$^{10}Be/^{9}Be$ ratios of Cauvery river delta sediments, southern India: implications for palaeo-denudation rates in the catchment and variation in summer monsoon rainfall during Late Quaternary

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Present and past denudation rates (D) of the Cauvery river catchment determined using meteoric $^{10}Be/^{9}Be$ on drill-core sediment samples from Uttarangudi and Valangaiman sites in the delta vary from 18.7 ± 1.6 to 48.1 ± 8.3 t/km^2/a. The present day denudation rates of 37.7 ± 4.9 t/km^2/a and 36.9 ± 5.2 t/km^2/a estimated for these sites are higher by a factor of two than that based on solute and suspended load of the Cauvery river. Denudation rates estimated using $^{10}Be/^{9}Be$ (reactive) is more accurate as it is not affected by damming of rivers. Based on ^{9}Be fraction (reactive + dissolved) and previous studies, we infer that sediments for Valangaiman site were mainly sourced from Western Ghats and Mysore plateau, whereas highlands bordering southwestern margin of the delta mostly supplied sediments to the Uttarangudi site. The Western Ghats and the delta received rainfall mainly during summer monsoon and NE monsoon respectively. Comparison of palaeo-denudation rates with various proxies of the Indian summer monsoon shows inverse relationship between them. Lower denudation rates are estimated for Early to Mid-Holocene period which is characterized by intense rainfall. Drier conditions after 4.5 ka BP caused increase in denudation rates after 2.5 ka BP for the Valangaiman core, consistent with a response time of 2 ka required to change $^{10}Be/^{9}Be$ in sediments of the Cauvery basin.

Keywords: Cauvery delta, denudation rate, Holocene, meteoric $^{10}Be/^{9}Be$, sediment cores, summer monsoon.

DENUDATION of mountains by rivers is an important process that moderates climate through removal of atmospheric CO_2, causes uplift of mountains and supplies sediments to form floodplains as well as deltas and solutes and nutrients to oceans[1–6]. Therefore, determining past denudation rates will be useful to understand variations in climate and uplift history of mountains. The present as well as past denudation rates of river catchments can be reliably estimated using the cosmogenic nuclide, ^{10}Be (refs 7, 8). Cosmic rays cause spallation reactions with atoms of various elements present in the atmosphere and rocks at the Earth's surface which produce cosmogenic nuclides, such as, ^{10}Be and ^{26}Al that are known as meteoric and *in situ* variety respectively. Meteoric flux of ^{10}Be from the atmosphere is $1.21 \pm 0.26 \times 10^6$ atoms/cm^2/a (ref. 9) whereas, *in situ* ^{10}Be production rate at the Earth's surface is 6 atoms/g(quartz)/a at sea level and geomagnetic latitude >50°, where a = y = year (ref. 10). Meteoric ^{10}Be gets attached to dust and aerosol and is removed from the atmosphere due to dry and wet precipitation followed by accumulation in soils and sediments. Therefore, its concentration in the surface sediments is much higher than *in situ* produced ^{10}Be in quartz. Beryllium present in trace quantities in rocks is mostly made up of ^{9}Be and it is released to river and groundwater due to weathering. von Blanckenburg *et al.*[11] suggested that both ^{10}Be deposited from the atmosphere and ^{9}Be released from weathering combine and get attached or adsorbed to fine-grained sediments as well as get chemically precipitated along with Fe–Mn oxy-hydroxides that form coatings over sediment grains. However, the *in situ* ^{10}Be produced in quartz (and other silicate minerals) can be released only when it is fully dissolved and therefore does not participate in the above surface reactions. Even in case of partial dissolution of quartz ^{10}Be released is insignificant compared to ^{10}Be reactive fraction. Thus $^{10}Be/^{9}Be$ ratios of adsorbed and precipitated species of sediments deposited in flood plains, deltas and marine depositional systems potentially archive information on rate of denudation and weathering[12].

^{10}Be in authigenic phases of soil profile to determine the age and denudation rates has been studied[13–16]. It was

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proposed[17] that meteoric ^{10}Be adsorbed on fine-grained soil and sediment particles can be used to estimate their ages and erosion rates. These are subject to uncertainties, as concentration of adsorbed ^{10}Be in soil profile or in river sediments is dependent on their grain size and other chemical properties particularly, Eh–pH variations[18]. To circumvent this, a set of mass balance equations was developed[11] which can be applied to reconstruct global palaeo-denudation rates from sedimentary records. von Blanckenburg and Bouchez[19] studied the applicability of ^{10}Be/^{9}Be to determine variations in palaeo-denudation rates up to 10 Ma in marine sediments. Palaeo-denudation rates were estimated[12] using ^{10}Be/^{9}Be of authigenic marine sediments. Using a similar approach, ^{10}Be/^{9}Be ratios determined on drill core samples of fluvial sediments formed in deltas and flood plains can be used to determine palaeo-denudation rates in river catchments. In this study the present and palaeo-denudation and erosion rates are estimated for the Late Quaternary period using ^{10}Be/^{9}Be ratios on sediment core samples from Uttarangudi and Valagaiman sites in the Cauvery delta of southern India following the theoretical framework outlined by von Blanckenburg *et al.*[11].

Theoretical background

Determination of denudation rate in Cauvery catchment

Sources of ^{10}Be in river basin sediments are meteoric (atmospheric ^{10}Be fall out) and *in situ* production and as the latter is negligible compared to the meteoric flux $F_{\text{met}}^{^{10}\text{Be}}$, its effect on ^{10}Be/^{9}Be ratios in dissolved fraction will be negligible[17]. $F_{\text{met}}^{^{10}\text{Be}}$ ranges from 0.4 to 1.5 × 10^6 atoms/cm^2/a and its value for a given area can be obtained from fallout maps[20,21]. A certain fraction of ^{10}Be atoms delivered to the Earth's surface is adsorbed on to mineral surfaces or co-precipitates with Fe- and Al-oxides or hydroxides that coat mineral grains. This ^{10}Be pool exchanges with dissolved ^{10}Be through dissolution–precipitation or desorption–adsorption reactions and is thus called 'reactive' (^{10}Be$_{\text{reac}}$) and the remaining ^{10}Be atoms are transported in dissolved condition (^{10}Be$_{\text{diss}}$). ^{9}Be present in bedrock minerals (^{9}Be$_{\text{parent}}$) is released to water due to chemical weathering. The released ^{9}Be that adsorbs onto mineral surfaces or incorporated into precipitates are called as ^{9}Be$_{\text{reac}}$. ^{9}Be that remains in solution, known as ^{9}Be$_{\text{diss}}$, is exported as dissolved material into water. The fraction of ^{9}Be that remains locked in mineral is called as ^{9}Be$_{\text{min}}$ (ref. 11). Average concentration of ^{9}Be in upper continental crust was estimated at 2.5 ± 0.5 ppm (refs 22, 23) and revised to 2.2 ± 0.5 ppm by Rudnick and Gao[24]. The catchment of river Cauvery is predominantly made up of tonalite, trondjhemite and granodiorite (TTG) gneisses, granites and granulites. Representative samples (n = 14) from different locations were analysed for ^{9}Be$_{\text{parent}}$ using ICP-MS after complete digestion. The Be abundance ranges from 0.67 to 6.56 ppm and the average value of 2.13 ppm is indistinguishable from the continental crust value which is used to estimate denudation rates.

Pattanaik *et al.*[25] reported pH for various tributaries and main course of the river Cauvery, which ranges from 7.4 to 8.8. Hence, the partition co-efficient K_{d} (in l kg^{-1}) value for Be is 10^6 l/kg (for pH > 7) which suggests that dissolved Be flux will be insignificant. The annual fallout of ^{10}Be for various places in India varies from 0.31 × 10^6 to 2.73 × 10^6 atoms/cm^2/year and for Bengaluru, southern India, the value is 0.6 × 10^6 atoms/cm^2/year (ref. 26). Absolute rates of denudation (D) and erosion (E) determined will depend on the flux of ^{10}Be (meteoric) deposited in catchment of a river. Based on global atmospheric model, Heikkila and von Blanckenburg[27] have given ^{10}Be flux distribution for the whole Earth. Average ^{10}Be meteoric flux for the entire Cauvery basin (1.6 × 10^{10} atom m^{-2} year^{-1}) was calculated based on the pre-industrial model given by the above authors. Denudation rates at different depths can be determined using the equations of von Blanckenburg *et al.*[11] that are appropriate for the geological settings of the Cauvery basin

$$\left(\frac{^{10}\text{Be}}{^{9}\text{Be}}\right)_{\text{reac}} = \left(\frac{^{10}\text{Be}}{^{9}\text{Be}}\right)_{\text{diss}} = \left(\frac{F_{\text{met}}^{^{10}\text{Be}}}{D*[^{9}\text{Be}]_{\text{parent}}}\left(\frac{^{9}\text{Be}_{\text{min}}}{^{9}\text{Be}_{\text{reac}}}+1\right)\right)\Bigg/ \left(1+\frac{Q}{K_{\text{d}}}*\frac{^{9}\text{Be}_{\text{min}}}{D*[^{9}\text{Be}]_{\text{parent}}}\right), \quad (1)$$

where (^{10}Be/^{9}Be)$_{\text{reac}}$ = ratio of number of atoms of ^{10}Be and ^{9}Be in the reactive species (adsorbed or chemically precipitated); (^{10}Be/^{9}Be)$_{\text{diss}}$ = ratio of concentrations of ^{10}Be and ^{9}Be in river water; $F_{\text{met}}^{^{10}\text{Be}}$ = meteoric ^{10}Be flux for the catchment; ^{9}Be$_{\text{parent}}$ = concentration of ^{9}Be in the sediments; ^{9}Be$_{\text{min}}$ = concentration of ^{9}Be in the sediment after removal of ^{9}Be reactive species by leaching; ^{9}Be$_{\text{reac}}$ = concentration of ^{9}Be in reactive species (adsorbed or precipitated); K_{d} = Concentration of Be in reactive species/concentration of Be in dissolved species; D = Denudation rate (in t/km^2/y); and Q = Water flow rate (in m^3 m^{-2} y^{-1} or in m y^{-1}).

But when

$$\frac{Q}{D} \ll K_{\text{d}} *[^{9}\text{Be}]_{\text{parent}} /[^{9}\text{Be}]_{\text{min}},$$

the denominator part can be considered as 1 and the equation gets modified to

$$\left(\frac{^{10}\mathrm{Be}}{^{9}\mathrm{Be}}\right)_{\mathrm{reac}} = \left(\frac{^{10}\mathrm{Be}}{^{9}\mathrm{Be}}\right)_{\mathrm{diss}} = \frac{F_{\mathrm{met}}^{^{10}\mathrm{Be}}}{D^{*}[^{9}\mathrm{Be}]_{\mathrm{parent}}}\left(\frac{[^{9}\mathrm{Be}]_{\mathrm{min}}}{[^{9}\mathrm{Be}]_{\mathrm{reac}}}+1\right). \quad (2)$$

For Uttarangudi and Valangaiman sites the water flow rate (Q) is very low while K_d is high, i.e. 1×10^6. Hence we calculated the denudation rate by using eq. (2) proposed by von Blanckenburg *et al.*[11]. ^{10}Be/^{9}Be ratios on sediment samples provide denudation rates of the river catchments, whereas ^{10}Be concentrations on reactive phases provide information about the erosion rates. Erosion rates can be estimated[11] as

$$E = \frac{F_{\mathrm{met}}^{^{10}\mathrm{Be}}}{[^{10}\mathrm{Be}]_{\mathrm{reac}}} - \frac{Q}{K_{\mathrm{d}}}, \quad (3)$$

where E is the rate of erosion of the catchment by chemical weathering (in t/km^2/y). This equation gets simplified to

$$E = \frac{F_{\mathrm{met}}^{^{10}\mathrm{Be}}}{[^{10}\mathrm{Be}]_{\mathrm{reac}}}, \quad (4)$$

for the settings where $Q/D \ll K_d$ (ref. 11). The eqs (1) and (4) are used in this study to estimate denudation and erosion rates respectively, in the Cauvery catchment.

The fraction of ^{9}Be released during weathering of parent rock is given by von Blanckenburg *et al.*[11] as

$$f_{\mathrm{reac}}^{^{9}\mathrm{Be}} + f_{\mathrm{diss}}^{^{9}\mathrm{Be}} = \frac{1}{\left[\left(\frac{^{9}\mathrm{Be}_{\mathrm{min}}}{^{9}\mathrm{Be}_{\mathrm{reac}}}\right)+1\right]}. \quad (5)$$

Above equation is useful in estimating the extent of chemical weathering.

Regional settings

Cauvery river is one of the major rivers of southern India and its basin covers an area of 87,900 km^2 between lat. 10°7′N–13°28′N and long. 75°28′E–79°52′E. The river and its major tributaries originate from the Western Ghats (Figure 1) at an elevation of 1000 to 2000 m amsl and travels ~800 km over the Mysore plateau towards southeast and plains of Tamil Nadu that are made up of different Precambrian terrains to join the Bay of Bengal[28–31]. Formation of Western Ghats due to uplift around 88 Ma ago[32] resulted in easterly tilt of peninsular India and developed various eastward flowing river systems like Cauvery.

The upper ~300 km of the river flows through a relatively flat landscape which is on an average 800 m amsl, middle ~100 km passes through narrow passes and water falls at Shivasamudram and Hogenakkal and finally lower ~400 km passes through plains and drains into the Bay of Bengal. Upper reaches of Cauvery river catchment flows through Archean greenstone–granite terrains, minor granulites and dykes of Paleoproterozoic age of Dharwar craton[32]. Middle reaches comprise exposure of granulites and migmatitic gneisses consisting of plagioclase, quartz, orthopyroxene, garnet and biotite[33]. In the lower reaches thick sequences of Cretaceous sediments consisting of calcareous sandstone, limestone, marlstone and shale are exposed[25].

The river starts branching at Tiruchirapalli depositing a thick sequence of sediments that forms the fertile Cauvery delta (~6566 km^2). The quarternary sediments of the Cauvery delta are underlain by tertiary and mesozoic sediments and Archean–Proterozoic crystalline rocks. In the western part of the delta, Cretaceous sediments (Uttatur, Ariyallur and Tiruchirrapalli Formation) and sandstone (Cuddalore Formation) of Mio-Pliocene age[34] are exposed. The southern part of Cauvery delta is prominently marked by Mio-Pliocene sandstone in Mannargudi–Vallam area in the west and intensely dissected sandstone in Pattukottai area in the east[35].

The Cauvery river basin experiences a semi-arid, tropical humid and sub-humid climate. Annual mean temperature is 26°C. Maximum temperature at summer reaches up to 41°C (March–May) whereas in winter it may fall to 13.5°C in the upper reaches. Both southwest or Indian summer monsoon (June–September) and northeast or winter monsoon (October–December) are responsible for the bulk of rainfall in the Cauvery basin. However, the upper catchment represented by Western Ghats receives annual rainfall of ~2500 mm of which more than 80% of rainfall occurs during the summer monsoon and the remaining during northeast monsoon and pre-monsoon[36–38]. The western part (Mysore plateau) also receives maximum rainfall from SW monsoon and contributes more than 80% of annual flow and sediment load in Cauvery. Middle and lower reaches of the river receive more rainfall during the NE monsoon. Sediment load of 681×10^3 t/a gets suddenly reduced to 15.6×10^3 t/a due to storage of water at Mettur Dam[25]. The suspended sediment load was mostly deposited in the flood plain and contributed to the growth of the delta prior to construction of several major and many minor dams across the river.

Ramasamy *et al.*[35] observed that the Cauvery delta experienced several tectonic activities during the Quaternary and occurrence of several palaeo-channels indicated multiple migrations of the main Cauvery river from south to north in an anti-clockwise direction. This also resulted in uplift of Manargudi–Vallam area along the western part of the delta. During the Last Glacial Maxima (LGM), the sea level dropped approximately by 125 m which resulted in shifting of the coastline and delta depo-centre. Subsequent sea level rise brought back deposition of sediments in the delta.

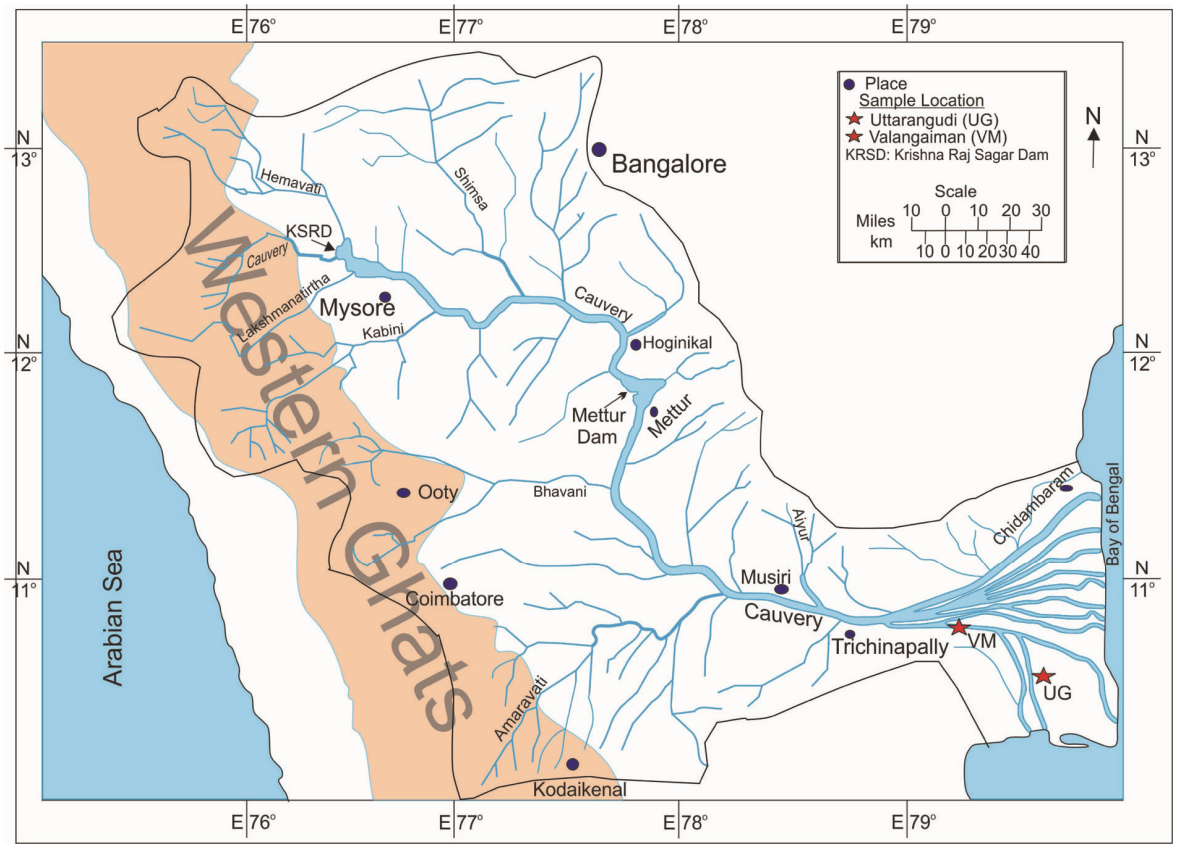

Figure 1. Map of the Cauvery river basin showing tributaries and catchment region[25]. The Cauvery and its major tributaries originate from the Western Ghats of southern India. VM and UG are sites for Valagaiman and Uttarangudi cores.

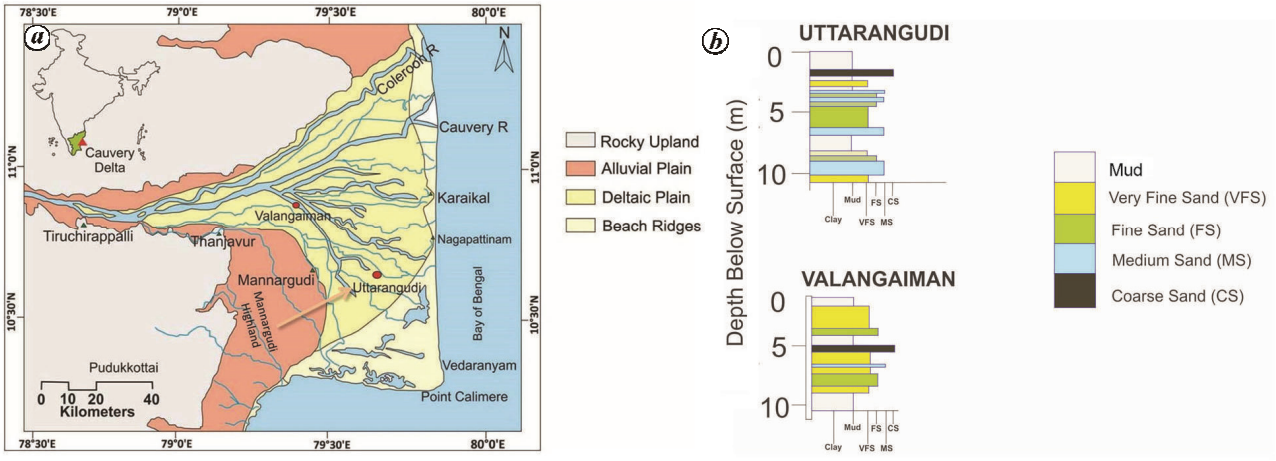

Figure 2. ***a***, Map of the Cauvery delta showing the river and its distributaries. Valangaiman and Uttarangudi core sites are indicated[34]. Sediment cores up to a depth of 10 m and 8.5 m are taken from Uttarangudi and Valangaiman sites which were used in this study. The arrow indicates that Mannargudi–Vallam highlands supplied sediments to the Uttarangudi area influenced by NE monsoon during the Quaternary. ***b***, Litholog of the sediment cores collected from Uttarangudi and Valangaiman sites[39] and the sampled depths are indicated.

The Manargudi highland receives rainfall mainly during NE monsoon and supplies sediments to the delta region near Uttarangudi site (Figure 2 *a*). Delta near Valangaiman site located at the proximal part receives sediments from Western Ghats and Mysore Plateau experiencing high rainfall essentially due to summer (SW) monsoon. The presence of thin channels towards the north of Manargudi highland does not allow movement of sediments towards Valangaiman. Hence, the sediments from the Valangaiman core record events that took place

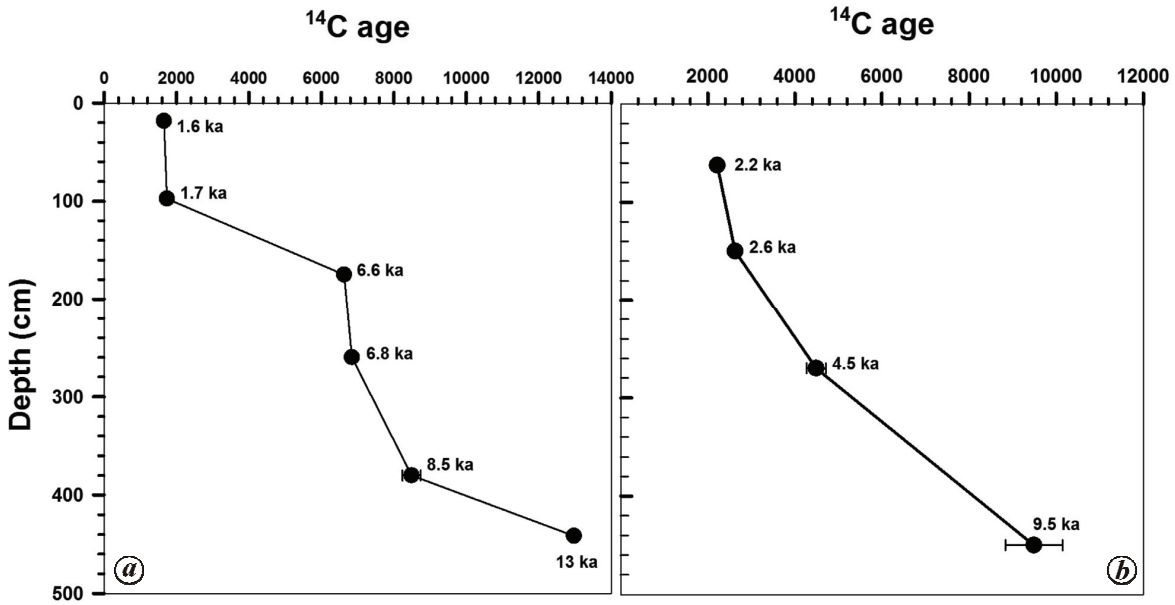

Figure 3. Calibrated ^{14}C ages in ka before present (BP)[39] are plotted against different depths for (***a***) Uttarangudi and (***b***) Valagaiman cores and interpolated ages are calculated for the corresponding depths that were sampled for this study.

in the upper and middle Cauvery catchment. Thus, these two sites receive sediments from distinct sources that receive rainfall under different monsoons.

Materials and methods

Sampling and materials

Among the eight sediment cores collected from the Cauvery delta, two were selected for this study as age of deposition has been determined for them using different methods. Uttarangudi (10°39′17.7″N; 79°39′42.2″E) is located in the southern periphery of the Cauvery delta, towards north of Thiruthuraipoondi. Valangaiman (10°52′51.4″N; 79°23′38.1″E) is located in the central part of the delta, south of Kumbakonam (Figure 2 *a*). The uppermost part of the Uttarangudi (total core depth 55 m) core contains clay, silt and organic matter whereas, deeper part consists of fine to medium sand with occasional layer of coarse sand and lateritic pebbles. Valangaiman core contains upper fine sand, middle clay and lower sand and pebble layer (Figure 2 *b*). Details of the cores are described by Alappat *et al.*[34]. Twelve samples from Uttarangudi core and eight from Valangaiman core were taken from different depths for the present study.

Ages of Cauvery delta sediment cores were determined using ^{14}C (Figure 3) and Optical Stimulated Luminescence (OSL) methods. Calibrated ^{14}C ages of Uttarangudi core samples were 1.65 ± 0.05, 1.73 ± 0.12, 6.84 ± 0.12, 8.48 ± 0.25 and 12.97 ± 0.06 cal ka BP for depths 17–20, 88–108, 250–270, 370–390 and 440–443 cm respectively (Figure 3 *a*, Singh *et al.*[39]). Calibrated ^{14}C ages are 2.2 ± 0.09, 2.6 ± 0.02, 4.5 ± 0.2, 9.4 ± 0.6 cal ka BP for depths 55–70, 140–160, 260–280 and 440–460 cm respectively for the Valangaiman core[39] (Figure 3 *b*). At depths of 305, 913, 1358 cm of Uttarangudi core, the fading corrected OSL ages on K-feldspar are 4 ± 1, 193 ± 28 and 212 ± 31 ka respectively. Alappat *et al.*[34] have in addition derived OSL ages for depths 91 and 470 cm as 0.8 ± 0.1 and 108 ± 14 ka respectively.

Chemical procedure

Samples were dried at 80°C for removal of moisture and made to a fine powder and homogenized using agate mortar and pestle. Brown *et al.*[40] and Graham *et al.*[41] suggested that 90% of authigenic and adsorbed Be can be extracted by leaching sediments with concentrated hydrochloric acid. Shibata *et al.*[42] compared yield efficiencies of leaching sediment samples with oxalic acid–ammonium oxalate, hydroxylamine–hydrochloride and hot 8 N hydrochloric acid and found that maximum amount of ^{10}Be can be extracted with hot 8 N HCl acid. In this study, precisely weighed samples of about 1 g were first treated with 2 ml of 30% H_2O_2 for 4 h to remove organic matter and then leached at 25°C in centrifuge tubes with 10 ml of 9 N HCl for 12–14 h to extract maximum amount of ^{10}Be and ^{9}Be of the reactive species. Samples were centrifuged and washed 3 times and the liquid part was collected, filtered and dried. Dried samples were made to 10 ml volume by adding 1N HCl and MilliQ® water. One ml aliquot was taken to measure natural $^{9}Be_{reac}$ using ICP-AES and repeated with ICP-MS and the remaining 9 ml was spiked with 0.1 g of ^{9}Be carrier and

dried. The residue was completely digested with HF and HNO_3 acids and diluted to determine $^9Be_{mineral}$ using ICP-MS. Wittmann *et al.*[18] used milder reagents, 0.5 N HCl, hydroxylamine–hydrochloride to extract authigenic and adsorbed Be from the sediments. Treating samples with 9 N HCl acid could have partially dissolved silicate minerals and thereby increased ^{9}Be concentration. However, solubility of silicate minerals in 9 N HCl acid at room temperature is negligible and it may not have significantly increased the concentration of ^{9}Be of the reactive species. Even if a small amount of ^{9}Be from silicates was leached, as all the samples were treated with 9 N HCl, the relative down-core variations in ^{10}Be/^{9}Be ratios of sediment samples will not be affected.

Rate of production of *in situ* ^{10}Be in quartz is several orders lower than meteoric variety for a given location. Even if zero erosion rate and saturated condition are assumed, the *in situ* ^{10}Be abundance will be about 100 times lower than the meteoric variety[43] and hence partial release of this while leaching with HCl acid will not affect the ^{10}Be reported. However, sediment sorting effect may influence the distribution and as this data is not available, we use the ^{10}Be abundance only for determining the denudation rate.

The chemical separation of Be from leached fractions was carried out with suitable modifications of procedures described earlier[44,45]. Samples were dissolved in 4 ml of 6 N HCl and loaded to anion exchange column (Bio-Rad, AG 1X8, 200–400 mesh) and collected in 6 ml of 6N HCl and dried. Maximum Fe along with Co and Ti ions were separated in anion exchange column which reduces the matrix. Again it was loaded in cation exchange column (Bio-Rad, AG-MP resin, 200–400 mesh) in 0.2 M H_2SO_4 + 2% H_2O_2 and Be was collected in 45 ml of 1.2 N HCl. The dried samples were dissolved in 1N HCl followed by 9 ml of MilliQ® water and carefully collected in centrifuged tubes. NH_4OH was added slowly and Be was precipitated as $Be(OH)_2$ at 7–8 pH which was collected in quartz vials and converted to BeO powder by stepwise heating and keeping at 900°C for 8 h (ref. 45). BeO was mixed with Nb powder in 1 : 3 ratio by weight and loaded into ion source of the AMS system[45].

AMS measurement

AMS measurements were performed at the Inter University Accelerator Center (IUAC), New Delhi. The details of the measurement technique are described in Kumar *et al.*[45]. Standard reference material (SRM 4325) procured from National Institute for Standards and Technology (NIST), USA, was used as standard sample. The blank, prepared following the same protocol as that of sediment samples, was also measured and its value in this measurement was 7.47×10^{-14}. However, typical blank values for IUAC AMS facility are for the blank prepared with ^{9}Be solution procured from NIST standard reference material (SRM) 3105a, which is ~7×10^{-15} or better[45]. In this particular experiment the blank values were one order of magnitude higher, which could be due to various factors such as chemical processing for separation of Be and accelerator conditions, etc. However, ^{10}Be/^{9}Be ratios measured for all the samples were in the range of 10^{-11} and therefore, blank correction was very small, which was carried out on measured ^{10}Be/^{9}Be ratios.

Radioactive and ^{10}Be flux corrections

Radioactive decay correction was made and found to have little effect on concentration of ^{10}Be atoms from these cores as the half-life of ^{10}Be (refs 46, 47) ($T_{½}$ = 1.387 Ma) is much higher than the age of deposition of sediments studied (maximum age ~200 ka). However, applying correction for past variation in ^{10}Be flux is more complex. Frank *et al.*[48] studied variation in global ^{10}Be production rate in last 200 ka on marine sediments and proposed a model for its past variation assuming constant solar activity. Christl *et al.*[49] reconstructed global ^{10}Be production rate over the past 250 ka on the marine core samples from high accumulation environment of North, North-west and South Atlantic Ocean. In this study, flux corrections were not applied for sediments up to Holocene as the variation in the ^{10}Be production rate was found to be negligible compared to the present day[48]. For Uttarangudi core samples UG503, UG622 and UG803 with interpolated OSL ages 17.5 ka, 180 ka and 188 ka respectively and Valangaiman core samples, VM460-465 and VM600-605 with interpolated OSL age of 108 and 110 ka respectively (correction factors (flux factor)) were applied (Table 1) using the model given by Frank *et al.*[48]. For these ages ^{10}Be flux correction factors were determined from Figure 4 *a* given in Frank *et al.*[48] where the present-day ^{10}Be production rate was assumed as 1.

^{10}Be Production rate at time t = flux correction factor at t × present day production rate.

The correction factor for age t was calculated by averaging flux factor for integration time. Integration time varied from 10,000 years to 2,500 years which was calculated assuming an average soil thickness of 1 m and denudation rate initially estimated for that sample[50].

Results

Uttarangudi

^{10}Be/^{9}Be ratios vary from $7.17 \pm 0.14 \times 10^{-9}$ to $2.9 \pm 0.38 \times 10^{-10}$ whereas, ^{10}Be concentration varies from $1.38 \pm 0.19 \times 10^{10}$ atoms/kg to $3.82 \pm 0.48 \times 10^{11}$ atoms/kg (Table 1). ^{10}Be concentration increased from the surface up to a depth of 45 cm and then decreased continuously up to 622 cm depth except at 503 cm. From 622 cm an abrupt fall of ^{10}Be concentration

Table 1. $^{10}Be/^{9}Be$ ratio on sediment core samples of Uttarangudi and Valangaiman cores from Cauvery delta, South India. Present and past denudation (D) rates in the river catchment were estimated using equations given in von Blanckenburg *et al.*[11]. Concentrations of $^{9}Be_{reac}$ and $^{9}Be_{min}$ along with $f(^{9}Be_{reac} + {}^{9}Be_{min})$ and Flux factor for respective samples are given. ^{14}C and OSL ages for different depths are from Singh *et al.*[39] and Allapat *et al.*[34]

Av. depth (cm)	Sample weight	Age (ka)	Flux correction factor[@]	Corrected flux ($\times 10^{10}$)	$^{9}Be_{reac}$ (atoms/ kg $\times 10^{19}$)	$^{9}Be_{min}$ (atoms/ kg $\times 10^{19}$)	$^{10}Be/^{9}Be$ ($\times 10^{-11}$) measured	$^{10}Be/^{9}Be$ ($\times 10^{-9}$) (carrier and decay corrected)	^{10}Be (atoms/ kg $\times 10^{11}$)	$f(^{9}Be_{reac} + {}^{9}Be_{diss})$	D(t/km^2/y)
Uttarangudi											
0.001	0.97423	0.00	1.00	1.60	3.72 ± 0.15	3.25 ± 0.13	2.9 ± 0.38	5.60 ± 0.73	2.08 ± 0.28	0.53 ± 0.03	37.7 ± 4.9
2	0.88005	0.15*	1.00	1.60	5.44 ± 0.22	4.56 ± 0.19	3.6 ± 0.55	5.23 ± 0.78	2.84 ± 0.44	0.54 ± 0.03	39.6 ± 5.9
22	0.89375	1.60*	1.00	1.60	5.42 ± 0.22	4.16 ± 0.17	4.1 ± 0.58	5.84 ± 0.82	3.16 ± 0.46	0.57 ± 0.03	34.1 ± 4.8
45	0.90693	1.68*	1.00	1.60	6.75 ± 0.28	4.62 ± 0.19	5.1 ± 0.61	5.66 ± 0.68	3.82 ± 0.48	0.59 ± 0.04	33.5 ± 4.0
101	0.94816	1.74*	1.00	1.60	5.46 ± 0.22	3.94 ± 0.16	4.7 ± 0.47	6.23 ± 0.62	3.40 ± 0.37	0.58 ± 0.03	31.1 ± 3.1
218	0.92087	6.8*	1.00	1.60	6.85 ± 0.28	4.40 ± 0.18	4.5 ± 0.63	4.88 ± 0.68	3.34 ± 0.49	0.61 ± 0.04	37.9 ± 5.3
358	1.0005	8.2*	1.00	1.60	2.31 ± 0.09	4.20 ± 0.17	2.4 ± 0.45	7.17 ± 1.40	1.65 ± 0.32	0.35 ± 0.02	44.4 ± 8.4
503	0.99896	17.5*	1.24	1.98	2.91 ± 0.12	4.00 ± 0.16	2.6 ± 0.16	6.11 ± 0.37	1.78 ± 0.13	0.42 ± 0.03	54.1 ± 3.2
622	1.00202	180**	1.33	2.12	4.78 ± 0.20	4.31 ± 0.18	0.2 ± 0.02	2.90 ± 0.04	0.14 ± 0.09	0.53 ± 0.03	982 ± 128
803	1.00205	188**	1.68	2.69	4.64 ± 0.19	4.35 ± 0.18	1.2 ± 0.14	1.86 ± 0.22	0.86 ± 0.11	0.52 ± 0.03	197 ± 24
1003	1.00317	196**	1.00	1.60	3.82 ± 0.16	4.56 ± 0.19	2.4 ± 0.36	4.67 ± 0.70	1.78 ± 0.28	0.46 ± 0.03	53 ± 8
Valangaiman											
2.5	1.0026	0.00	1.00	1.60	3.70 ± 0.15	3.72 ± 0.15	2.09 ± 0.29	3.85 ± 0.54	1.43 ± 0.21	0.80 ± 0.05	36.9 ± 5.2
72.5	1.00095	2.3*	1.00	1.60	2.95 ± 0.12	4.21 ± 0.17	1.30 ± 0.22	3.03 ± 0.52	0.90 ± 0.02	0.78 ± 0.05	48.1 ± 8.3
122.5	1.00227	2.5*	1.00	1.60	2.57 ± 0.11	3.85 ± 0.16	1.71 ± 0.22	4.56 ± 0.58	1.17 ± 0.16	0.79 ± 0.05	31.4 ± 4.0
207.5	1.00084	3.4*	1.00	1.60	2.94 ± 0.12	2.94 ± 0.12	2.92 ± 0.34	6.77 ± 0.78	1.99 ± 0.25	0.83 ± 0.05	20.1 ± 2.3
352.5	1.00115	6.8*	1.00	1.60	2.93 ± 0.12	2.47 ± 0.10	3.09 ± 0.27	7.08 ± 0.61	2.07 ± 0.20	0.86 ± 0.05	18.7 ± 1.6
462.5	1.00456	9.9*	1.00	1.60	2.01 ± 0.08	3.02 ± 0.12	1.91 ± 0.23	6.52 ± 0.80	1.31 ± 0.17	0.83 ± 0.05	20.9 ± 2.6
602.5	1.00136	110**	1.16	1.85	1.98 ± 0.08	2.77 ± 0.11	1.54 ± 0.24	5.22 ± 0.80	1.04 ± 0.16	0.84 ± 0.05	29.8 ± 4.6
842.5	1.00365	120**	1.12	1.79	1.82 ± 0.07	2.74 ± 0.11	1.22 ± 0.14	4.59 ± 0.52	0.834 ± 0.09	0.84 ± 0.05	32.8 ± 3.7

[@]Flux correction were made by multiplying $^{10}Be_{meteoric}$ present day flux value of 1.6×10^{10} atoms /m^2/y by the flux correction factor.
Flux correction factor is calculated based on the model for past flux variations given by Frank *et al.*[48].
* and ** represent interpolated ^{14}C and OSL ages respectively.

was observed. Denudation rates (D) calculated on samples from different depths and ages using the equation (2) of von Blanckenburg *et al.*[13] show a variation from 31.1 ± 3.1 to 54.1 ± 3.2 t/km^2/a except at depth of 622 cm and 803 cm where the value abruptly increased to 981.6 ± 127.6 and 197.1 ± 23.7 t/km^2/a respectively (Figure 4, Table 1). Denudation rates versus $^{10}Be/^{9}Be$ ratios were plotted and fitted in a model suggested by von Blanckenburg *et al.*[13] taking appropriate ^{10}Be flux values and bedrock $^{9}Be_{parent}$ concentration as 2.13 ppm (Figure 5 *a–d*). From these plots it is observed that ($f_{reac} + f_{diss}$) values for all samples fall between 0.4 and 0.6.

Valangaiman

$^{10}Be/^{9}Be$ ratios for Valangaiman core samples taken at different depths vary from $3.03 \pm 0.52 \times 10^{-9}$ to $7.08 \pm 0.61 \times 10^{-9}$ (Table 1). ^{10}Be concentration at different depths (or ages) of the core varies from $0.834 \pm 0.09 \times 10^{11}$ to $2.07 \pm 0.2 \times 10^{11}$ atoms/kg sediment. ^{9}Be (reactive) concentrations vary from $1.82 \pm 0.07 \times 10^{19}$ atoms/kg to $3.7 \pm 0.15 \times 10^{19}$ atoms/kg and do not show any particular trend in this core whereas, $^{9}Be_{min}$ concentrations vary from $2.47 \pm 0.10 \times 10^{19}$ to $4.21 \pm 0.17 \times 10^{19}$ atoms/kg at different depths (Table 1). Denudation rates (D) calculated on samples from different depths and ages were found to vary from 18.7 ± 1.6 to 48.1 ± 8.3 t/km^2/a for Valangaiman core (Figure 6, Table 1). ^{9}Be ($f_{reac} + f_{diss}$) value for most of the samples was above 0.6 and samples at depth 462.5 cm and 602.5 cm fall close to 1.0 (Figure 5 *e–g*).

Discussion

There is little possibility for enhancement of ^{10}Be concentration in sediments at deeper level due to precipitation from groundwater. Gopinath and Srinivasamoorthy[51] studied chemical parameters of ground water from 6 to 40 m depth from a number of wells (n = 122) around Nagapattinam and Karaikal region, part of the Cauvery delta and found that pH varies from 6 to 8.4 with an average value of 7.4. Therefore, dissolved Be flux in groundwater of the Cauvery delta can be assumed as negligible and the measured Be isotope abundances on core sediment samples were inherited from the catchment.

Denudation rates estimated on sediment core samples from both Uttarangudi and Valangaiman sites were similar to each other except for two samples of the

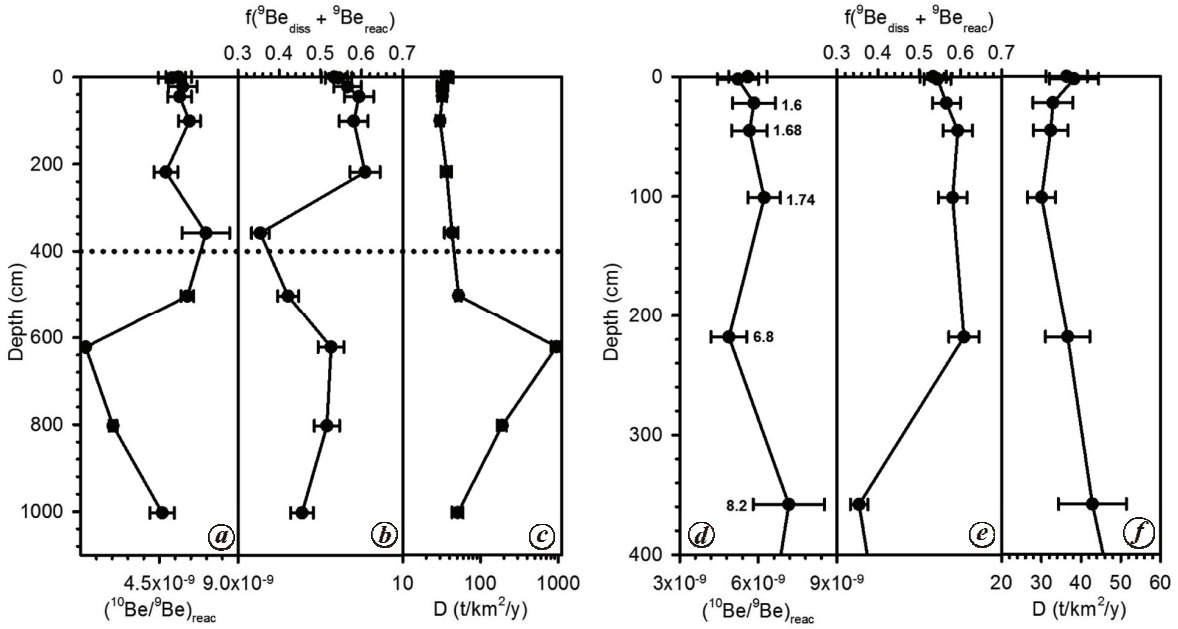

Figure 4. ***a–c***, Variation of $(^{10}Be/^{9}Be)_{reactive}$, ^{9}Be ($f_{dissolved} + f_{reactive}$), palaeo denudation (D) determined on sediment samples from a drill core at Uttarangudi as a function of age. Dotted line at depth of 400 cm represents ca. 10 ka BP. ***d–f***, Holocene part of the core is expanded and interpolated ages are indicated next to error bars in the panel *d*.

Uttarangudi core at depths of 622 and 803 cm that showed anomalously high values. The $^{10}Be/^{9}Be$ ratio depends on cosmic ray flux, decay of ^{10}Be and denudation rate. As cosmic ray flux and radioactive decay corrections are made on samples, variation of $^{10}Be/^{9}Be$ ratios could be attributed to changes in rate of denudation.

The interpolated OSL ages for 622 cm and 803 cm depths are 180 ka and 188 ka respectively, which are within Quaternary. During this period the Mannargudi area (Figure 2 *a*) had been affected by several tectonic activities and uplift which led to migration of main channel of Cauvery river[35]. Tectonic uplift might have caused sudden and excessive sediment influx from the Mannargudi uplands to the Uttarangudi site which resulted in dilution of ^{10}Be and low $^{10}Be/^{9}Be$ ratio. It is speculated that ^{10}Be can be used as a tracer for identifying sudden and increased sediment influx due to various reasons such as landslide, mudslide and uplift.

Present-day denudation rates of catchment obtained from surface sediments of Uttarangudi and Valangaiman sites are 37.7 ± 4.9 t/km^2/a and 36.9 ± 5.2 t/km^2/a respectively. Gaillardet *et al.*[3] and Pattanaik *et al.*[25] determined silicate weathering rates (SWR) as 27.2 t/km^2/a and 7.9 t/km^2/a respectively, based on solute load of the Cauvery river. Physical erosion rates (W_{ph}) also have been determined in some locations in Cauvery delta. Annual W_{ph} values at Musiri, Kodumudi and Urachikottai locations were determined as 6.1, 4.58 and 0.36 t/km^2/a respectively (Integrated Hydrological Data Book, 2007)[36]. Gaillardet *et al.*[3] determined denudation rates for Cauvery basin based on data given in Ramanathan *et al.*[28] which were not corrected for atmospheric and anthropogenic inputs. This could have led to higher estimation of denudation rate compared to Pattanaik *et al.*[25]. von Blanckenburg *et al.*[11] observed that denudation rate using meteoric ^{10}Be on Amazon and other rivers were a factor of almost 2 higher than the conventional methods. The D values determined in the present study is ~2.3 times that estimated by Pattanaik *et al.*[25]. The higher value could be due to differential weathering of various rock types in the source and difference in the integration times between meteoric $^{10}Be/^{9}Be$ and conventional methods as explained by Wittmann *et al.*[18]. The Cauvery river basin is highly populated and with intensive agricultural activities. Estimating the anthropogenic inputs into total dissolved solute (TDS) load is difficult which leads to error in estimation of D, whereas there is negligible anthropogenic contribution for ^{10}Be and hence D estimated for Cauvery catchment by this method is likely to be more accurate. Estimation of physical erosion rate depends on suspended sediment load of the rivers. Due to extensive damming of the Cauvery river and its tributaries the suspended sediment load is drastically reduced and the estimated W_{ph} rate will be much lower than the true value. However, denudation rate determined using $^{10}Be/^{9}Be$ ratios will be closer to actual values than that based on sediment load of rivers because damming of the river will not affect $^{10}Be/^{9}Be$ ratio. Hence, in this study the denudation rate estimated based on $^{10}Be/^{9}Be$ ratios is a little higher than those determined based on suspended sediment and solute loads carried by the Cauvery river.

Similar intensity of chemical weathering is observed for sediment samples of each core as inferred from ^{9}Be ($f_{reac} + f_{diss}$) values (Figure 5). The Valangaiman core

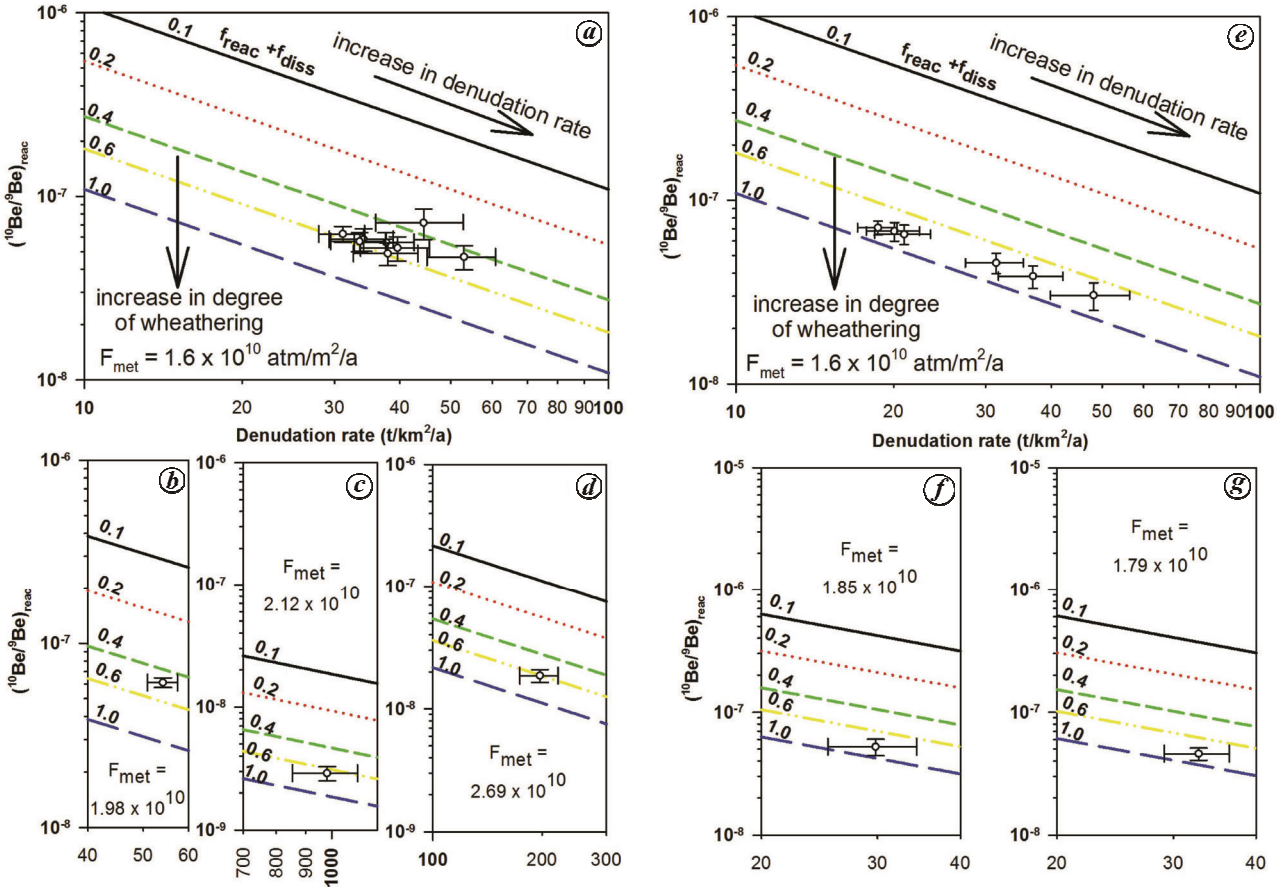

Figure 5. Denudation rate plotted against $^{10}Be/^{9}Be$ ratio[11] for ***a–d***, Uttarangudi and ***e–g***, Valangaiman cores. ^{10}Be flux (F_{met}) of 1.6×10^{10} atom m^{-2} $year^{-1}$ estimated based on the model for ^{10}Be depositional flux (preindustrial period) given by Heikkila and von Blanckenburg[27] used in *a* and *e*, while for *b*, *c*, *d*, *f* and *g*, F_{met} values corrected for the past variation in the flux indicated in respective plots were used. Uttaragudi sediment samples deposited during Holocene have ^{9}Be ($f_{dissolved} + f_{reactive}$) values around 0.5 while the Valagaiman samples have an average value of 0.8.

samples appear to have undergone higher extent of chemical weathering as they have higher ($f_{reac} + f_{diss}$) values (~0.8) than Uttarangudi core samples with ($f_{reac} + f_{diss}$) values of ~0.5 (Table 1, Figure 5). The extent of chemical weathering determined for the present day samples in this study is in broad agreement with those based on solute and suspended load of the Cauvery river by Gaillardet *et al.*[3] and Pattanaik *et al.*[25].

Relationship between denudation rate and past rainfall

Sediment deposition history of Uttarangudi and Valangaiman sites is different from each other. Valangaiman is located in the proximal part of the Cauvery delta close to one of the main channels of the river (Figure 2 *a*) and therefore, experienced continuous supply of river water and sediments from the Western Ghats catchment that receives rainfall mainly during the summer monsoon. But Uttarangudi is located in the distal part of the delta (Figure 2 *a*) and receives sediments from the Mannargudi highland only during flood time due to NE monsoon. Distinct range of ^{9}Be ($f_{reac} + f_{diss}$) values for the Uttarangudi and Valangaiman cores also suggest that sources of their sediments were different.

A variety of proxies based on continental and marine archives indicate intensification of Indian summer monsoon between 11 and 9 ka, an arid phase due to weakening of monsoon at around 4.5–3.5 ka and a brief intensification of monsoon 2.3 ka ago[52–58]. Past denudation rates estimated using meteoric $^{10}Be/^{9}Be$ ratio of sediments from the Valangaiman core of the Cauvery delta show relatively low denudation rate from Early Holocene to 2.5 ka BP and higher values during 2.5–0.5 ka BP compared to the present day. Intensification of the summer monsoon during the Early Holocene supported thick vegetation cover dominated by C3 type plants that covered the Western Ghats resulting in lower denudation rate. Whereas relatively drier phase leading to lower density of vegetation with increased proportion of C4 type plants caused higher denudation rates. However, there is a lag of about 2 ka between various proxies and ^{10}Be indicating start of weakening of the summer monsoon (drier period)

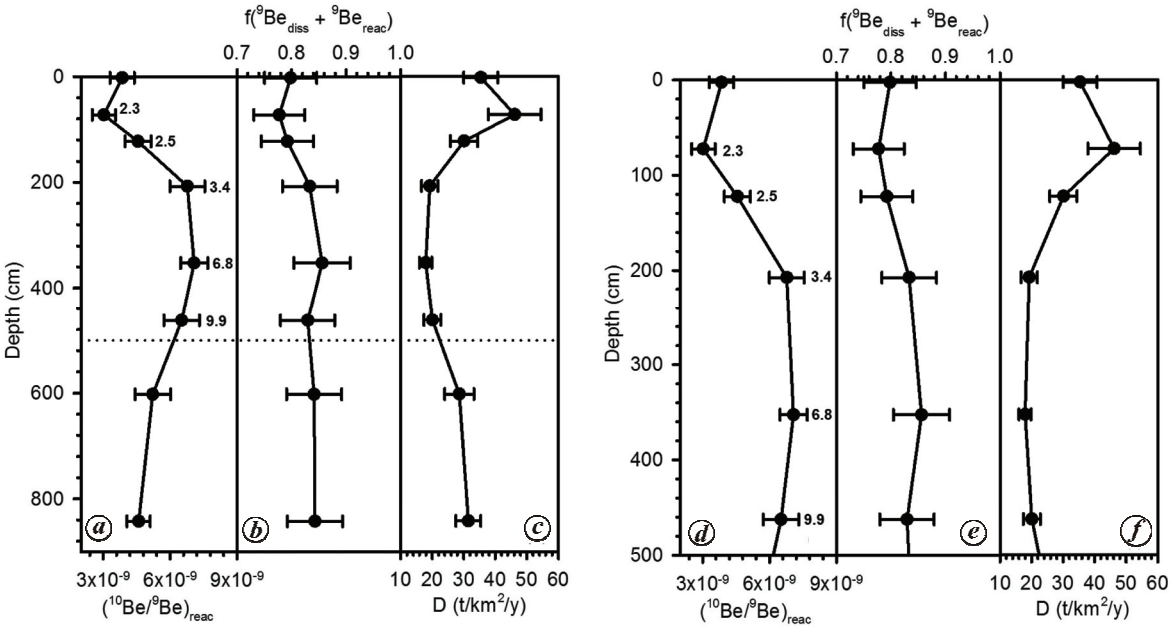

Figure 6. ***a–c***, Variation of $(^{10}Be/^{9}Be)_{reactive}$, ^{9}Be ($f_{dissolved} + f_{reactive}$), palaeo denudation (D) determined on sediment samples from a drill core at Valangaiman as a function of age. Dotted line at depth of 500 cm represents ca. 10 ka BP. ***d–f***, Holocene part of the core is expanded and interpolated ages are indicated next to error bars in the panel *d*.

and increase in denudation rate (Table 1). This could be explained due to relatively longer response time required to change $^{10}Be/^{9}Be$ (reactive) ratios which is around 2 ka assuming soil thickness of 0.5 m and D of 0.25 mm/y compared to various proxies for rainfall. The response time depends on soil thickness and denudation rate in the catchment[8,50].

The Uttrangudi sediment core samples show a different trend in variation of their past denudation rates from that of Valangaiman (Table 1). Relatively higher denudation during early Holocene and lower denudation at 1.5 ka BP are observed. As noted earlier, sediments of Uttarangudi core were derived from catchment that predominantly receives rainfall during NE monsoon. Hence, the change in denudation rates could be due to relatively less NE monsoon rainfall during the Early Holocene and its intensification during Mid- to Late-Holocene. A high resolution study of $^{10}Be/^{9}Be$ ratio on core sediments from floodplains and delta is needed to further substantiate the relationship observed in this study between palaeodenudation rates determined using meteoric $^{10}Be/^{9}Be$ and rainfall.

Conclusion

The present and past denudation rates (D) determined for the Cauvery river catchment based on ^{10}Be (meteoric) study of sediment samples from two cores drilled in Uttrangudi and Valangaiman sites of the Cauvery delta vary from 18.7 ± 1.6 to 48.1 ± 8.3 t/km^2/a during the Holocene. The present-day denudation rate of 36.9 ± 5.2 t/km^2/a determined for the Valagaiman site is higher than that estimated based on solute and suspended load of Cauvery river and its tributaries (14 t/km^2/y, from Integrated Hydrological Data Book[36] and Pattanaik *et al.*[25]). D estimated using $^{10}Be/^{9}Be$ (reactive) gives more accurate estimate of long-term denudation rate as it is not affected by damming of the river.

Based on ^{9}Be fraction (reactive + dissolved) and previous studies[39], we infer the sources of sediments for Valangaiman site is Western Ghats while highlands bordering south western margin of the delta mostly supplied sediments to the Uttarangudi site. The Western Ghats and the delta received rainfall during the summer monsoon and NE monsoon respectively.

A comparison of past denudation rate with various proxies of the Indian Summer Monsoon shows that Early to Mid-Holocene is characterized by intense rainfall and lower denudation rate and drier conditions after 4.5 ka BP as inferred from the Valangaiman core. The denudation rate however increased after 2.5 ka BP only as the response time to change $^{10}Be/^{9}Be$ (reactive) is ~2 ka for the Cauvery catchment. Variation of denudation rates of Uttarangudi core mostly reflect changes in the past fluctuations in NE monsoon rainfall.

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