Fertile farmlands in Cauvery delta: evolution through LGM

Pramod Singh[1],*, M. G. Yadava[2], Malik Z. Ahmad[1], P. P. Mohapatra[1], A. H. Laskar[2], S. Doradla[1], J. Saravanavel[3] and C. J. Kumanan[3]

[1]Department of Earth Sciences, School of Physical, Chemical and Applied Sciences, Pondicherry University, R.V. Nagar, Kalapet, Puducherry 605 014, India
[2]Geoscience Division, Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India
[3]Centre for Remote Sensing, Bharathidasan University, Khajamalai Campus, Tiruchirappalli 620 023, India

The Cauvery delta encompasses legendary farmlands for at least over the last ~2300 years BP that had supported the growth of the famous Chola and Pandya kingdoms. The chrono-stratigraphic study from six sediment cores taken from the Cauvery basin indicates Holocene evolution of the present delta in response to the past sea-level changes. It is found that at the time of lower sea level during the Last Glacial Maximum, older sediments from the present delta plain, were removed and the extent of removal in different parts was observed to have been controlled by the variation in shelf morphology. Subsequent sea-level rise during the deglaciation after the Last Glacial Maximum, led to filling of the incised valleys with the younger sediments of the Holocene. Nilgiri–Kodaikanal–Palani–Biligirirangan hills granulites and Brahmagiri regions constitute the upper catchment. Geochemistry of the sediments indicates presence of plagioclase and dominance of 2 : 1 clay, suggesting weathering-limited provenance of southern granulite-type rocks, the source of which is perhaps the high relief and tectonically more active Nilgiri–Kodaikanal–Palani–Biligirirangan hills mountain region rather than the Brahmagiri region. A continuous deposition since the beginning of the Holocene has resulted in the formation of fertile farmlands in the Cauvery delta region.

Keywords: Cauvery, delta, farmlands, Holocene evolution, sea-level change.

Introduction

FERTILITY of an alluvial soil is largely because it is inherited from physical and chemical characteristics of the catchment area. However, the nature of weathering and erosion may alter the minerals which form the final sediment and are deposited over the floodplains by the river inundating usually every year. For example, when there is a rapid transportation, nutrient-rich primary minerals may experience insignificant chemical weathering that may otherwise alter nutrient composition of the sediments. In a natural ecosystem, nutrients released by minerals are used by the living biota and dead components are recycled, retaining them within the soil–plant system with only little outgoing losses. However, during the past few centuries the ecosystem is being disturbed due to change in the society from nomadic to agrarian; harvesting of every crop has resulted in increased leakage of nutrients out of the system. In recent times increase in food requirements as a consequence of population growth has resulted in the adoption of intense agriculture practices which have further enhanced such leakage, making farmlands infertile. The rate of conversion of the farmlands from fertile to barren, has been further augmented by building of dams in the catchment region that have checked the natural annual cycle of adding fresh sediments with useful minerals.

In view of the above it has become important to know the sustainable rate of exploitation of these farmlands, which in turn requires understanding of long-term natural processes which in the past had contributed to fertile farmlands. River deltas are the best place for such a study; they, among all the sedimentary environments world over, have the most extensive farmlands which have sustained their fertility till the recent past, until the advent of modern agricultural practices. For centuries deltas have supported the growth of many great human civilizations and their livelihoods because of their extremely fertile soils. People living in the delta region were benefited and influenced by the changing environmental conditions that affected the farmlands.

In this article we present, results from studies based on six sediment cores taken from the Cauvery delta (locations shown in Figure 1) that include chronology, texture, mineralogy and geochemistry, to understand the processes that have led to the formation of the delta region and evaluate the role of local and global factors in making this delta fertile.

Methods

Drilling employed a diamond impregnated head in a double-barrel core tube. A PVC pipe was inserted inside

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the core tube to retrieve the cored sediments. A slow, direct circulation rotary method was used for the muddy formation with almost 100% core recovery, whereas for unconsolidated sandy strata a combination of rotary and percussion methods was used to arrest the core with slightly lesser recovery (70–80%). Subsamples were taken at 2 (or 5) cm interval from one half of the longitudinal section of the core for dating, mineralogical and geochemical studies. The other half was used for logging and preserved for future analyses. For radiocarbon dating, subsamples were first treated with acid to remove carbonate fraction and later after neutralizing with distilled water they were dried and preserved for benzene synthesis from the organic carbon fraction. For concentration measurements of major and trace elements, ICP-AES method was adopted. X-ray diffraction (XRD) method was used for mineralogical studies. Further details will be discussed elsewhere.

Sea-level changes along the Cauvery delta

The Cauvery delta is known to be fertile and is popularly known as the rice bowl of south India. Presently, agriculture in this region supports livelihood of 4.8 million people. The legendary Cauvery delta, has served as a natural granary of south India right from ~2300 years BP and has led to the emergence of the old Chola and Pandyas Tamil kingdoms[1,2]. A number of megalithic sites indicating the older human habitations are found in

Figure 1. Map showing the study area[3], locations of the borehole sites, and transects for Figure 4 *a–c*. Locations for cores 1–6 are respectively, Valangaiman, Nannilam, Porayar, Kadlangudi, Uttrangudi and Vadapadi. TV, Thirumullaivasal; WDC, Western Dharwar Craton.

Pudukkotai district (Figure 1) fringing the southwestern part of the delta. Transformation from megalithic culture to large kingdoms, which appears to have happened around 300 BC, is marked by shifting of the settlements from highlands to delta plains[4,5]. Historical inscriptions during the rule of Ashoka in North India, mention the Chola kingdom of south India[1,4,6].

Deltas which are formed in the transitional environment between river and sea are affected by the long-term changes in sea level and the depositional environment. The paleo sea-level changes along the east coast of India have been reconstructed based on coral remains and morphological indicators and to some extent from archaeological data[7]. During the Last Glacial Maximum (LGM, around ~20 kyrs ago), due to significant extension of ice caps, the world sea levels dropped dramatically by 120–150 m below the present level. Using relict coral reefs, studies from the Bay of Bengal also show that about 18,390 ± 220 years BP ago, the sea level was below –120 m (ref. 8) and during 14,510 ± 190 years BP ago it was near –115 m (ref. 8). Several other studies have shown subsequent rise in the sea level: a mollusc shell ~17 m below mean sea level is dated 8200 ± 120 years BP[9,10]; marine shells at 3.9 m elevation are dated 6310 ± 120 years BP[7]. Records based on the high stand paleo beach ridges and emerged coral colony indicate that the sea on the east coast of India reached the present level during ~7300–6500 years BP[11,12] and rose to +4m during 4223 years BP[7]. The oldest ^{14}C date obtained on shells from the strandline is 5760 ± 140 years BP[13]. The age of 2740 years BP obtained on Cardium present 2 m above sea level, indicates that the sea remained at this level for ~2 k years (ref. 14). Based on the above published literature, it can be surmised that the sea level in the east coast of India had reached a lower limit of –125 m below present sea level (PSL) during LGM. Then after subsequent rise, it reached a level of +4 to +5 m above PSL and inundated the coastal region around 7000 years BP and after minor fluctuations established itself at the present level.

Post-LGM evolution of the Cauvery delta

The mid to late Holocene, sea-level changes have left noticeable imprints on the coastal landscape of the Cauvery delta in the form of paleo beach ridges and swales. The paleo beach ridges separated by swales show NE–SW orientation in the southern part of the delta plain, whereas in the northern part they are oriented in NNW/SSE direction (Figure 2). These two sets of beach ridges converge in the central part of the coastal delta plain, where their width is minimum. Traces of the innermost beach ridge marking the palaeo-shoreline, indicate an arcuate shape of the delta during the mid-Holocene highstand[15]. The innermost beach ridge in the southern part located at Tiruthuraippondi (Figure 2) adjoining the arcuate delta is dated 6090 ± 230 years BP and the outermost
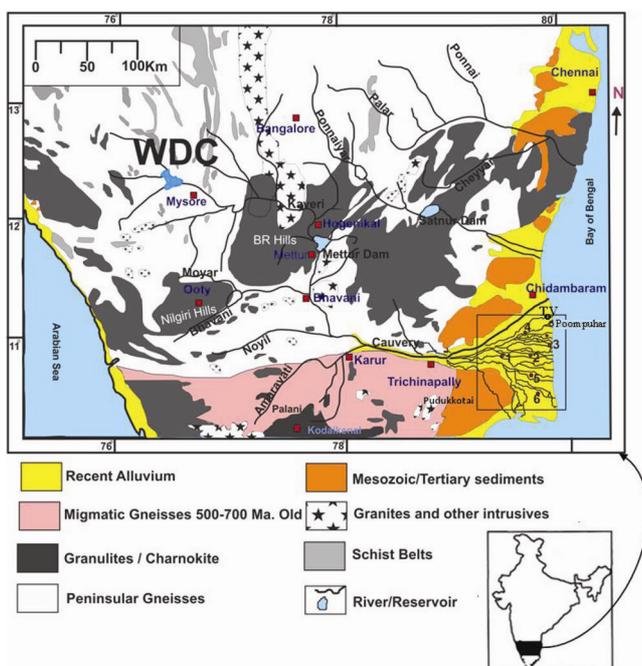
beach ridges at Kodiyakkarai (Figure 2) have been dated 1020 ± 80 years BP[16]. The progressively younger paleo beach ridges towards the shore indicate their formation during successive regressive phases of the sea after the maximum highstand. In the northern part of the delta the archaeological remains, found during excavation over land and under-sea exploration at depths up to –15 m, suggest that the above regressive phase had re-exposed part of the shelf which again was submerged during the later transgression before the sea-level stabilized[1,17]. The excavation carried out by the Archaeological Survey of India at Poompuhar (Figure 2) yielded a wharf structure in Kilayur (Figure 2) located ~2 km inland from shore[18], suggesting the presence of a port town of the early Chola kingdom around this location. Two wooden poles of this wharf have been dated as 2200 ± 100 years BP and 2265 ± 100 years BP[18] respectively. Underwater exploration has revealed the existence of early Chola site up to 7–15 m depth off Poompuhar, extending to around ~1 km off the present coastline[1,2,19]. The historical remains and radiocarbon dates indicate the existence and flourishing of this site up to a depth of ~7 m below PSL between ~2300 and ~1700 years BP. This indicates that the sea had

regressed from the present shoreline ~2300 years BP and subsequently transgressed during ~1700 years BP, before stabilizing at the present sea level.

The sea-level fall up to ~125 m suggests that the shelf may have got exposed up to this depth during the LGM. As a result, during this period the site of deltaic sedimentation would have shifted further east near the edge of the newly exposed shelf. The present isobath contour lines in the shelf region off Cauvery delta (Figure 3 a) indicate that this part does not have uniform width and slope and shows variation from north to south. The present depth profile drawn along different E–W transects suggests that width of the shelf is narrower and steeper in the northern part. It widens significantly in the southern part with gentle change in the slope (Figure 3 b). Thus due to opening of the shelf during the glacial period, additional distance the river had to travel to reach the sea would have been less in the northern and central parts compared to the southern part. Variation in width of the shelf and the slope would have guided the flow path of the river differently in different parts of the delta plain. The channels might have changed their course towards area of maximum gradient, along the northern and central parts of the delta. Lowering of the sea level would have resulted in progradation of river valleys towards the basin and incision in the present delta plain and even in the exposed shelf region. This should have resulted in dissection of the surface into incised valleys and formation of divides by regions that escaped erosion. These depressions may have got inundated by rising sea water during the post-LGM period and formed estuary and bays affecting the retrogression and back filling of the valleys through
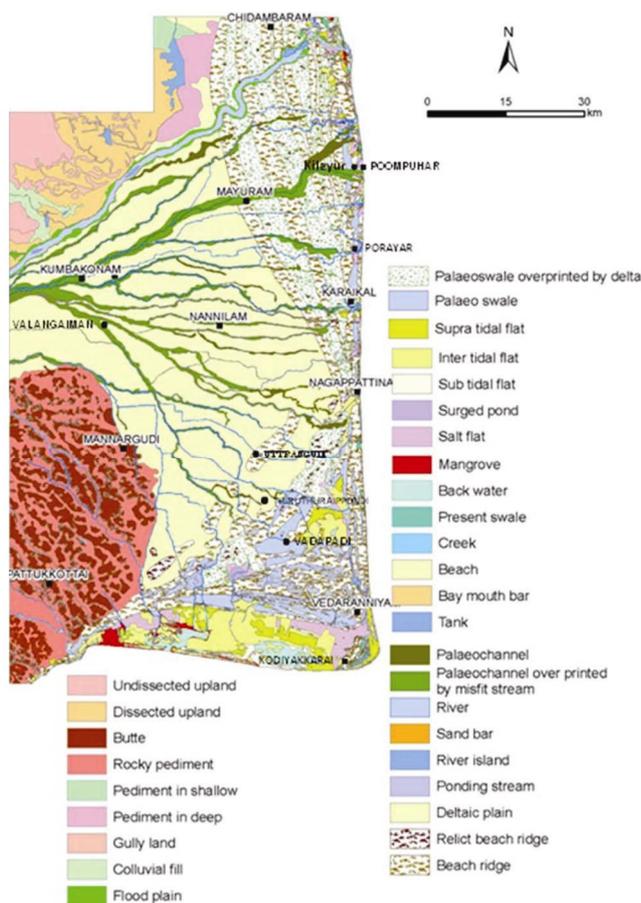
Figure 2. Geomorphological map of the Cauvery delta showing the paleo beach ridges. The western most beach ridge marks the Holocene transgressive highstand and the others towards east mark the successive regressive phases.
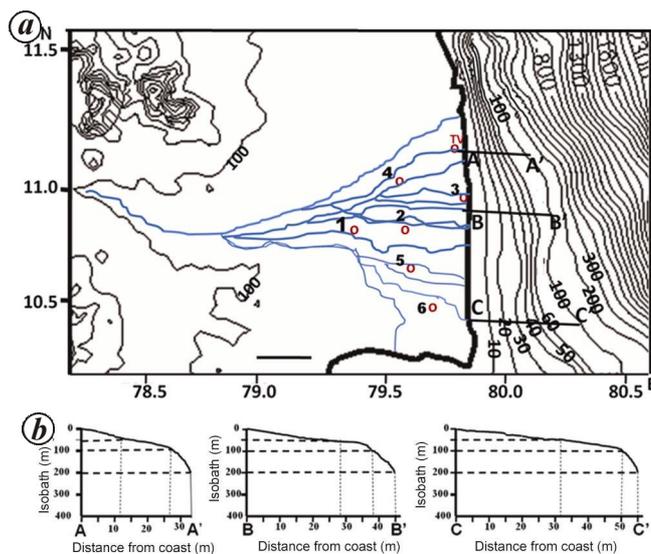
Figure 3. Map showing the bathymetric contour in the adjoining shelf region of the Cauvery delta and associated E–W depth profiles. Note the narrowness of the shelf width and higher slope along the northern transect A–A′ and gradual increase of width and decrease of slope while moving from north to south.
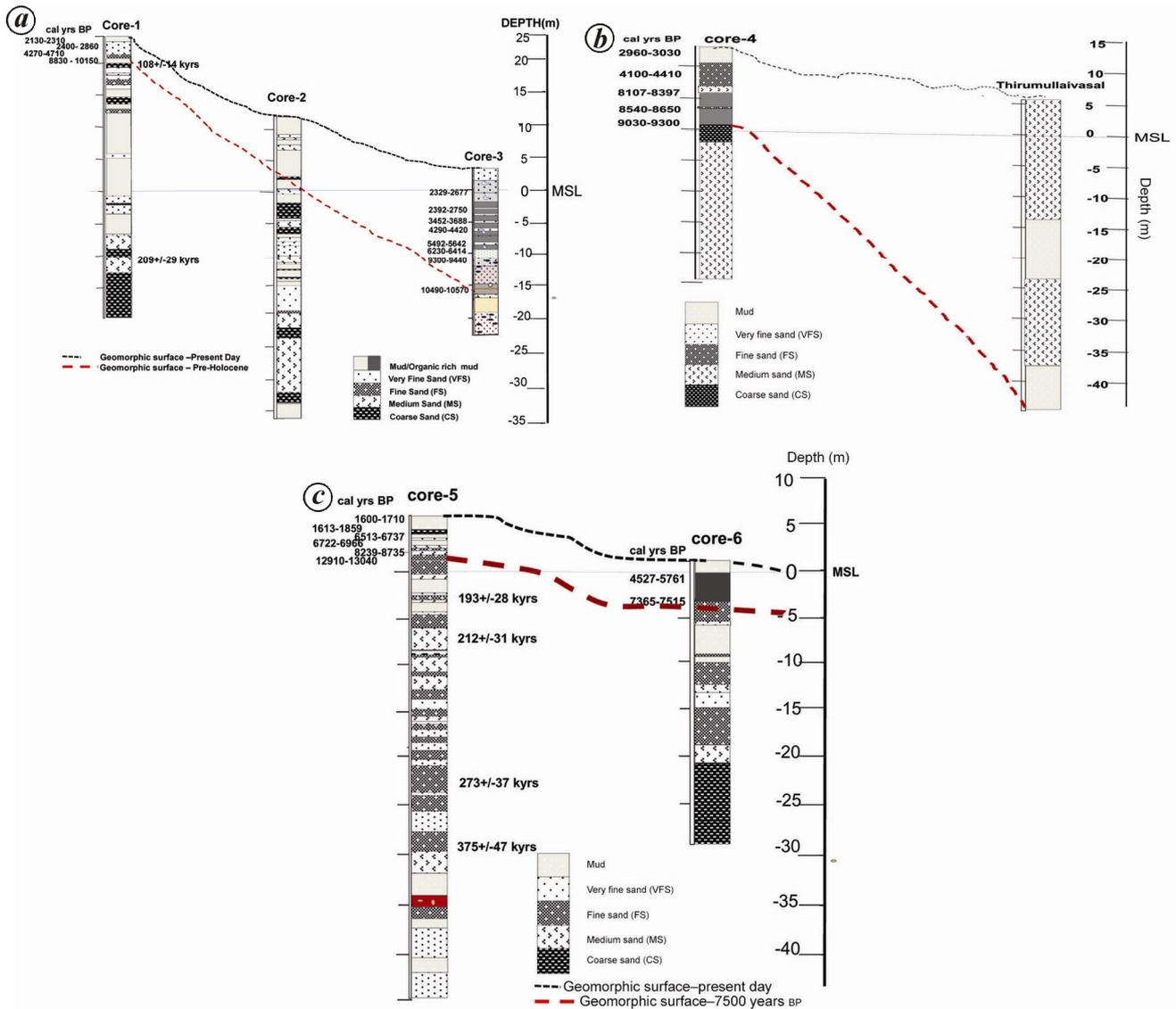
Figure 4. *a*, Longitudinal chronostratigraphic cross-section of the studied cores 1–3 along the central axial transect of the delta region. Calibrated radiocarbon age ranges (cal years BP, 1-standard deviation) are shown for the respective sediment layers. *b*, Longitudinal chronostratigraphic cross-section along the northernmost studied core-4 and Thirumullaivasal section[20]. *c*, Chronostratigraphic cross-section of the studied cores 5 and 6 along NS transects in the southern part of the delta.

sedimentation in the voids carved out during the lower sea level. Thus the thickness record of the post-LGM sedimentation in different parts of the present delta may provide a clue to the incision suffered in response to low sea-level condition.

Sediment cores from Cauvery delta

The chronostratigraphic sequence along the central axial part of the delta is established from three cores taken along an E–W alignment from Valangaiman (core-1), Nannilam (core-2) and Porayar (core-3) (Figure 4 *a*). One more core from Kadlangudi (core-4) located in the northern part has been compared (Figure 4 *b*) with the Holocene section earlier reported by Meijerink[20] from Thirumullaivasal (location TV, in Figure 1) in the NE part

of the delta. The sequence along N–S transect passing through the southern part of the delta is reconstructed using two cores taken from Uttrangudi (core-5) and Vadapadi (core-6) (Figure 4 *c*). The easternmost core taken from Porayar (core-3) is located 1.5 km inland from the coast. The cores 1, 2, 6 and 4 are 51, 26, 29 and 22 km respectively, inland from the coast. A few ^{14}C ages have been determined at different depths from these cores and are shown in the logs (Figure 4).

The chronostratigraphic sequence constructed involving three cores (1–3) along the central axial part of the delta records wedge-shaped Holocene sediments along EW transect; an increase in sediment thickness is observed from <5 m in the innermost core-1 to 16 m in core-3 (Figure 4 *a*). Using the oldest dates, the isochron line drawn between core-1 and core-3, intersects core-2 (for which
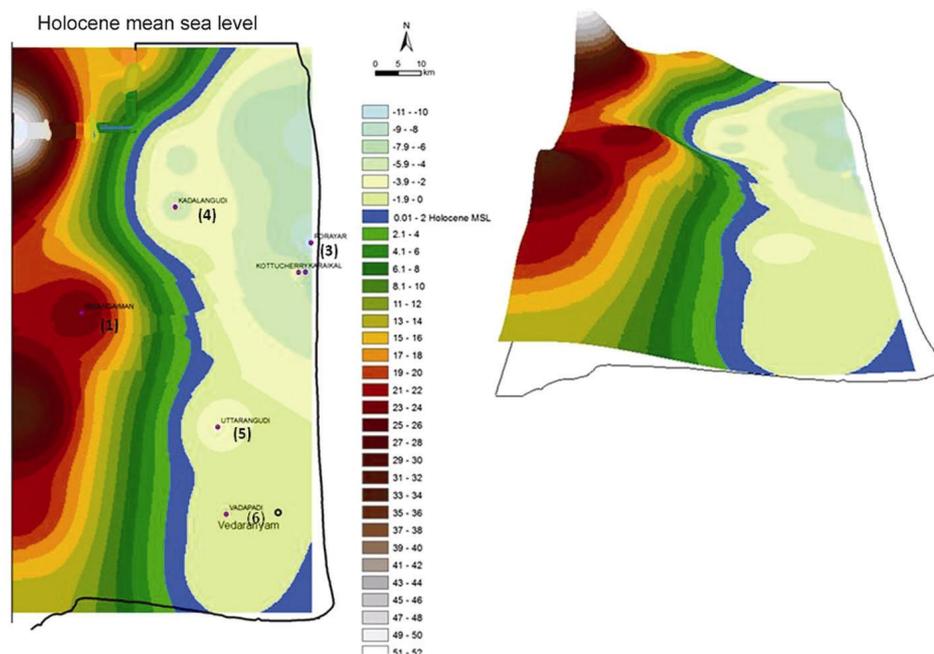
Figure 5. The paleo surface profile generated at ~7000 years BP based upon the date/depth data obtained from different cores. Note the colour codes show formation of the Bay in the north central part around this time.

presently we do not have any ^{14}C dates) ~ 10 m below the surface (+5 m above the PSL). Assuming that an equilibrium profile was established between these three sites (cores 1–3), we may infer that ~10 m thick sediments had got deposited in response to Holocene transgression and regression at the site of core-2. In Figure 4 b, core-4 which shows 12 m Holocene sequence is compared with the lithostratigraphy earlier reconstructed using a ~40–45 m thick Holocene deposit from Thirumullaivasal[20]. This chronostratigraphic sequence suggests thicker Holocene deposit in the northern part compared to that observed along the central axial part (cores 2 and 3). In contrast, near core-5, which is 25 km inland in the southern part of the delta, the sequence has only ~4 m Holocene sediments that overlie Pleistocene sediments (at ~9 m an OSL date reported is ~193 kyrs (ref. 21)). Similarly, in the southern part of the delta, along the NS transect, cores 5 and 6 show that sediments are only ~5 m thick (Figure 4 c). At 7000 years BP, the surface profile is generated (using Arc GIS 3D analyst module) using ages obtained from different cores. Simulated results (Figure 5) show that surface in the north and central parts in the delta basin was deeper by about 10 m compared to that in the southern part.

The observed pattern between chronology and sediment thickness, therefore, suggests that during the time when the sea level was low, accumulation of the sediments in the delta region was not uniform, possibly due to non-uniform erosion at that time. The difference in the Holocene sediment thickness is inferred to be due to different extents of incision carried out by the river in an attempt to attain new equilibrium condition in response to

lowering of sea level, and thus modifying the base level from LGM to post-LGM period. Higher incision in the northern and central parts of the delta (Figure 2) compared to the southern part (which shows insignificant erosion) suggests that possibly the higher subsidence (due to the shelf topography inclined more northward) exerted a major control on the flow path of the rivers during the LGM. As a result sediments varying in thickness from 5 to 20 m got deposited in the northern and central part of the delta during the period of Holocene sea-level rise (transgressive phase) and until the present. Although we do not have thickness records for the sediments deposited in the marine part of this delta, further investigation of the same may be helpful to understand the role of shelf morphology in the variable sediment thickness as discussed above. Depressions and valleys carved (due to erosion during the LGM) into the underlying Pleistocene and Tertiary rocks got filled and attained their present level making the delta region suitable for farming and settlement. It is worth noting that ages obtained near the surface of these cores (Figure 4) are around ~2000 years BP. Soil organic matter is usually a mixture of several age components: primarily consisting of old organic carbon deposited during sedimentation into which zero-age modern organic carbon is continuously added (due to percolation of fresh labile organic compounds). If there is no carbon loss, then the soil near the surface should show zero age. However, as radiocarbon ages obtained here are close to ~2000 years, it suggests that either modern surface carbon is consistently being lost due to run-off or there is deep ploughing which is mixing well the modern carbon with the old buried components. This can be

addressed further if dating of surface soils is carried out in future.

Sediment characteristics

The 5–20 m thick sediment cover on the old Archean terrain, deposited during the Holocene over the Cauvery delta, has developed into fertile farmlands and is historically known to have supported human civilization for at least the past ~2000 years. For the delta to be fertile, it should have the right kind of texture, mineralogy and nutrient-specific elements that are inherently carried by the sediments from the catchment area.

A ternary diagram for core-3 (Porayar, Figure 6) shows that the sediments consist of sand, silt and clay in different proportions. The dominant fractions are silt and sand that range from 20% to 80% whereas clay constitutes less than 20%, indicating that the sediments are prominently loamy and vary from sandy loam to silty loam. In contrast, sediments from core-5 (Uttrangudi) are in the silty loam domain. The sediments from the other cores in the central and northern parts of the delta (results not shown here) also show texture variation between sandy loam and silty loam. Thus the sediments seem to be moderately to poorly sorted, which indicates that they are immature and have not undergone much of reworking.

XRD study shows that quartz and feldspar, including plagioclase constitute the dominant primary minerals, whereas hornblende and pyroxene form minor phases. The dominant clay minerals are smectite, kaolinite and illite (D. Srikanth, unpublished). Results from the ongoing study on soil profiles developed in Kodaikanal–Palani, Biligirirangan and Nilgiri hills regions (C. G. Lakshmidevi, pers. commun., locations shown in Figure 1) show illite and smectite as the dominant clay minerals, although some profiles from Nilgiri show formation of

gibbsite, whereas kaolinite and minor amount of smectite are present in soils developed over the Western Dharwar Craton forming the upper catchment region[22,23]. This suggests that the sediments may have been predominantly derived from the southern granulite terrain forming part of the Kodaikanal–Palani, Biligirirangan and Nilgiri hills. These regions are tectonically more active than the Brahmagiri region in the upper catchment and also have immature topography with higher relief.

The immature nature of the minerals and presence of 2 : 1 clays suggest that sediments are nutrient-rich. Chemical nature of the sediments eroded and transported from the source and deposited in the delta region is mainly controlled by chemical weathering at the source and also further (of sediments) in the delta region. Higher chemical weathering would generally leach out elements that are then carried by water to the oceans. Unweathered or less weathered sediments are known to retain the nutrient elements provided by soil and therefore form fertile farmlands.

Geochemical study was carried out on three cores, 1, 3 and 5. The weathering history of the source can be
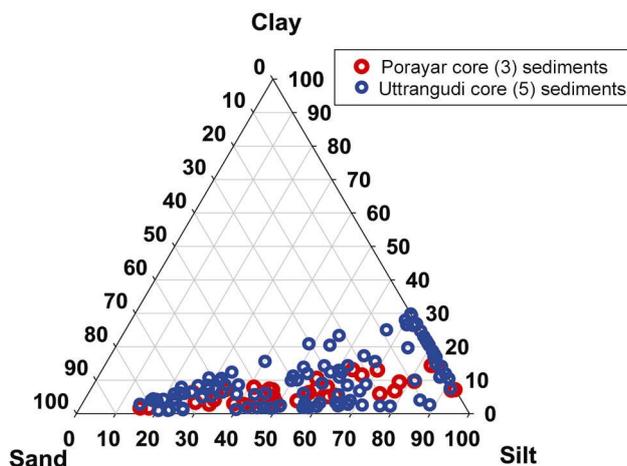
Figure 6. Ternary diagram showing the textural distribution of sediments from two representative cores (3 and 5). Note the immature nature of sediments indicated by the textural variation between sandy loam and silty loam, which has made it suitable for agriculture.
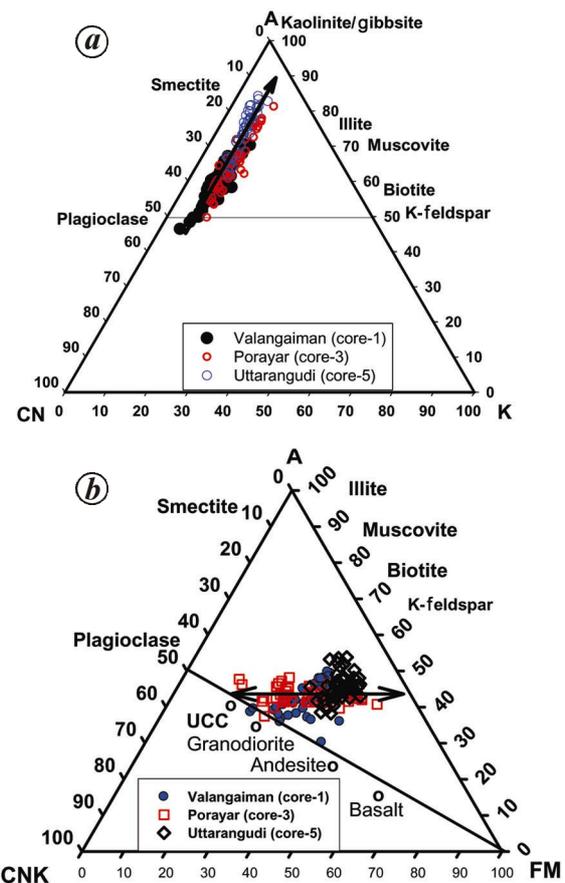
Figure 7. A–CN–K (*a*) and A–CNK–FM (*b*) diagrams showing the common primary and secondary minerals and weathering trends of sediments. Note that a trend parallel to A–CN (*a*) indicates little loss of K and moderate loss of Ca and Na. The trend parallel to CNK–FM (*b*) indicates little effect of weathering and more mineral sorting resulting in varying proportion of feldspar and mafic minerals.
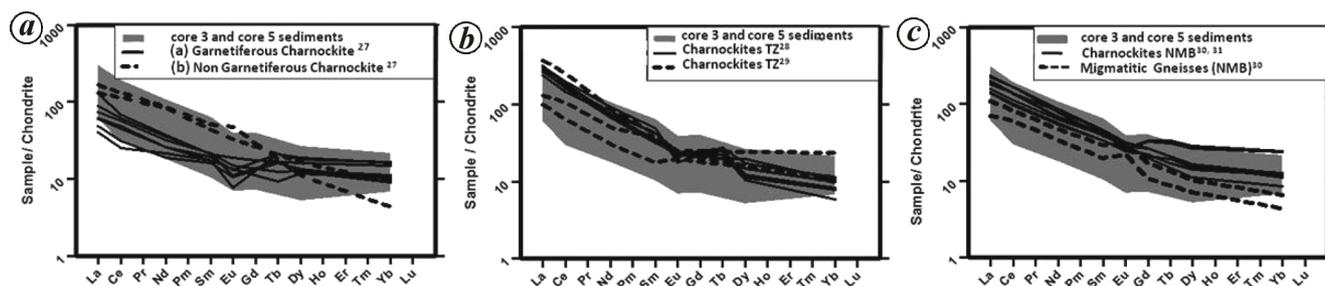
Figure 8. Chondrite normalized REE plot for sediments from cores 3 and 5 along with the plot of different catchment rocks from (*a*) Nilgiri hills[27], (*b*) Biligirirangan hills[28,29] and (*c*) Kodaikanal and Palani hills of Northern Madurai Block (NMB)[30,31]. Note the inferred source rocks are within the REE range for sediments (grey shade) and are similarly fractionated.

examined by the relationship between alkali and alkaline earth elements such as Na_2O, K_2O and CaO, and Al_2O_3 in the silicate phases. Nesbitt and Young[24] proposed a parameter known as the chemical index of alteration (CIA) to quantify the degree of feldspar weathering (CIA = $[Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$, where CaO^* is the amount of CaO incorporated in the silicate fraction of rocks). The measured values of CIA in the core samples vary between 50 and 75, which indicate low to moderate degree of chemical weathering. It is observed that the coarser sediments have lower CIA values, whereas the finer sediments have higher CIA values. This indicates that the variation in the CIA values may be because of mineral sorting. To evaluate feldspar weathering, we plot the geochemical measurements as A–CN–K ternary diagram (Figure 7 *a*). In this plot, A, CN and K represents the molar proportions of Al_2O_3, $CaO + Na_2O$ and K_2O respectively. A trend parallel to the A–CN line suggests that only plagioclase among feldspar had weathered resulting in the loss of some amount of CaO and Na_2O, whereas weathering of K-feldspar seems to be insignificant. Additionally, trend line starts from almost unweathered value of 50 to moderately weathered value of ~70, which suggests that the variations observed in the CIA values are due to mineralogical sorting and the actual value of CIA of the sediments should be between the two extreme cases. Similar results were obtained earlier by Singh and Rajamani[25] on sediment samples of the mid-Holocene from the middle reaches in the same area.

To further understand the effect of sorting in addition to weathering, these sediments are plotted in the A–CNK–FM diagram (here A, CNK and FM represent the molecular proportion of Al_2O_3, $CaO^* + Na_2O + K_2O$ and $FeO + MgO$ respectively). This diagram helps in understanding the weathering and sorting-related changes involving Fe–Mg-bearing minerals[24,26]: sediments showing a trend away from the CNK–FM line indicate weathering, whereas a trend parallel to this line indicates sorting. In the A–CNK–FM diagram (Figure 7 *b*), sediments exhibit overall trend line parallel to the CNK–FM line, suggesting negligible influence of Al. Observed variation is mainly due to the change in the relative proportion of CNK and

FM, whereas Al does not vary significantly. This would suggest that the trend is mainly due to varying proportion of feldspar and mafic minerals, i.e. mineral sorting.

The earlier study by Singh and Rajamani[25] and results (M. Z. Ahmad, unpublished) on the concentration of rare earth elements (REE) (Figure 8) carried out on these cores suggest that the sediments in the Cauvery delta have origin primarily from the Biligirirangan and Kodaikanal–Palani hills, with some contributions from Nilgiri hills and shear zones separating these hills, all forming part of the Southern Granulite Terrain.

All the inferred sources of sediment discussed above lie in the rain-shadow zone in the Western Ghats. Perhaps due to the winds and rainfall during northeast monsoon, unweathered regolith cover over these hilly terrains having immature topography was rapidly eroded. Moreover, short distance between the catchment and delta region helped in retaining the primary nature of the minerals and therefore sediments in the Cauvery delta have the required nutrients along with the loamy texture resulting in the formation of fertile farmlands. High-energy suspended and dissolved loads in the Cauvery river would have regularly recharged the fresh fertile sediments to sustain highly productive agriculture for a long time. Lastly, the beginning of the legendary Chola kingdom was also probably governed by the above delta-forming processes that led to the filling of incised plain making it suitable for sustained agriculture activity.

Conclusions

This study indicates that the present farmland on the Cauvery delta was formed during the Holocene in response to the sea-level rise after the LGM. The chronostratigraphic correlation between the cores reveals that the northern part of the Cauvery delta has accumulated maximum sediments during the Holocene. Thickness of the sediments is found to decrease from north to south. The bathymetry of the shelf adjoining the delta indicates higher gradient in the northern part, which changes gently towards the south. This would have diverted the channels towards the northern part where it eroded to a greater depth in an attempt to re-establish the equilibrium profile

in response to lowering of the base level during the LGM. The chronology of the sediment cores suggests that deposition of younger sediments in the present delta plain resumed only when deglaciation started after the LGM, leading to sea-level rise and marine transgression that has left its imprint in form of paleo beach ridges over the present delta plain.

The presence of plagioclase and dominance of 2 : 1 clay in the sediments deposited during the Holocene suggest weathering-limited provenance, perhaps due to rapid erosion of rocks from the southern mountains – Nilgiri–Kodaikanal–Palani–Biligirirangan hills. The geochemical results also suggest Southern Granulite Terrain as the dominant source for the sediments in the Cauvery delta.

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