

Mechanism and geochemical implications of the Late Holocene organic carbon burial event: an example from the southwest coast of India

B. Ajaykumar · Mahesh Mohan · M. S. Shylesh Chandran ·
K. K. Jayasooryan · K. S. Unni · A. P. Thomas

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Abstract Carbonaceous clay found in the palaeo-deposits of Meenachil River basin was analysed for the total organic carbon, nitrogen and textural characters. Radiocarbon dating of this clay formation and the embedded carbonized wood fragments was also done. The values obtained for the organic carbon, nitrogen and C/N ratio of the carbonaceous clay exhibited a very remarkable range, suggestive of different environmental conditions of formation. It is evident from the present study that since the lignin and cellulose are the dominant components of terrestrial higher plants, allochthonous and submerged organic matter have high C/N ratio. The radio carbon dating of the sediment and wood samples suggested that the palaeo-deposits of Meenachil River basin were formed as result of many transgressive–regressive episodes, which had started even before the formation of Vembanad Lake. The formation of carbonaceous clay, as found sandwiched in palaeo-deposits, was due to the global eustatic sea-level fluctuations and tectonism.

Keywords Palaeo-deposits · Carbonaceous clay · Organic carbon · Nitrogen · Radiocarbon dating

Introduction

Organic matter embraces the whole non-mineral fraction and consists essentially of a series of products, which range from decayed plant and animal tissues to fairly amorphous brown to black material bearing no trace of the anatomical structure of the material. The organic matter present in the sedimentary deposits records several types of information depending on the abundance, provenance and preservation of the constituent components (Sifeddine and Wirmann 2004). The roles of organic matter in relation to physical conditions are widely recognized. The organic matter is the source of plant nutrients, which are released in assimilable forms during microbial degradation. Meanwhile, nitrogen (N) is found mostly attached to organic material. The N contents are needed for the evaluation of carbon–nitrogen (C/N) ratio, which can give an indication of the processes of transformation of organic nitrogen to available nitrogen. It has been proved that the analysis of sediment organic carbon content and pollens as well as the ^{14}C dating can excellently be incorporated in depicting the palaeo-ecological reconstruction of long-term landscape and vegetation changes (Eisner et al. 2005; Chakraborty et al. 2006).

The chronological deployment of the stratigraphic sequences has attained prime attention in portraying the Late Holocene environmental changes all over the world, especially in the coastal areas of India. The evolution of the Kerala coast and the formation and orientation of the lake system along it were discussed under the geochronology of the sedimentation. According to Menon (1967),

B. Ajaykumar (✉) · M. Mohan · M. S. Shylesh Chandran ·
K. K. Jayasooryan · K. S. Unni · A. P. Thomas
School of Environmental Sciences, Mahatma Gandhi University,
Priyadarshini Hills P.O., Kottayam 686 560, Kerala, India
e-mail: jemnair@gmail.com

M. Mohan
e-mail: mahises@gmail.com

M. S. Shylesh Chandran
e-mail: msshylesh@gmail.com

K. K. Jayasooryan
e-mail: kkjayasurya@gmail.com

K. S. Unni
e-mail: sesmgu@yahoo.co.in

A. P. Thomas
e-mail: sesmgu@gmail.com

Kerala was under the influence of the local marine environment to a minor extent in the geological past. The Quaternary sediments in Kerala, which are named as Vembanad Formation, have overlain the Tertiary sediments of Vaikom, Quilon and Warkalli Formations, and the laterite is found to separate the Tertiary Formations from the Quaternary sediments (Jayalakshmi et al. 2005). The contrasting feature of the south Kerala estuaries and freshwater lakes is that their general alignment is coast perpendicular/oblique within the Neogene sediments, whereas the general alignment within the Quaternary province is coast parallel (Joseph and Thriuvikramaji 2002; Soman et al. 2002). The radiocarbon dating of the marine molluscs collected from inland areas showed that the sea level at this region was about 7–8 m higher than the present and the coastline extended up to 8–25 km eastward than the present during 35,000 ^{14}C years before present (years BP) and 40,000 ^{14}C years BP (Pillai et al. 1999; Farooqui et al. 2005).

The studies on the deposition of late Quaternary peat deposits of Vembanad Lake by Narayana et al. (2002) suggested that the central Kerala coast was covered with intensive mangrove and other forest vegetation even during 40,000 years BP. Later, during the last glacial maxima (around 20,000 years BP), the sea level along this part of the coast stood about 60–100 m below the present mean sea level (msl). The rivers flowing at that time incised their valley to this base level (Prakash et al. 2001). The oolitic limestone confined to the western shelf of India, which dated to 11,000–9,000 years BP, indicated that the sea level was 65–130 m lower than the present msl (Nair 1975). Van Campo (1986) suggested the presence of humid climate with maximum representation of mangrove vegetation at around 10,000 years BP in the Arabian Sea area.

An event of transgression (8,000–6,000 years BP) and another event of regression (5,000–3,000 years BP) occurred along the Kerala coast during the Holocene (Rajendran et al. 1989). The pattern of rivers and geomorphological setup suggest that the coastline was much towards east during the geological past. The present Vembanad Lake and low-lying lands marked the eastern limits (Malik and Suchindan 1984). The occurrences of peat sequence in the sediments in the low-lying area around Vembanad Lake and the radiocarbon dating studies indicated that their formation was from submerged coastal forest, especially of mangrove vegetation (Rajendran et al. 1989). The geochronology of the western coastal regions of India along with the evidences from historical background, sea-level and geomorphic indicators, archaeology and lithological sequences helped Nair (2005) to put forward a five-stage transgressive–regressive model for the Holocene epoch.

These studies showed a drastic change in geomorphology along the Kerala coast, including the Vembanad Lake region, during the period of marine transgression and regression. Shifts in the courses of the Meenachil River, including its tributaries of lower reaches, might be linked to fluctuations and modifications of the base level erosion and the tectonic processes (Renjith et al. 2007). The flood plain of the Meenachil River remarkably possesses palaeo-deposit of sand. These palaeo-deposits characteristically contain a thin layer of carbonaceous clay, which is found sandwiched between the sand layers. The present study deals with the physicochemical analysis of the sandwiched carbonaceous clay and the radiocarbon dating of the clay and the embedded carbonized woods, hence depicting the age and conditions of deposition as well as the palaeo-environmental scenario of the region during the time of deposition.

Materials and methods

Meenachil River watershed extends from $9^{\circ}25'$ to $9^{\circ}55'N$ latitudes and $76^{\circ}20'$ to $76^{\circ}55'E$ longitudes. The locations, which are characterized by the presence of palaeo-deposits of sand, were identified from the lower reaches of the Meenachil River (Fig. 1) and their geographical positions were recorded (Table 1).

The major physicochemical parameters analysed were texture, organic carbon, nitrogen and C/N ratio. The relative proportion of sand, silt and clay in the carbonaceous sediment samples collected from the palaeo-deposits were determined by the International pipette method (Maiti 2003) using a textural triangle. The total nitrogen was estimated with a semi-automated nitrogen analytical system (Kel Plus-KES 4L digester and Kel Plus-Elite Ex distillation system, Pelican Equipments, India). Sediment samples were dried and powdered and an aliquot of 0.1–1 g were taken for the analysis (Jackson 1973). The organic carbon content of the Holocene clay formation, found sandwiched between the sand columns of the Meenachil flood plain area as palaeo-deposits, was estimated using standard procedure (Maiti 2003). Pearson's correlation was used to interpret the interrelationship between these physicochemical parameters and was calculated using SPSS 11 (Statistical Package for Social Sciences version 11). The radiocarbon dating of the carbonaceous clay and embedded carbonized wood of five selected locations (P1, P2, P4, P6 and P8) were done at the Birbal Sahni Institute of Palaeobotany, Lucknow, India, using liquid and advanced scintillation counter.

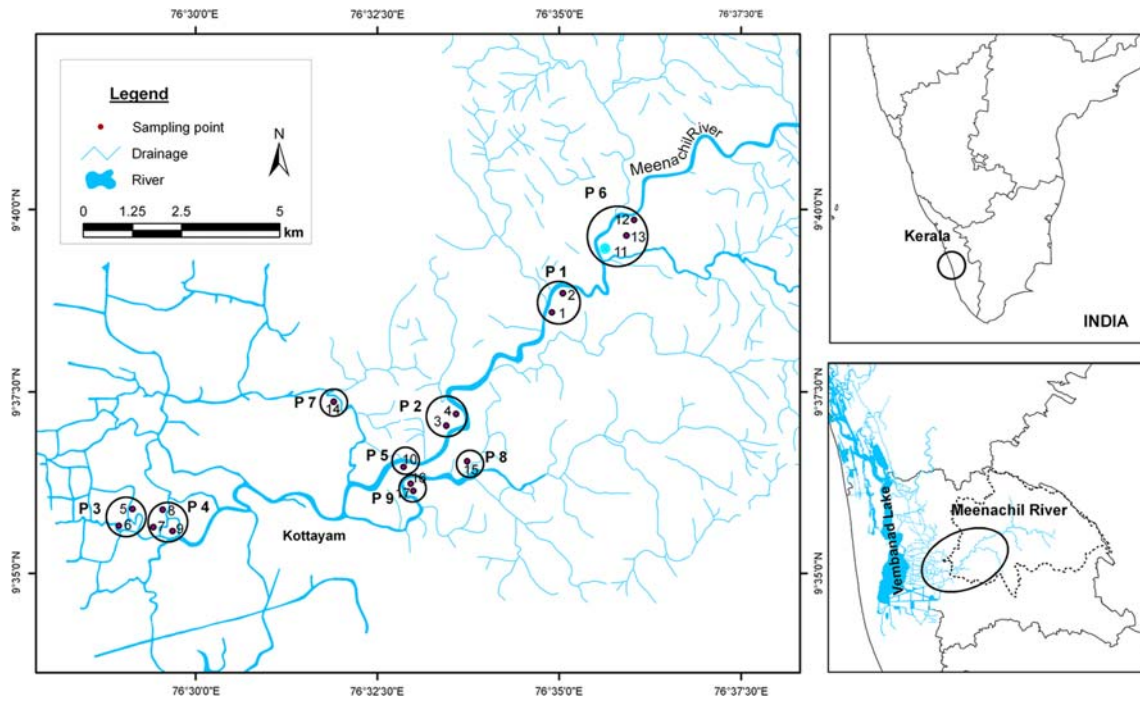


Fig. 1 Map showing study area and sampling locations

Table 1 Geographical positions of the sampling locations

Location	Sample no.	Thickness of overburden (m)	Approximate thickness of overlying sand column (m)	Approximate distance from the Meenachil River/tributary (m)
P1	S1	2.5–3.5	3.0–3.5	100
	S2	1.9	3.5	250
P2	S3	1.0–1.5	2.1	150
	S4	2.6	3.0	50
P3	S5	1.5	3.2	20
	S6	1.5	2.9	20
P4	S7	1.5–2.0	2.5	25
	S8	1.5	2.3	25
	S9	1.5–2.0	2.5	25
P5	S10	0.4–0.5	2.1	250
P6	S11	0.80	1.8	250
	S12	1.5–2.0	2.8	250
	S13	1.6	2.4	100
P7	S14	2.4	3.0	400
P8	S15	2.0–3.0	3.0–4.2	80
P9	S16	0.75–1.0	2.1	25
	S17	1.9	2.0	25

Results and discussions

Samples were collected from 17 locations lying at the lower reaches of the Meenachil River, which have remarkable presence of palaeo-deposits of sand and sandwiched carbonaceous clay (Fig. 2). The salient geopositional features of the locations selected are as given in Table 1.

The maximum thickness of the overburden was recorded from locations P2 and P8, while minimum thickness was recorded at P5 and P6. All the sites exhibited a well-developed sand column over the carbonaceous clay formation, where the maximum was observed at P1 and P8 (Fig. 3). Except P3, P4 and P9, all other palaeo-deposit regions were located at least 50 m away from the

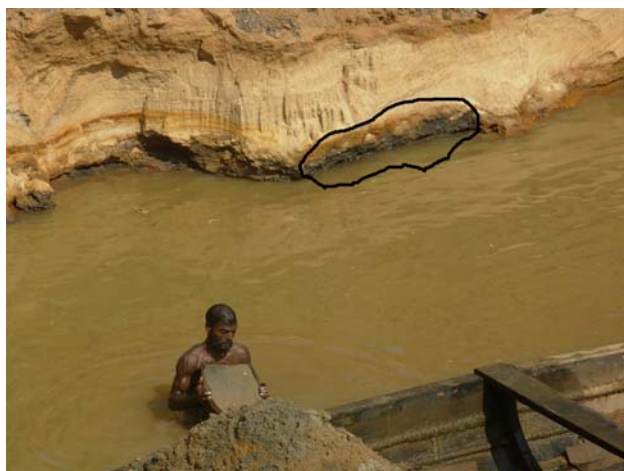


Fig. 2 The presence of carbonaceous clay within the palaeo-deposit

neighbouring water courses. The carbonaceous clay ranged in colour from place to place, even within a single region. The samples were dark in colour for those collected from P8, P7, P6, P2, P5 and P9, while others had a brownish colour.

The results of the textural analysis (Table 2) revealed that their deposition had a regime of water stagnancy. The percentage-wise comparison of the constitutional fragments indicated that the samples collected from P7 had more sand fractions, while those collected from P2–S3 had dominance of clay (Table 2). The conditions of deposition clearly indicated that the elevated base level of erosion (sea level rise?) was responsible for the water stagnancy by closing down the process of one fluvial realm in the region.

The geochemical analysis of the carbonaceous clay revealed that the level of organic carbon was very high in all the samples (Table 3). The samples collected from P5–S10 (8.75%), P6–S13 (6.20%), P1–S2 (5.83%), P4–S7 (5.83%) and P2–S3 (5.11%) had very high values and they were well above the mean organic carbon percentage of all locations (4.25%). Compared to all other samples, those collected from P6–S11 (1.02%) and P1–S1 (0.55%) had very low organic carbon content (Table 3). The percentage of total nitrogen was very high in samples of P5 (0.21%), P3–S5 (0.21%), P4–S7 (0.21%) and P2–S4 (0.20%), while the same was lower than the average value in samples of P1–S1 (0.059%), P6–S11 (0.90%) and P6–S12 (0.90%) when compared with the mean value of all the locations (0.16%). The values of the C/N ratio was remarkably high in the samples collected from P6–S13 (44.29), P5 (41.67) and P6–S12 (40.56), and the same was particularly lower than the mean value of all samples (26.19) in P4–S8 (15.37), P6–S11 (11.33), P3–S5 (10.43) and P1–S1 (9.17).

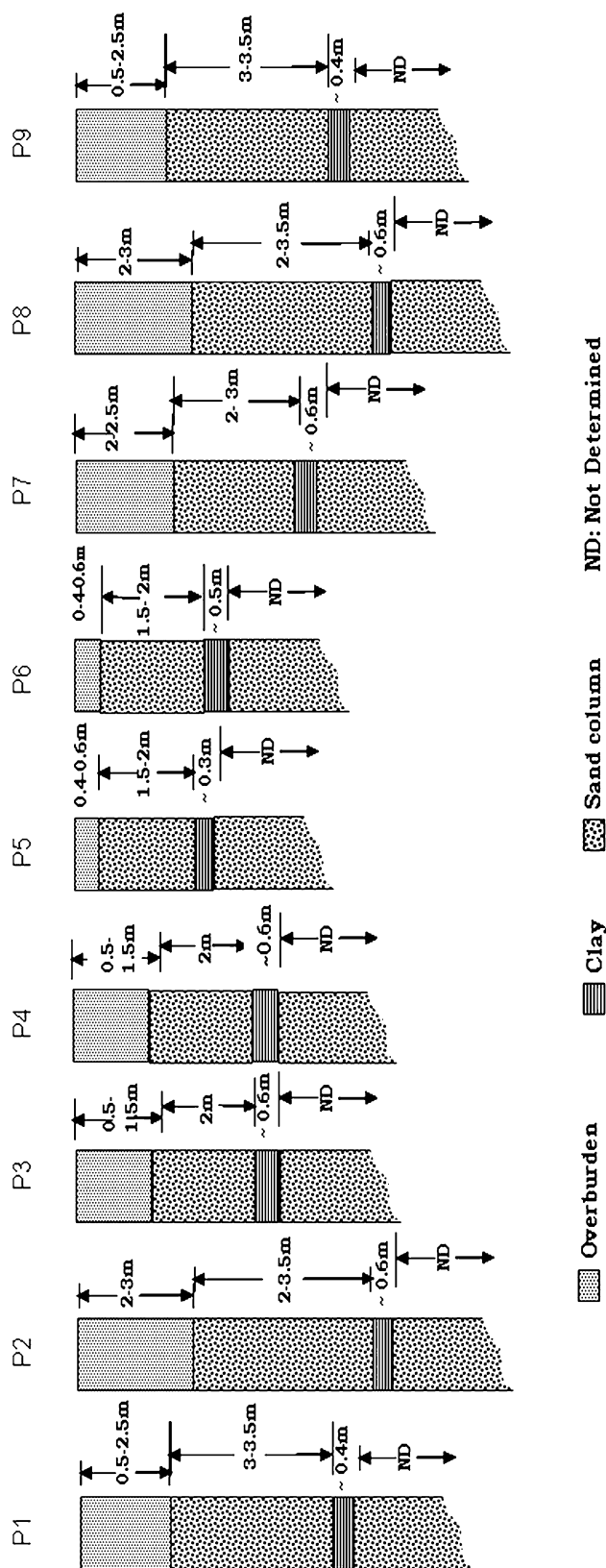


Fig. 3 Schematic representation of the vertical profile of palaeo-deposits at different regions

Table 2 Particle proportions of sand–silt–clay in samples collected from the sandwiched clay layer

Name of the location	Sample number	Clay	Silt	Sand	Terminology
P1	S2	13.86	1.07	85.07	Clayey sand
P2	S3	53.95	8.99	37.06	Sandy clay
P2	S4	11.65	0.53	87.82	Clayey sand
P3	S6	29.03	1.65	69.32	Clayey sand
P6	S11	39.66	4.18	56.16	Clayey sand
P7	S14	07.59	2.17	90.24	Sand

Table 3 Interpretation of the level of organic carbon in sediments

Region	Sample number	Organic carbon (%)	Total nitrogen (%)	C/N ratio
P1	S1	0.55	0.06	9.17
	S2	5.83	0.17	34.29
P2	S3	5.11	0.19	26.89
	S4	4.38	0.20	21.90
P3	S5	2.19	0.21	10.43
	S6	4.38	0.18	24.33
P4	S7	5.83	0.21	27.76
	S8	2.92	0.19	15.37
	S9	4.74	0.17	27.88
P5	S10	8.75	0.21	41.67
P6	S11	1.02	0.09	11.33
	S12	3.65	0.09	40.56
	S13	6.20	0.14	44.29
P7	S14	4.74	0.18	26.33
P8	S15	4.38	0.12	36.50
P9	S16	3.65	0.16	22.81
	S17	4.02	0.17	23.65
	Mean	4.25	0.16	26.19

The average value of organic carbon for all the sampling locations was extraordinarily comparable with those recorded from some other regions of the world (Table 4). The global distribution of organic carbon, total nitrogen and C/N ratio was found to be fluctuating, based on the climatic variability and monsoon patterns. Many contend that the relativity of the inter-tropical convergence zone (ITCZ) played a major role in the Holocene climatic variability, and hence the vegetational pattern and distribution.

The correlation matrix of the samples in relation with sand–silt–clay fractions and the organic carbon–nitrogen proportions were analysed and are given in Table 5. The analysis showed that the sand fraction in a sample had significant negative correlation with clay and silt fractions, while the level of organic carbon showed a positive significant correlation with the level of nitrogen.

The radiocarbon dating of samples collected from selected palaeo-deposits (Table 6) revealed that the samples collected from the southern part of the Meenachil River were pretty older than those collected from the northern side. It was noticed by Rajendran et al. (1989) that the deposition of the shells in the Vembanad Lake was associated with the event of regression around 5,000–3,000 years BP, as these organisms, after being trapped in their ecological niche, were destroyed due to the regression of the sea (Table 7). Hence, the present backwater system of Vembanad had its origin during this regression period. On comparing the same with the radiocarbon dating of the samples collected from the lower reaches of the Meenachil River, it is pointed out that the deposition of the carbonaceous clay on the southern side of the Meenachil River had occurred even before the formation of the Vembanad Lake system. The radiocarbon dating of the samples collected from the northern side of the existing channel of Meenachil River had pointed to a relatively younger age of deposition (Table 6).

The level of organic carbon (C) and total nitrogen (N) and the C/N ratio in almost all samples, except P1–S1, P3–S5, P4, S8 and P6–S11, have shown a remarkable comparison with other Holocene deposits. The level of organic carbon is a measure of productivity, detrital input and preservation/degradation processes, and the level of total nitrogen is higher in lower plants such as aquatic phytoplankton and in bacteria, since the organic nitrogen occurs preferentially in proteins and nucleic acids. The high ratio of C/N ruled out the formation of organic carbon by algae and phytoplankton in a closed environment. But, it clearly was produced by terrestrial plants. As lignin and cellulose are the dominant components of terrestrial higher plants, allochthonous and submerged organic matter have high C/N ratio. The warm and humid climate, as recorded all over the tropical regions during 10,000–4,000 years BP (related with the position of ITCZ?) with high intensity rainfall (Jayalakshmi et al. 2005; Van Campo 1986; Thamban et al. 2001), has contributed to the high productivity in the study area (Fig. 4). The aridity, which was witnessed during the late Holocene has reflected in the low productivity in locations like P3–S5 and P4–S8. The presence of yellow ochre within the top sand column (Fig. 5) at P2 also revealed the arid climate during the receding of the sea level.

The radiocarbon dating suggested that the palaeo-deposits at the southern part of the Meenachil River were formed well before the formation of the Vembanad Lake. The global eustatic sea level change had contributed a lot to its formation, especially the formation of the sandwiched carbonaceous clay within the sand column. Phenomena such as river avulsion and channel abandonment were also developed inconsequent to changing morphology. The shift

Table 4 Comparison of the present result with some other palaeo-deposits

Location	Age	Organic C (%)	Total N (%)	C/N	Remarks
Lower reaches of Meenachil River	Holocene	4.254	0.162	26.116	Present study
Kochi offshore, Kerala	Mid Holocene	0.710	ND	ND	Reddy (2003)
South-west margin, India	Late Pleistocene	1.4–3.0	0.02–0.15	>15	Kessarkar and Rao (2007)
South-west margin, India	Early Holocene	1.7–2.5	0.02–0.15	8.5–27.2	Kessarkar and Rao (2007)
South-west margin, India	Late Holocene	2.5–4.4	0.05–0.43	14.1–40.5	Kessarkar and Rao (2007)
Eastern Atlantic off Ghana	Pliocene – Pleistocene	0.5–1.4	0.06–0.14	4.0–18.0	Wagner (1998)
Rhone Delta, France	Late Holocene	7.64	ND	ND	Stanley (2000)
Sangla Valley, Himalaya	Holocene	0.04–1.6	0.04–0.12	8–18	Chakraborty et al. (2006)
Lake Ossa, Cameroon	Middle-Late Holocene	3.0–6.0	0.25–0.50	12	Sifeddine and Wirmann (2004)

ND not detected

Table 5 Correlation matrix for the samples

	Clay	Silt	Sand	Carbon	Nitrogen	C/N ratio
Clay	1					
Silt	0.882*	1				
Sand	−0.998**	−0.913*	1			
Carbon	−0.327	−0.100	0.298	1		
Nitrogen	−0.293	−0.097	0.269	0.854*	1	
C/N Ratio	−0.343	−0.137	0.317	0.957**	0.669	1

*Correlation is significant at the 0.05 level (two-tailed)

**Correlation is significant at the 0.01 level (two-tailed)

in the main channel of the Meenachil River from south to north, which could be seen right from just the upstream region of location 12 to location 17, is attributed to the tectonism around 4,000 years BP as suggested by Soman (1997). The study also coincides with the observation of Joseph and Thirvikramaji (2002) that the different sectors of the Kerala coastal land had experienced non-uniform tectonic activity.

The formation of the palaeo-deposits of the northern side of the Meenachil River is of later age, contemporaneous to the development of the Vembanad Lake and the local base level of erosion. An elevated sea level than the present is suggested during 3,000 years BP. Apart from the normal block faults along the Kerala coastal belt, the possibility of a tectonic combination of horst-graben

development around the Cochin estuary during the Middle to Late Holocene cannot be ruled out, not only by the present study, but also on the basis of the prominence in channel development in the case of the northern distributaries of the Meenachil and Muvattupuzha Ar, and shrinking of the southern distributary of the Periyar River. Narayana et al. (2001) identified a palaeo-delta near the mouth of the Periyar River, one of the major rivers of Kerala, formed by its more youthful northern branch. A series of cymatogenic up-arching and down-warping in Peninsular India, developed during the Pleistocene (Ramamamy and Balaji 1995), also might have influenced the defining of the channel morphometry during the transgressive and regressive episodes. Hence, apart from the global eustatic sea-level fluctuations; tectonism also had played a decisive role in shaping the channel geometry of rivers of central Kerala, which also included the Meenachil River.

Conclusion

The Meenachil River basin of the southwestern coast of India had experienced different climatic phases during the Holocene. The region experienced a wet climate due to intense rainfall with maximum representation of vegetation during the earlier part. The elevated sea level and the formation of palaeo-deposits due to channel rearrangements were attributed to this period. Later, during the Late

Table 6 The radiocarbon dating results of the palaeo-deposits of the Meenachil River basin

Sl. no.	Location name	Sample number	Material	Age (^{14}C year BP)	Geographical position in relation to the Meenachil River
1.	P1	AMR VI	Sediment	5,786 ± 94	South
2.	P2	AKLM I	Wood	2,888 ± 78	North
3.	P4	LAK II	Sediment	1,466 ± 69	North
4.	P6	PRA II	Wood	5,780 ± 95	South
5.	P8	SES 1A	Wood	5,570 ± 30	South

Table 7 Comparison of different radiocarbon dates of Late Holocene samples from Kerala coast

Location	Sample type	Age	Remarks
Ernakulam Lagoon 1	Sediment	8,330 ± 110	Jayalakshmi et al. (2005)
Ernakulam Lagoon 2	Sediment	3,800 ± 80	Jayalakshmi et al. (2005)
Iranimangalam	Peat	7,050 ± 120	Rajendran et al. (1989)
Kalarkodu	Sediment	6,740 ± 120	Jayalakshmi et al. (2005)
Kavanar 1	Shell	7,090 ± 100	Jayalakshmi et al. (2005)
Kavanar 2	Sediment	2,180 ± 70	Jayalakshmi et al. (2005)
Muhamma	Shell	3,130 ± 100	Rajendran et al. (1989)
Muthukulam 1	Wood	7,176 ± 82	Jayalakshmi et al. (2005)
Muthukulam 2	Wood	6,276 ± 112	Jayalakshmi et al. (2005)
Muthukulam 3	Shell	3,362 ± 114	Jayalakshmi et al. (2005)
Pachcha	Shell	6,690 ± 160	Jayalakshmi et al. (2005)
Parayakadavu	Shell	4,610 ± 100	Jayalakshmi et al. (2005)
Pathiyoor	Wood	7,510 ± 100	Jayalakshmi et al. (2005)
Payyannur	Shell	4,370 ± 100	Rajendran et al. (1989)
Ramapuram	Wood	2,460 ± 120	Jayalakshmi et al. (2005)
Tannisseri	Peat	6,420 ± 120	Rajendran et al. (1989)
Tellicherry	Peat	7,230 ± 120	Rajendran et al. (1989)
Varkala offshore	Shell	5,470 ± 115	Soman (1997)
Vechoor	Shell	3,710 ± 90	Rajendran et al. (1989)
Wellington Island	Peat	8,080 ± 120	Rajendran et al. (1989)



Fig. 4 The increased rainfall was a vital component in making the palaeo-deposits, as inferred from coarse-grained sand particles



Fig. 5 The presence of yellow ochre within the sand deposit indicated an arid condition during the late Holocene

Holocene, the region experienced a dry climate. The marine regression and other episodes of channel modification were attributed to this phase. It is evident from the study that the carbonaceous clay found sandwiched between the palaeo-deposit of sand marked the water stagnancy due to the elevated sea level and the end of the fluvial realm that existed at that time. Allochthonous and submerged organic matter also have contributed to the formation of the carbonaceous clay.

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