Monsoon variability over Peninsular India during Late Pleistocene: Signatures of vegetation shift recorded in terrestrial archive from the corridors of Western Ghats

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ABSTRACT

The fossil flora recovered from the Kangvai well, Ratnagiri District, Maharashtra (17°53′41″ N; 73°12′23″ E) has been used to reconstruct the monsoon variations and seasonal rainfall pattern during the Late Pleistocene (44,020 ± 390 years BP) by using the Coexistence Approach. The reconstruction suggests that the Southwest (SW) and Northeast monsoons (NE) contributed ~64% and 18% of the total rainfall, respectively. Moreover, the pre-monsoon showers were responsible for about 15% of the annual rainfall. As both SW and NE monsoons were very active, along with the pre-monsoonal rainfall, the length of rainy season increased and extended up to 9 months in a year favouring the evergreen continuum and prevalence of wet evergreen forests until the Late Glacial Maximum or slightly prior to it. However, due to the weakening of NE and pre-monsoon rainfall later in the Late Pleistocene and Early Holocene, the area experiences only four months of rainy season now on account of the present-day SW monsoon. These changes resulted in the extinction of wet evergreen taxa which are now endemic to the wetter parts of Western Ghats, from the fossil locality. Our reconstruction agrees with the previous studies from the Western Ghats suggesting that the wet evergreen taxa require <4 months of dry season for their survival. This is the first quantitative rainfall reconstruction from India measuring the pre-monsoon, summer monsoon, post-monsoon and dry season from fluvio-lacustrine sediments.

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1. Introduction

The monsoon is considered as one of the most important features of the modern climate because two-thirds of the world population is impacted by monsoon rainfall which accounts for 31% of the total global rainfall (Wang and Ding, 2008). It is characterized by the seasonal reversal of wind which is governed by temperature gradients between land and adjacent ocean (Trenberth et al., 2006; Zhang and Wang, 2008). India has a typical monsoonal climate with varied rainfall i.e., maximum over the west coast (2000–2900 mm) and northeastern part (1530–2220 mm), moderate over central India (700–1200 mm), and minimum over northwestern and southeastern parts (Shukla, 1987). The Indian monsoon is characterized by annual reversal of the prevailing surface winds and has a distinct rainy summer and arid winter. In India, there are two monsoon seasons, namely the Southwest monsoon (SW) of the summer season (June–September/JJAS) responsible for about 70–90% of the annual rainfall (Pant and Rupa Kumar, 1997) in most parts of the country and the Northeast monsoon (NE) season (October–December/OND) contributing 50% of the annual rainfall in the east coast (Pankaj Kumar et al., 2007). The Northeast monsoon is also known as winter monsoon (Nageswara Rao, 1999) or post-monsoon (Singh and Sontakke, 1999).

India is an agriculture-based country where major crops (Kharif and Rabi) depend on the monsoon seasons. The growing season of Kharif crop coincides with the SW monsoon, while that of Rabi crop corresponds with the NE monsoon (Kumar et al., 2004). However, not only the crops, but the spatial distribution of modern as well as ancient forests also depends on the monsoon rainfall (Champion and Seth, 1968; Srivastava et al., 2012, 2014; Kumaran et al., 2013; Shukla et al., 2014). Accordingly, it is important to study the variation in rainfall over India. Some work was done to study the fluctuations of modern monsoon in India (Gadgil, 2003; Goswami et al., 2006; Pai and Rajeevan, 2006;

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Raju et al., 2007; Rajeevan et al., 2008; Nayagam et al., 2009; Deshpande et al., 2011; Naidu et al., 2011; Sarthi et al., 2012; Lacombe and McCartney, 2014). However, for better understanding of the dynamics of modern monsoon it is important to study the palaeomonsoon, too. A large number of studies based mainly on micropaleontological evidences have been made for the reconstruction of Quaternary monsoon in India and reviewed by Saraswat et al. (2014). However, all the reconstructions were qualitative assessments except for the tree ring data, and the latter was limited about 2000 years BP (Yadav, 2012).

In a recent study, Kumaran et al. (2013) on the basis of palaeofloral assemblage hypothesized that along the west coast of south India around ~44,000 years BP there was an extended period of rainfall because of both the SW and NE monsoons under which the wet evergreen forest taxa flourished. However, because of the weakening of NE monsoon in the later part of the Late Pleistocene and Holocene, the wet evergreen species were replaced by the moist deciduous species in the area. The main objective of the present communication is to substantiate/appraise the hypothesis of Kumaran et al. (2013) through quantitative reconstruction of the palaeomonsoon (SW and NE) as well as the pre-monsoonal rainfall. The present work is from the region where monsoon first reaches on land. This is also the first quantitative rainfall reconstruction from India integrating the pre-monsoon, summer monsoon, post-monsoon and dry season from fluvio-lacustrine sediments.

1.1. Rainfall profile of India: a brief review

India has an omnifarious and exceptional type of climate ranging from distinctly tropical climate in the southern peninsula to continental climate in the northern part of the country. The distribution and amount of rainfall may vary according to the place and topography of the region within the country, influenced by the monsoons mentioned above (Attri and Tyagi, 2010).

According to Attri and Tyagi (2010), the pre-monsoon season consists of 3 months, typically March, April and May, the SW monsoon envelops four months i.e. June, July, August and September, while the post-monsoon includes three months, namely October, November and December. The pre-monsoon season (March, April, May) is characterized by cyclonic storms. On land, the weather is influenced by the thunderstorms associated with rain. Local severe storms, associated with strong winds and rain, mainly occur over the eastern and northeastern regions including Bihar, West Bengal and Assam. Thunderstorms are also observed in central India and to Kerala. The SW monsoon is the most prominent feature of the climate of India. The maximum rainfall is received only during this 4 month-season (June, July, August, September). However, the actual period and amount depends on the onset and withdrawal dates of the monsoon. It varies from less than 75 days over west Rajasthan to more than 120 days over the southwest region of the country. The SW monsoon enters from the Kerala coast, at the southern tip of India, in June and covers the whole country by the middle of July. It generally starts withdrawing from Rajasthan during the early September and from northwestern part of India by mid-September. As a whole, the SW monsoon conditions finish in all parts of the country by mid-October. The post-monsoon season (October, November, December) starts with the commencement of northeasterly wind over the country. The coastal Andhra Pradesh, Tamil Nadu, Kerala and south Karnataka are most affected by this rainfall. The winter season includes mainly January and February, however, December can also be included for northwestern part of the country. Rainfall during this season occurs more often over the western Himalayas, northeasternmost India, Tamil Nadu and Kerala. The westerly disturbances are the main cause for the rainfall in northern and eastern parts of the country (Attri and Tyagi, 2010).

1.2. Forest vegetation types of India: a brief review

Champion and Seth (1968) categorized 16 major forest types in India (www.biologydiscussion.com/forest/5-types-of-forests-found-in-India-explained/6940; accessed on Oct. 6, 2015). The tropical wet evergreen forests are often present in the regions having rainfall greater than 2500 mm such as Western Ghats, Upper Assam, Arunachal Pradesh, Andaman and Nicobar Islands. The tropical semi-evergreen forests form a transition zone between evergreen and moist deciduous forests. They are primarily found in the Western Ghats, Assam, Arunachal Pradesh, Orissa and the Andaman and Nicobar Islands. The moist deciduous forests occur in an area having 1500–2000 mm of rainfall with a dry season of 4–6 months and are found in the Western Ghats, Assam, Arunachal Pradesh, Mizoram, Bihar, West Bengal, Orissa, Uttarakhand and along the foothills of the Himalaya. The littoral and swampy forests are associated with mesic habitats. The littoral and tidal forests occur along the coast, while swampy forests are found in northeast India along the major rivers. The tropical dry deciduous forests extending from southern tip of the country to the foothills of Himalaya covering Rajasthan, Madhya Pradesh, Maharashtra, Orissa, Uttar Pradesh, Karnataka, Andhra Pradesh and Tamil Nadu have rainfall in between 750–1250 mm. The tropical thorn forests are found in Punjab, Haryana, Gujarat and Rajasthan where the rainfall ranges from 250–750 mm. They are also found in the Upper Gangetic plains and Deccan plateau. The tropical dry evergreen forests mainly occur on the Carnatic coast which receives much less summer rainfall. The subtropical broad-leaved hill forests are found on the lower slopes of the Himalaya in Bengal and Assam and on the hills of Khasi, Nilgiri, Mahabaleshwar, Pachmarhi, Amarkantak and Parasnath areas, while the subtropical pine forests can be noticed in central and western Himalaya and on the Khasi hills in Meghalaya. The subtropical dry evergreen forests exist in low rainfall areas, particularly in northwest corner of India, while the montane wet temperate forests are present in eastern Himalaya in areas with high rainfall. The Himalayan moist temperate forests are mainly found in central and western Himalaya in between 1500–3000 m elevation, while the Himalayan dry temperate forests are distributed in the upper ranges of the Himalaya in between 2500–4000 m elevation having low rainfall. The sub-alpine forests occur all along the Himalaya above 3000 m elevation, while moist and dry alpine scrubs occur above the tree line in Himalaya.

1.3. Regional setting, modern climate and vegetation types of the study area

The study area is situated in the Ratnagiri District of Maharashtra (Fig. 1). It is bounded by Arabian Sea to the west and Western Ghats to the east. In the geological context, the region is covered by the basalts of Late Cretaceous–Eocene age overlain by the Neogene laterites and superficial deposits of the Late Quaternary sediments. The area experiences a maritime climate with monsoonal rainfall. The mean annual temperature (MAT) is ~26.8 °C, warm month mean temperature is ~27.7 °C and cold month mean temperature is ~25.6 °C. In the area, the SW monsoon is the major source of rainfall during June–September. According to Champion and Seth (1968), the vegetation around the studied area is mainly dominated by moist deciduous forests with some evergreen to semi-evergreen elements. The main evergreen elements are *Anodendron paniculatum* A. DC. of the Apocynaceae, *Caryota urens* L. of the Arecaceae, *Salacia chinensis* L. of the Celastraceae, *Albizia chinensis* Merrill and *Derris scandens* Benth. of the Fabaceae, *Lagerstroemia speciosa* Pers. of the Lythraceae, *Macrosolen capitellatus* Dancer of the Loranthaceae, *Syzygium caryophyllatum* Alston of the Myrtaceae, *Aporosa cardiosperma* Merr. of the Phyllanthaceae, *Ixora coccinea* L. of the Rubiaceae and *Leea indica* Merr. of the Vitaceae, while the semi-evergreen taxa are represented by *Carissa spinarum* L. of the Apocynaceae, *Memecylon umbellatum* Burm. f. of the Melastomataceae, *Ficus amplissima* Sm. and *Ficus racemosa* L. of the Moraceae and *Jasminum malabaricum* Wight of the Oleaceae. The moist deciduous include *Lannea coromandelica* Merr. of the Anacardiaceae and *Bombax ceiba* L. and *Firmiana colorata* R. Br. of the Malvaceae and *Homonoia riparia* Lour. of the Euphorbiaceae (Kumaran et al., 2013).
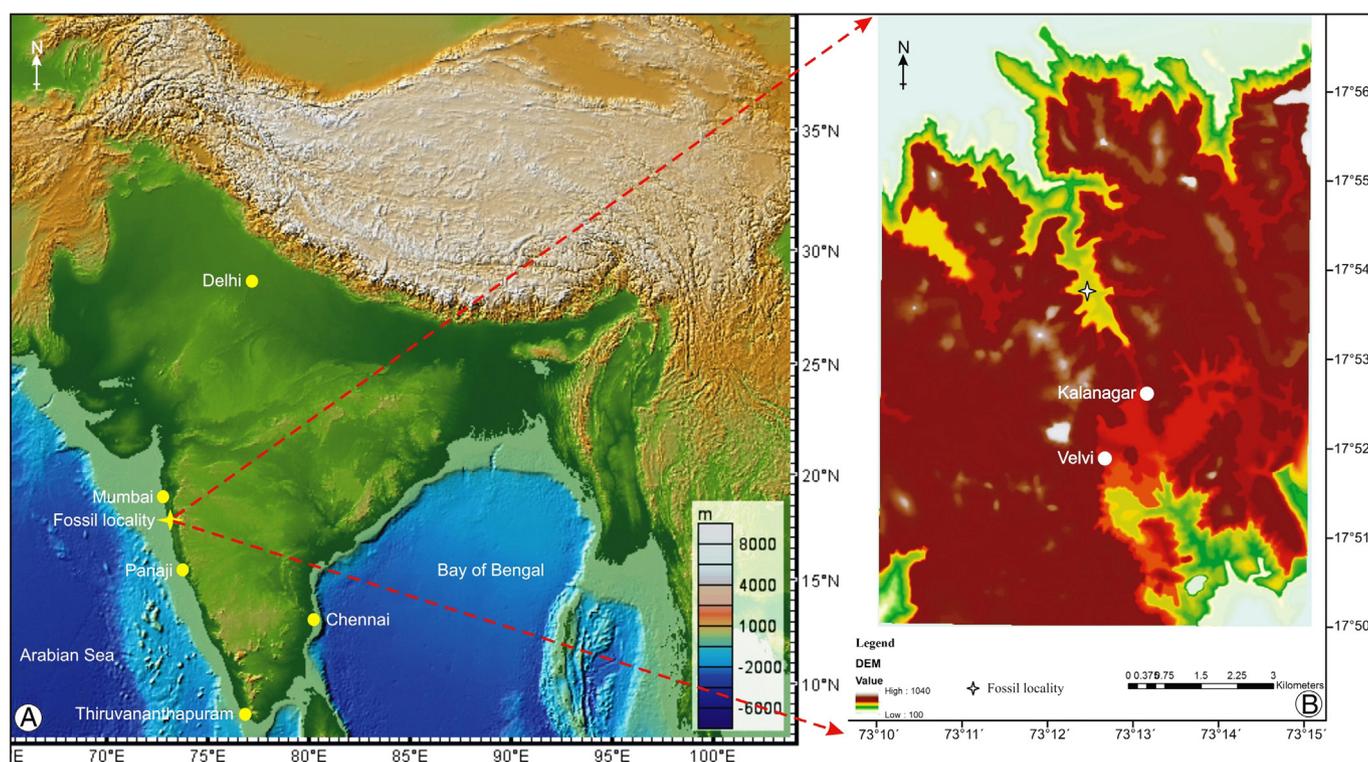
Fig. 1. Map showing the fossil locality. a. Physiographic map showing the studied area (yellow asterisk); b High resolution Digital Elevation Model showing the fossil locality. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

2. Materials and methods

2.1. Material

The present study is based on the published megafossil and pollen data of Kumaran et al. (2013). The fossil leaves and pollen were extracted from the Kangvai well situated in Dapoli, Ratnagiri District, Maharashtra (17°53′41″ N; 73°12′23″ E) (Fig. 1). As the detailed lithology of the well was given by Kumaran et al. (2013), it has been discussed here in brief.

The Kangvai well was dug to a depth of about 12 m, though only up to 8 m was explored (Fig. 2). The lithological and sedimentological details of the well are provided in Tables 1 and 2. The whole lithocolumn is divided into I–V units. The lowermost unit (IV–V, from 5.7 m–8.0 m) contains organic rich siltstone which was deposited in the lacustrine environment. This unit is highly fossiliferous and all the fossils (leaf impressions, charcoalified wood and pollen) were recovered from this unit. The rest of the units (III–I) seem to be deposited in the braided fluvial system, ephemeral or seasonal where fossil leaves were completely absent. The dating of this stratigraphic sequence is based on the radiocarbon dates of organic rich sediments (from the 3.3–5.0 m) and carbonized wood (from the 4.5 m and 7.0 m) (Kumaran et al., 2013). The lowermost fossiliferous units (IV and V) are dated as 44,020 ± 390 years BP. The detailed methodology for the dating was given by Kumaran et al. (2013).

The Digital Elevation Model (DEM) of the studied area is made with the help of Survey of India topographical maps on 1:50,000 scale, toposheet no. 47G/1 (Survey of India, 1954). The vegetation and minimum as well as maximum elevations of the area have been digitized by using ARC MAP 10.1 and ERADAS 13 softwares.

2.2. Methods

For the quantitative reconstruction of palaeomonsoon using palaeobotanical proxy there are mainly three methods viz., Climate Leaf Analysis Multivariate Program (CLAMP) (Wolfe, 1993; Kovach and Spicer, 1995; Spicer et al., 2009, 2011; Srivastava et al., 2012), Coexistence Approach (CA) (Mosbrugger and Utescher, 1997; Utescher et al., 2014) and Bioclimatic Analysis (Thompson et al., 2008, 2012). CLAMP and CA are the two more commonly used land plant based palaeoclimate methods to reconstruct the seasonal variation in rainfall. As a database is generated by us for CA for some tropical plants which are endemic to the Western Ghats (India), we have used this method in the present communication.

2.2.1. Coexistence Approach (CA)

The CA is based on the nearest living relative approach (NLRs) and can be used to any fossil assemblage containing leaves, fruits, wood, seeds and pollen etc. (Mosbrugger and Utescher, 1997; Utescher et al., 2014). The CA implies that the fossil plants have a close relationship with their modern analogs and assumes that their NLRs are still living in the same climatic conditions as those in the past and because of this the CA can be used reliably on the Neogene and Quaternary fossil assemblages where very little or no change in environmental requirements of each plant has occurred (MacGinitie, 1941; Hickey, 1977; Chaloner and Creber, 1990; Mosbrugger, 1999).

The reliability of CA was tested with other methods such as CLAMP and LMA (Leaf Margin Analysis) on the same fossil flora showing consistent results (Liang et al., 2003; Uhl et al., 2003, 2006, 2007; Roth-Nebelsick et al., 2004; Xing et al., 2012; Bondarenko et al., 2013) and the results also compliment with the marine and continental reconstructions (Mosbrugger et al., 2005; Utescher et al., 2009, 2012; Larsson et al., 2011; Rasmussen et al., 2013). For the quantitative reconstruction of palaeoclimate, CA can be used at the regional level as well as continental scale (Bruch et al., 2004, 2006, 2007, 2011; Mosbrugger et al., 2005; Utescher et al., 2007, 2011; Ivanov et al., 2011; Liu et al., 2011; Mehrotra et al., 2011; Quan et al., 2011; Erdei et al., 2012; Tiwari et al., 2012; Yao et al., 2012).

In the present study we have only reconstructed the precipitation regime to test the hypothesis of extended period of rainfall which
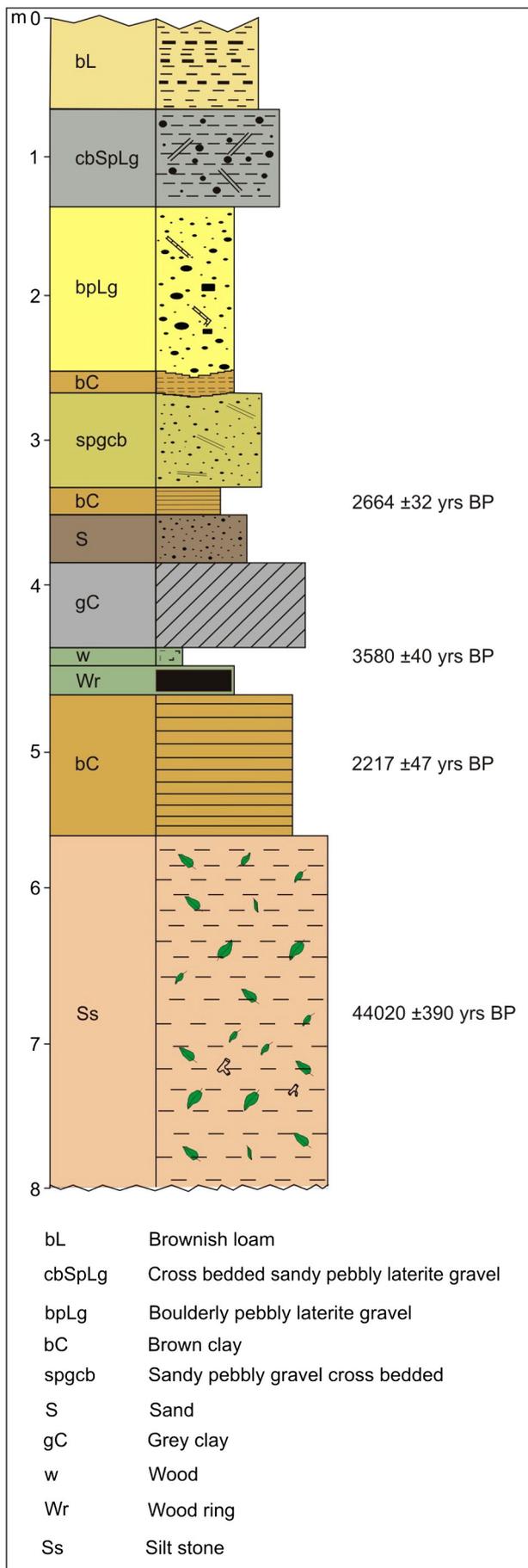
Fig. 2. Litholog of the studied Kangvai well section.

supports the growth of evergreen elements in the vicinity of the fossil locality during the Late Pleistocene (Kumaran et al., 2013). The precipitation parameters which are discussed are mean annual precipitation (MAP), mean precipitation of the pre-monsoon season (Pre-MP), mean precipitation of the monsoon season (PWET), mean precipitation of the post-monsoon season (Post-MP) and mean precipitation of the driest season (PDRY). The modern distribution of all NLR taxa was ascertained from Champion and Seth (1968), Pascal (1988), Sharma et al. (1993), Sharma and Sanjappa (1993, 1997), Ramesh et al. (1997) and Sahni (2010). The climatic tolerances of the species were determined from the Climatological Tables of Observatories in India (1931–1960) which contains the climatological normal data of 30 years taken from 235 climate stations distributed all over the country. The calculation for Pre-MP has been made by adding the mean monthly rainfall data for 3 months (March, April, May) of each NLR taxon separately and then a range has been determined by taking a minimum and maximum values in which a particular NLR species can exist. However, for the quantification of PWET 4 months such as June, July, August and September have been selected and calculation has been made in similar manner as in Pre-MP. Likewise, the Post-MP has been determined by adding the mean rainfall data of October and November for each NLR species, while for PDRY mean rainfall data of December, January and February has been taken. For the above categorization, the definition given by Attri and Tyagi (2010) has been followed.

3. Results

3.1. Palaeovegetation during 44,020 ± 390 years BP

The modern analogs of the fossil taxa recorded by Kumaran et al. (2013) from the basal units (IV and V) dated as ~44,020 ± 390 years BP are *Semecarpus auriculata* Bedd. (leaf) of the family Anacardiaceae, *Cullenia exarillata* Robyns (pollen) of the Bombacaceae, *Dipterocarpus indicus* Bedd. (leaf) of the Dipterocarpaceae, *Mallotus ferrugineus* Müll. Arg (leaf) of the Euphorbiaceae, *Alseodaphne semecarpifolia* Nees (leaf) and *Cinnamomum malabatrum* Blume (leaf) of the Lauraceae, *Walsura trifoliata* Harms (pollen) of the Meliaceae, *Ficus microcarpa* L.f. (leaf) and *F. racemosa* L. (leaf) of the Moraceae, *Myristica malabarica* Lam. (leaf) of the Myristicaceae, *Eugenia codyensis* Munro ex Wight (leaf), *Eugenia mooniana* Wight (leaf), *Syzygium cuminii* Skeels (leaf) and *Syzygium munronii* Chandrab. (leaf) of the Myrtaceae, *Mimusops elengi* L. (pollen) of the Sapotaceae and *Tamarix ericoides* Rottle. (glands) of the Tamaricaceae.

3.2. Palaeoclimate during 44,020 ± 390 years BP

The reconstructed rainfall during the period of deposition at 44,020 ± 390 years BP is as follows: MAP is in range of 1839–1953 mm, Pre-MP ranges from 303–314 mm, while the PWET and Post-MP are about 1183–1515 mm and 355–395 mm respectively, however, the PDRY is about 28–84 mm (Figs. 3 and 4).

4. Discussion

4.1. Palaeovegetational analysis during 44,020 ± 390 years BP

The families of the fossil assemblage, namely Anacardiaceae, Bombacaceae, Calophyllaceae, Dipterocarpaceae, Euphorbiaceae, Lauraceae, Meliaceae, Myristicaceae, Myrtaceae, Sapotaceae and Tamaricaceae are predominantly pantropical in distribution (van Steenis, 1962). The taxa such as *Alseodaphne semecarpifolia*, *Calophyllum calaba*, *C. malabatrum*, *D. indicus*, *Myristica malabarica*, *S. auriculata*, *Syzygium malabaricum*, *Syzygium montanum* and *S. munronii* which were once growing in the fossil locality during the 44,020 ± 390 years BP are nowadays endemic to the Western Ghats (Champion and Seth, 1968; Pascal, 1988; Ramesh et al., 1997). The species such as

Table 1
Lithological details of Kangvai well section (Kumaran et al., 2013).

Depth (m)	Description	Color	Clay fraction	pH
2.6	Silty clay loam	Dark reddish gray	Kaolinite, illite, muscovite, quartz	4.46
3.7	Silty clay	Light brown	Kaolinite, montmorillonite, magnetite, gibbsite	5.74
4.0	Silty clay	Light brown	Kaolinite, illite, montmorillonite	5.85
4.4	Silty clay	Light brown	Kaolinite, illite, montmorillonite	5.86
5.0	Clayey silt	Brown	Siderite quartz (traces)	4.76
6.0	Clayey silt	Gray	Quartz (traces), siderite (traces)	6.26
7.0	Clayey silt	Gray	Quartz, siderite (traces), hematite	6.27

A. semecarpifolia, C. calaba, Cinnamomum malabatrum, C. exarillata, D. indicus, E. codyensis, E. mooniana, Ficus microcarpa, Mimusops elengi, S. auriculata, Syzygium malabricum, Syzygium montana, S. munronii and *W. trifoliata* are all growing in the wet evergreen rainforests; this indicates that the fossil area experienced an extended period of rainfall which is in contrast to the modern day dominance of moist deciduous taxa. The rarity of moist deciduous taxa such as *M. ferrugineus* and *S. cuminii* in the fossil assemblage also supports the aforesaid thought for extended period of rainfall. The presence of *Myristica malabrica* indicates a fresh water swampy environment which is now restricted to a few pockets in the Western Ghats.

4.2. Palaeoclimate analysis during 44,020 ± 390 years BP

The reconstructed MAP is in range of 1839–1953 mm which is less than the modern value i.e. ~2811 mm. The palaeo SW monsoon rainfall contributes ~64% of the total rainfall indicating the presence of strong summer monsoon but its intensity is weaker than the modern SW monsoon which is ~93.2% of the total rainfall. The palaeo NE monsoon contributes about 18% which is four times higher than the modern NE monsoon i.e. 4.5% of the total rainfall. The reconstructed pre-monsoon rainfall provides about 15% of the total rainfall which is about eight times greater than the modern pre-monsoonal rainfall i.e. 2%. The reconstructed dry season also gives ~3% of the total rainfall in contrast to 0.07% of the modern day (Fig. 5). All these data suggests that during the deposition of basal unit (IV and V) around 44,020 ± 390 years BP both SW and NE monsoons were very active and responsible for major rainfall. Moreover, due to the presence of pre-monsoonal showers, the duration of the rainfall extended up to nine months. This is in contrast to only four months of modern rainy season due to SW monsoon. Our quantitative reconstruction of extended period of rainfall gets more support from the previous study on modern vegetation of Western Ghats which suggests that the wet evergreen forest requires a dry season of < 4 months (Barboni et al., 2001).

On the basis of the palaeofloral assemblage Kumaran et al. (2013) hypothesized that the extended period of rainfall during the deposition of the sediments was due to the combined effect of SW and NE monsoon. Our quantitative reconstruction elaborates and validates their hypothesis and suggests that the extended period of rainfall was not only

due to the presence of SW and NE monsoon, but also because of prevailing pre-monsoonal rainfall supporting the growth of typical tropical wet evergreen rainforest vegetation during the deposition of the sediments. The modern analogs of the fossils are still growing in the same climatic conditions in rainforests of the Western Ghats (Champion and Seth, 1968; Pascal, 1988; Ramesh et al., 1997) indicating that the recovered fossils have the property of Ecological Niche Conservatism which is observed not only at the regional level but on the global scale as well (Crisp et al., 2009; Srivastava et al., 2015). The extended period of rainfall during the Late Pleistocene was not only recorded from south India, but also from the areas of southwest Pacific (Stevenson and Hope, 2005) indicating a teleconnection between the South Asian and Northeast Australian monsoons.

4.3. Possible factors responsible for high rainfall during 44,020 ± 390 years BP

The appearance of SW monsoon in South Asia dates back to the early Eocene (Shukla et al., 2014). Since then, large fluctuations were recorded in the intensity of the summer monsoon during the Palaeogene and Neogene (Srivastava et al., 2012; Khan et al., 2014; Licht et al., 2014). Similarly, the Quaternary period also witnessed several variations in the magnitude of the summer monsoon recorded from the Arabian Sea (Clemens and Prell, 2003; Rao et al., 2008), Bay of Bengal (Chauhan et al., 2004), continental interiors (Gibling et al., 2005, 2008; Tandon et al., 2006; Sinha et al., 2007; Agrawal et al., 2012), northern India (Sharma et al., 2004; Prasad and Enzel, 2006), southern India (Kumaran et al., 2013) and western part of the Tibetan Plateau (Van Campo and Gasse, 1993). The high rainfall regime was suggested by Schaefer et al. (2008) during the MIS 3 (ca 46.4–41.2 ka) from the continental interiors of Himalaya; this fact was also corroborated by other parts of South Asia (Prell and Kutzbach, 1987; Bhandari et al., 2005; Juyal et al., 2006; Williams et al., 2006; Sinha et al., 2007; Govil and Naidu, 2010; Ghosh et al., 2015). Recently, Ghosh et al. (2015) quantitatively reconstructed the palaeomonsoon by using pollen data from the Darjeeling Himalaya and suggested that during the MIS 3 the intensity of summer monsoon was high thus supporting our reconstruction, despite the fact that their reconstruction was only limited to summer monsoon. Here, the question arises what was the main factor which caused high rainfall during the pre-monsoon, summer monsoon and post-monsoon seasons. Recent studies indicate that the Himalayan/Tibet orogeny was the major factor for the evolution, development and intensification of the Asian summer monsoon (Srivastava et al., 2012 and references therein; Zhang et al., 2012). For the study of South Asian monsoon several numerical climate models are based on Tibet, Himalaya and East African orography (Chakraborty et al., 2006; Molnar et al., 2010). Molnar et al. (2010) suggested that the Tibetan plateau was not the major factor to act as a heat pump for the enhancement of South Asian monsoon, rather the major heat source was located somewhere in the northern India and Tibet played a major role in the intensification of East Asian monsoon (Liu and Yin, 2002; Zhang et al., 2012). Moreover, Tibet plays a principal role in checking the cool dry air coming from northwest of Tibet (Boos and

Table 2
Sedimentary history of the Kangvai well section.
Modified after Kumaran et al. (2013).

| Lithounit	Geoenvironment	Age (yrs BP)	Climate/rainfall/vegetation
I and II	Geomorphic features of channel integration strong but indication of seasonally flowing low order streams.	<2 ka Late Holocene	Sub-humid with short monsoon season. Deciduous forests along with patches of riparian flora.
III	Disorganized drainage of sheet 2 ka floods/shallow surface flow during rainy season – rainwater, surface sheet water ground water – mainly responsible for maintaining stagnant water bodies.	2 ka–3.5 ka Late Holocene	Humid with rainfall higher than lithounits I and II; patches of semi-evergreen forests.
Strong disconfirmity			
IV and V	Lacustral phase perennial with short episodes of hydrological fluctuations. Rainwater, sheet water and ground water responsible for maintaining freshwater body; not very deep, anaerobic and biologically rich.	~44 ka Late Pleistocene	Humid with higher rainfall than lithounits I, II and III; freshwater shallow lake/pond or swamp; prevalence of wet evergreen forest including *Myristica* swamp.
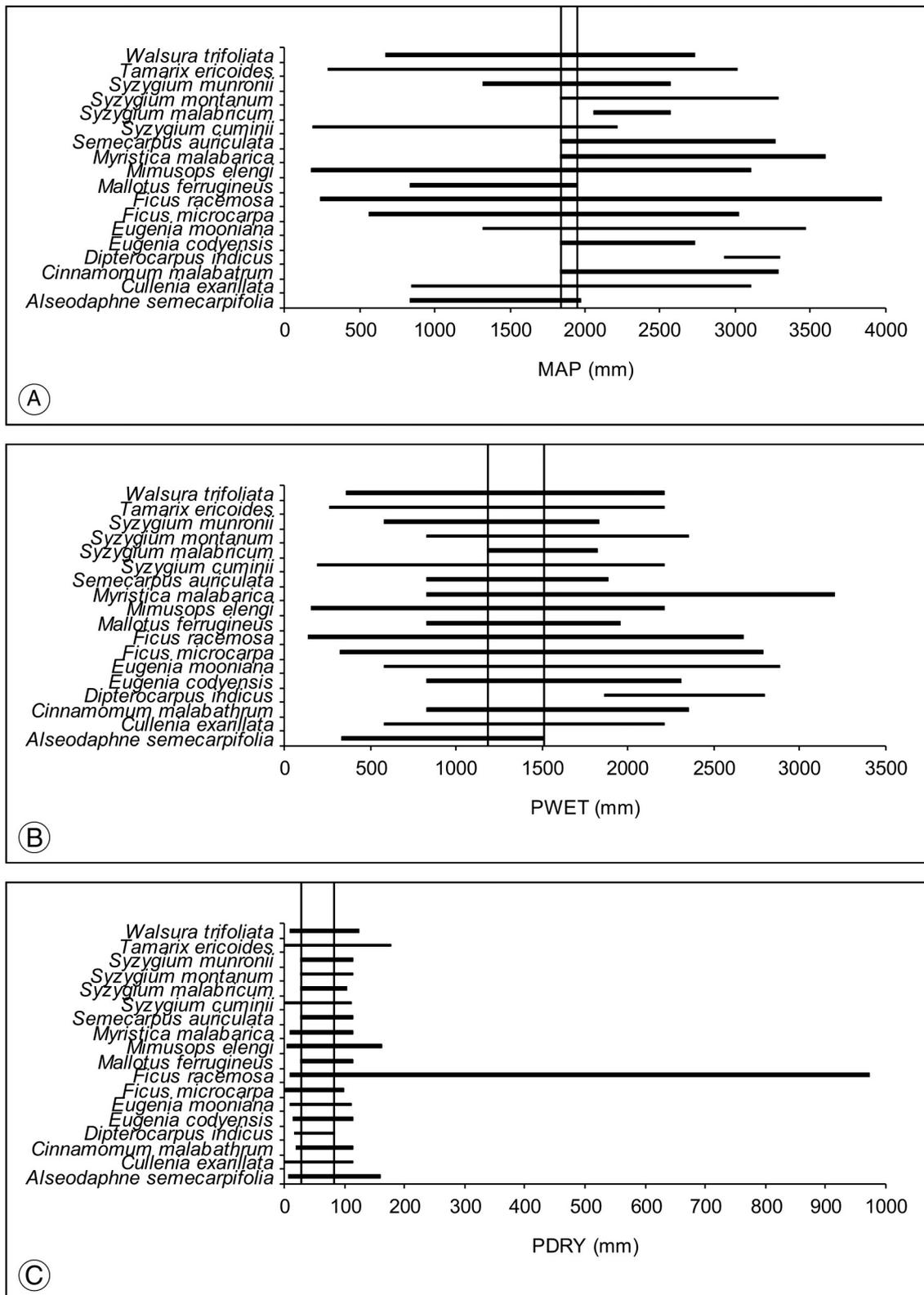
Fig. 3. The coexistence interval of the climatic parameters of the fossil assemblage showing. a MAP; b PWET; c PDRY (vertical lines indicating common range of all the modern comparable forms).

Kuang, 2010). Chakraborty et al (2006) in his numerical climate modeling study suggested that the topography of Asia west of 80° E had more significant effects on the Indian summer monsoon precipitation than the topography of Asia east of 80° E. However, based on modern climate data Rajagopalan and Molnar (2013) have suggested that heating over the

Tibetan plateau modulates the pre-monsoon and post-monsoon showers and might be independent of the ENSO. Similarly, it might be possible that the high intensity of pre- and post-monsoons during the deposition of the sediments was most likely due to the aforesaid reasons. The high intensity of summer monsoon during the period may be due to the
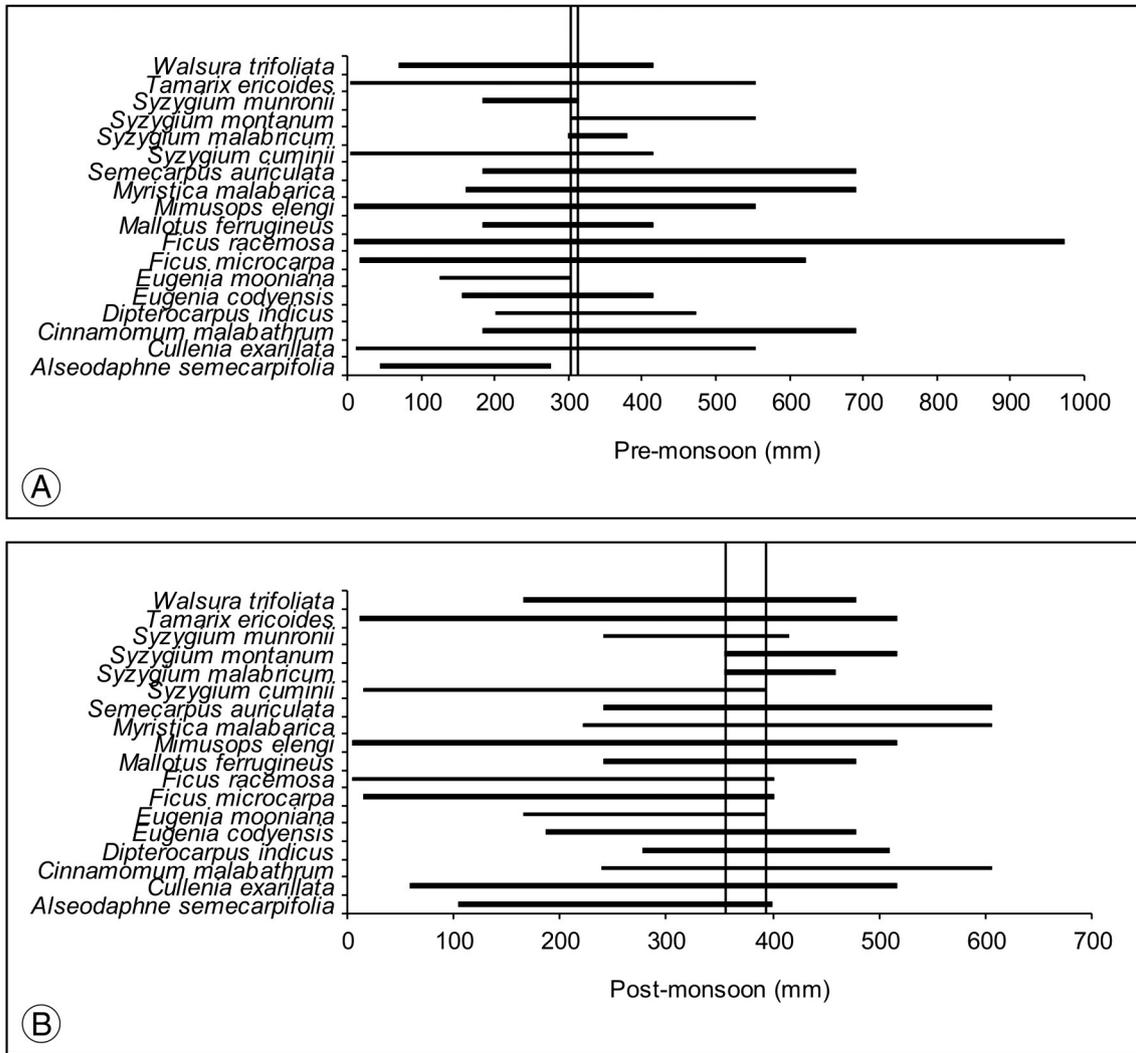
Fig. 4. The coexistence interval of the climatic parameters of the fossil assemblage showing. a. Pre-MP; b. Post-MP (vertical lines indicating common range of all the modern comparable forms).

high concentration of carbon dioxide at 44,020 ± 390 years BP (Ahn and Brook, 2008). The role of carbon dioxide concentration in the intensification of summer monsoon was also suggested during the late Eocene; this counterbalanced the negative impact of lower Tibetan plateau (Licht et al., 2014). Nevertheless, the role of orographic barrier of the Western Ghats on the west coast of India cannot be ruled out for high monsoonal shower (Xie et al., 2006). The weakening of pre-monsoonal and post-monsoonal rainfall was most likely due to the Last Glacial Maximum (LGM) towards the Late Pleistocene and the increased aridity during the Late Holocene as revealed by the palynological records from the same section (Kumaran et al., 2013) and elsewhere (Ghosh et al., 2015 and references therein).
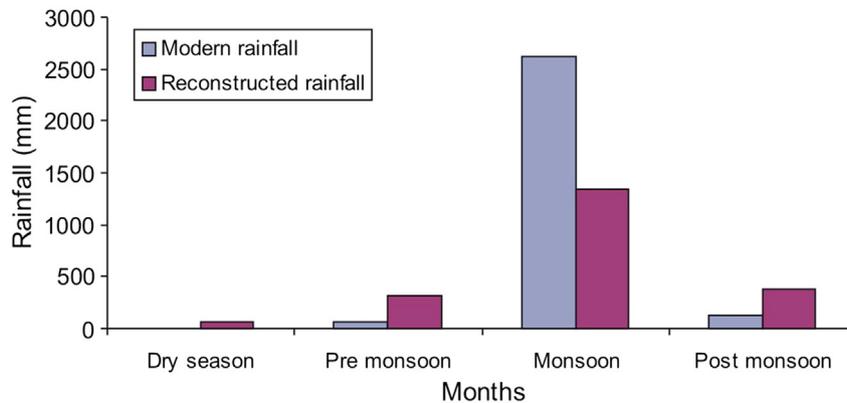

Fig. 5. Bar diagram showing the comparison of modern and reconstructed rainfall pattern.

5. Conclusion

Our quantitative rainfall reconstruction suggests that the extended period of rainfall during the Late Pleistocene was because of the monsoonal, post-monsoonal and pre-monsoonal rainfalls which supported the growth and sustenance of wet evergreen elements. The modern analogs of the fossil taxa are now endemic to those areas of the Western Ghats which have dry periods of less than 4 months. The fossil locality now experiences only 4 months of rainfall. Our reconstruction is also in congruence with the previous study which suggests that in the Western Ghats the wet evergreen endemic taxa require <4 months of dry season (Barboni et al., 2001). The present study also validates and extends the hypothesis of Kumaran et al. (2013).

Acknowledgments

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