry phase of environmental setting which is also evidenced from the presence of calcareous nodules. A sample at 11.5 m is C14 dated 4350±90 yrs BP which indicates the fact that the sediments are of Late Holocene age. The West Kallada borehole core yields high organic recovery in the middle clayey silt (cZ) layer. Pollen of the evergreen plant, *Cullenia exarillata*, as well as a few dinoflagellates (*Tuberculodinium vancampoae*) at this layer is indicative of heavy rainfall and marine influence during the depositional phase. It is supported further by the presence of foraminiferal linings and mangrove elements in the sample preparation. The profuse occurrence of *Rivularia* (cyanobacteria) indicates freshwater influx and a rise in the nutrient level in the depositional environment. The silty mud (zM) that lies above the clayey silt (cZ) exhibits dominance of fungal spores in addition to dinoflagellates (*Tuberculodinium vancampoae*), foraminiferal linings and pteridophytic spores, *Rivularia* and *Lirasporites*. The top clayey silt (cZ) layer, resting over the silty mud (zM) layer, registers the abundance of fungal and pteridophytic spores and pollen of *Cullenia exarillata*. The marine influence at this layer is indicated by the presence of dinoflagellates and foraminiferal linings. It is interesting that, marine influence noticed in this layer is comparatively weaker than the bottom layers.
Stable isotope studies of core sediments

The stable isotope studies of carbon ($\delta^{13}$C$_{org}$) and nitrogen ($\delta^{15}$N) are used widely for tracking the sources as well as post depositional changes of sediments/sedimentary rocks. In the present study, a total of 10 samples from Pangod core were selected for $\delta^{13}$C$_{org}$ and $\delta^{15}$N estimations. The isotopes values of carbon and nitrogen (i.e., $\delta^{13}$C$_{org}$ and $\delta^{15}$N) exhibit an increasing trend towards the top of the core. Although, the yellowish brown layer accounts for comparatively low content of organic carbon (0.12%) than that of the underlying carbonaceous clay (6.05%), the $\delta^{13}$C$_{org}$ show an opposite trend with higher values towards the top. This indicates clearly a gradual change in the depositional regime from terrestrial ($\delta^{13}$C-28.17%) to marine entity (-19.56%). It is now well understood that sediments of marine origin generally contain higher $\delta^{13}$C$_{org}$ values as a substantial proportion of C$_{org}$ has been evolved from marine phytoplankton with higher $\delta^{13}$C$_{org}$ values. The C$^{14}$ age of the upper most part of the organic carbon rich layer, just below the yellowish brown silt and clay layer at 3 m bgl is 5260±120 yrs BP. The low $\delta^{13}$C$_{org}$ values in the range of-28.17% to -26.88% shows that the organic input in the carbonaceous clay/peaty layer is from C$_{3}$ plants that flourished in the hinterlands during Early Holocene. The $\delta^{15}$N values vary from 3.92% to 8.85% with the highest values recorded for the top yellowish brown layer.

Discussion and conclusions

The evolution of coastal lands was influenced by many local and regional factors like climate and sea level changes and tectonics. Proxy evidences from the borehole cores (Palynological contents and stable isotopes) reveal that the region was subjected to several spells of sea level rises and falls in the past 10 kilo years. Lithology of the borehole core at Pangod shows a well-developed floodplain sequence formed during Early Holocene period. The backwater swamp that developed in the incure of Kallada River at Pangod was submerged under floodwaters and subsequently covered by overbank sediments during the high flood period of ~6000 yrs BP. The abundance of fossil/sub-fossil logs and the accumulation of organic carbon-rich sediments in the wetlands are attributed to the Holocene Climatic Optimum. The dated woods and sediments range in age from 5.3 to 7.6 kyrs BP (Fig. 2). Early Holocene witnessed heavy rainfall during 9.5-10.0 kyrs BP, but the excessive rainfall event started ~8.5 kyrs BP and continued till ~5.5 kyrs BP. This optimum climatic variation not only broadened the valleys developed over the Neogene and Archaean crystallines but also brought in huge volumes of sediments into the basins that are entrenched over the uplifted southern block (Trivandrum block) located south of the Achankovil Shear Zone (ASZ). The rise in sea level during Middle Holocene accelerated deposition of river-borne materials/alluvium in its own channels which began the build up of deltaic sediments in river mouth zones. The process is clearly evident in the detailed borehole coring investigations in the upper estuarine zones of the Ashtamudi basin. The development of the bay head delta in the upstream end of the lagoon was due to heavy influx of terrigenous materials under the rising sea levels during Early Holocene. This was responsible for the deposition of sediments in the upper end that later evolved into the Kallada Bay Head Delta (KBHD). The build up of KBHD was responsible for the quick burial of riparian vegetation in the basin boundaries. The bay head delta prograded further seaward during the middle and late Holocene periods filling up almost half of the Ashtamudi lagoon separating some of its prominent upper arms into discrete wetland bodies like Sasthamkotta lake, Chelupola and Chittumala chira. A similar kind of progradation of alluvial sediments towards the estuarine zones was responsible for the cut off of some of the arms of Paravur and Nadayara estuaries as well into separate wetland bodies like Kotta kayal and Poovankal wetland, respectively.

Fig. 2. Alluvial sediments deposited in the head of the Ashtamudi estuary, resulted in the cutting off of Sasthamkotta lake (SKL), Cherayathu lake (CL), Chelupola lake (CPL) and Chittumalachira(CC). The depth of the borehole cores is given in meters (Source Padmalal et al., 17).
The Pallikkal river debouching into the Kayamkulam lagoon also responded significantly to the Early Holocene climate change and sea level oscillations. The marked changes in the flow regime of the downstream and upstream reaches impart considerable effects on the grain size distribution pattern. The variation is in consonance with the flow pattern controlled by the gradient of the terrain. Thus, it can be seen that coarse sand marks the transitional phase in spectral changes among the sub-population of size fractions. Higher portion of fine and medium sand in the immediate vicinity of river and estuarine mouth are, perhaps, due to the scouring action of water jet infiltration which winnows very fine sand and results in deposition of fine, medium and very fine sand in the EM and central part of the estuarine basin. The heavy mineral assemblage of the riverine and the estuarine sand consist of opaque (mainly illmenite), sillimanite, garnet, zircon, rutile, monazite, inosilicates, biotite and some altered heavies and the first six minerals constitute the bulk of the heavy mineral crop, while the others are present only in marginal amounts.

Garnet is absent in the downstream reaches especially near the river mouth region whereas, opaque and sillimanite show an opposite trend indicating difference in the provenance of sediments (Fig. 3). The river sediments are generally monocyclic and derived mainly from the khondalite source rocks. The heavy mineral suite in the lower reaches of the river might have deposited in the rising spells of the sea during Holocene. The Pallikkal river appears to have debouched previously into the Kayamkulam estuary at its (middle near The Kayamkulam) town through the Krishnapuram Ar. The river later changed its course southerly linking the Late Pleistocene wetlands like Chunakkara Punja, Komallur Punja, Vatta kayal, Valummel Punja, presumably because of heavy rainfall and like sea level changes of the Early Middle Holocene. The radiocarbon age of 7270±250 yrs BP at 6.9m of Karunagapalli borehole core drilled on the banks of the Pallikkal River reiterates this view.

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