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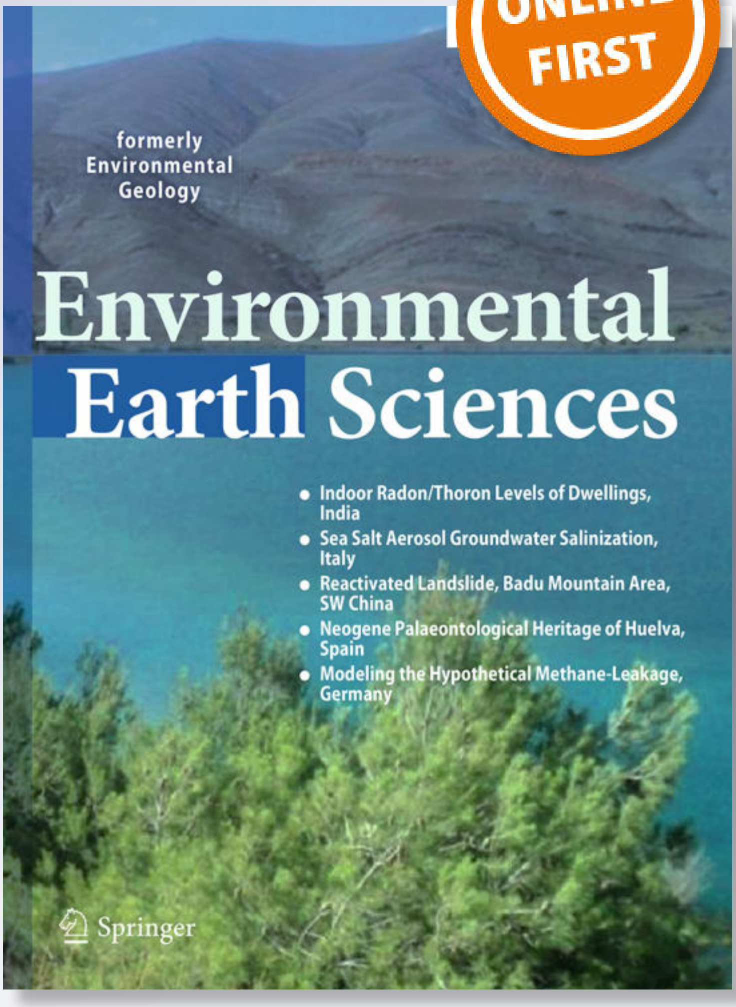

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ORIGINAL ARTICLE

Vegetational and climatic variations during the past 3100 years in southern India: evidence from pollen, magnetic susceptibility and particle size data

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Abstract Vegetational history *vis a vis* climate change during the past 3100 cal. years BP was deciphered from pollen data supplemented with magnetic susceptibility and particle size data for a 2.5 m long sediment core from Pookot Lake, Kerala, southern India. Pollen data suggest a mixed assemblage of upland tropical elements and wetland mangrove taxa. The presence of trace amounts of pollen grains of montane taxa like *Betula, Pinus* and *Alnus* points to their long distance dispersal. Pollen grains of *Ixora*, *Syzygium, Symplocos*, *Moraceae* and *Arecaceae* that represent tropical vegetation were also recovered, indicating modern vegetation in and around Pookot Lake. Mangrove elements are mostly represented by species of *Rhizophora* and *Ceriops decandra* along with other taxa. High-rainfall periods are characterised by high sand % and low clay % and vice versa. The pollen data correspond well with magnetic susceptibility and particle size data. The data obtained suggest three broad phases of climate, with minor oscillations, during the past 3100 cal. years BP: (1) wet climate during 3100–2500 cal. years BP; (2) dry climate spanning a long period that ended around 1000 cal. years BP; (3) amelioration in climate after 1000 cal. years BP, reflected in the presence of luxuriant vegetation and high magnetic susceptibility values.

Keywords Pollen · Palaeovegetation · Magnetic susceptibility · Pookot Lake · Southern India

Introduction

Pollen grains are an important component preserved in lacustrine sediments, which help not only in providing insights into the past vegetational changes but also in determining the past climate. Several studies have employed pollen, particle size and magnetic susceptibility of lake sediments to decipher the past climate (Peck et al. 2004; Chen et al. 2004; Peng et al. 2005). A fair number of palynological studies have been carried out from several sites in India viz., northeastern part (Chauhan 1995, 2000, 2004, 2005; Yadav et al. 2006), southeastern part (Chauhan 2002; Chauhan and Quamar 2010), central part (Shaw et al. 2007), east coast (Bhattacharyya et al. 2013; Barui 2011; Halit and Behling 2008; Khandelwal et al. 2006; Farooqui and Vaz 2000), and southwest coast (Kumaran et al. 2005). The pollen sequences from the respective sites have also offered insights into the changing floristic patterns and the coeval climatic episodes. Besides pollen, other proxies like foraminifera (Nagender Nath et al. 2012; Bassinot et al. 2011; Banakar et al. 2010; Khare et al. 2008), foraminiferal isotopic and elemental data (Saraswat et al. 2013), rock magnetic properties (Anil Kumar et al. 2005; Thamban et al. 2007), oxygen isotopes (Prabhu et al. 2004), nitrogen

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isotopes (δ^{15}N; Agnihotri et al. 2008), geochemical parameters (Chauhan et al. 2010a), biomarkers (Kurian et al. 2009), and clay mineral data (Chauhan et al. 2010a) of marine sediments have also been employed in reconstructing the palaeoclimate of the region. However, most of these do not provide much information on the important climatic events of the Holocene. In addition, continental records of climate, especially lake sediments, from southern India are limited (Shankar et al. 2006; Warrier and Shankar 2009; Warrier et al. 2014).

Here, we present pollen data for sediment cores from a small montane lake in southern India, based on which we have reconstructed the vegetation and climate during the past 3100 years. Our study aims to throw light on climatic changes during the Late Holocene through the analysis of pollen, supplemented with the magnetic susceptibility and particle size data.

Study area and site description

Pookot is a natural, fresh water lake situated in the Sahyadri (the Western Ghats) near Vythiri in Wayanad district, Kerala (11°32′30″N; 76°1′38″E; Fig. 1) at an elevation of about 775 m. This 6.5 m-deep lake covers an area of ~0.085 km^2. Panamaram, a tributary of the Kabani River, originates from Pookot Lake. The lake is surrounded by mountains on all sides. Tall trees and dense forests line the pathway around the lake. The lake catchment is characterised by ferruginous forest loamy type of soil that formed from the weathering of hornblende-biotite gneiss (Geological and Mineral Map of Kerala 1995; Soman 1997).

Climate

The climate (source: India Meteorological Department 2008) is generally moist with an average rainfall of 4200 mm/year. The instrumental record of rainfall for Vythiri Station, albeit with several gaps in data, reveals that the rainfall has varied significantly during the past century. The mean annual rainfall has varied from 2437 to 6420 mm/year (with 8233 mm/year recorded in 1961). The average rainfall during the period 1901–2004 AD is 4250 mm with a standard deviation of 885 mm. A decreasing trend of rainfall is documented during the past 20 years. Relative humidity in the area varies between 65 and 80 %, with the highest humidity registered during the

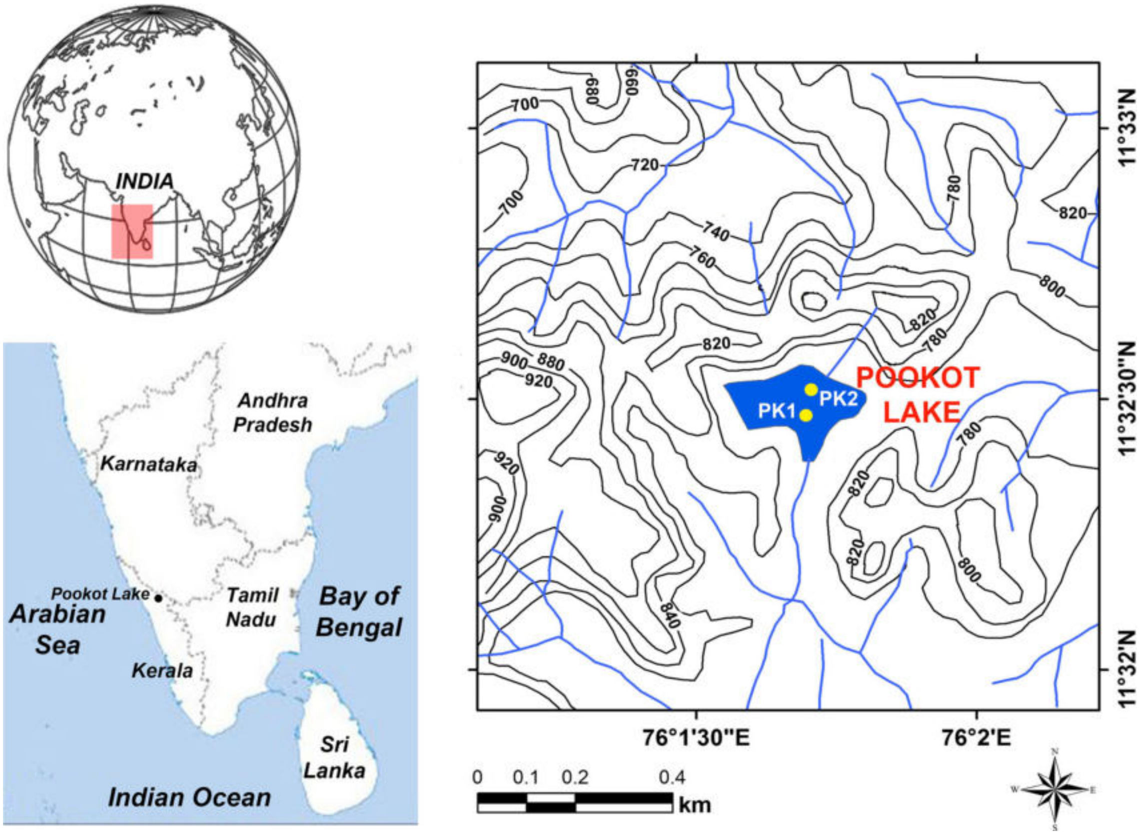

Fig. 1 Location map showing the Pookot Lake and its topography and the surrounding area. Topographic contours are in metres. The locations of cores PK1 and PK2 are shown

southwest monsoon (95 %). The temperature range is around 21–38 °C.

Vegetation

The forest around Pookot Lake belongs to the Kalpetta Range of South Wayanad Forest Division. It comes under the category of western tropical wet evergreen forests of low elevation (Champion and Seth 1968). The present day vegetation, especially trees growing around Pookot Lake, is summarized in Table 1 (Kerala Forest Department 1986, 2004).

Materials and methods

Sampling

Two undisturbed sediment cores (PK1 = 2.4 m and PK2 = 2.2 m length) were collected from the deepest part of Pookot Lake during November 2007 by manually pushing PVC pipes that were joined end-on-end (diameter 1.5 inches; total length 10 m) into the sediment. Core PK2 on which pollen analysis was carried out was sub-sampled at 1 cm interval. Twenty samples were selected for pollen analysis based on the peaks and troughs in the magnetic susceptibility profile. As a 1 cm slice of sub-sample was small, 5–6 adjacent sub-samples were clubbed to obtain the desired quantity of sample for pollen analysis. Core PK1, however, was sub-sampled at 0.5 cm interval to obtain high-resolution data. Particle size analysis was carried out on 33 sub-samples (31 and 2 sub-samples, respectively from cores PK1 and PK2) that represented the peaks and troughs in magnetic susceptibility profile. As a 0.5 cm-thick sub-sample of the core did not yield sufficient sample quantity; three or four adjacent samples were clubbed.

AMS ^{14}C dating

Carbon-14 dating by accelerator mass spectrometry was carried out on the organic matter of bulk sediment samples from selected depths at the Xi'an Accelerator Mass Spectrometer Center, Institute of Earth Environment, Chinese Academy of Sciences (CAS), China. The ^{14}C ages were calibrated using the code clam (Blaauw 2010) which runs on the open source software 'R' (R Development Core Team 2010) and uses IntCal09.14C calibration curve (Reimer et al. 2009). An age-depth model was constructed by the linear interpolation model. The maximum ^{14}C age obtained for the two cores is 2891 ± 26 years (Table 2). For core PK2, no dates are available beyond 236 cm depth up to the core-bottom (246 cm). Hence, ages were assigned by extrapolation in this segment of the core though this may have led to considerable uncertainties in age.

Table 1 The present day vegetation around Pookot Lake (Kerala Forest Division 1986, 2004)

	Species	Vegetation density (trees/hectare)	% Composition
1	*Aldina cordifolia*	0.33	0.04
2	*Antilaris toxicaria*	7.88	0.96
3	*Artocarpus hirsuta*	1.26	0.15
4	*Bombax malabaricum*	10.10	1.24
5	*Bridella squamosa*	1.74	0.21
6	*Butea Monosperma*	34.31	4.20
7	*Dalbergia latifolia*	0.22	0.03
8	*Dichopsis elliptica*	27.46	3.36
9	*Dillenia pentagyra*	13.51	1.65
10	*Diospyros ebenum*	7.55	0.92
11	*Donella roxburghii*	1.70	0.21
12	*Dysoxylum malabaricum*	21.36	2.61
13	*Dysoxylum purpureum*	1.70	0.21
14	*Elaeodendron glaucum*	4.59	0.56
15	*Evodia roxburghiana*	1.07	0.13
16	*Grewia tiliaefolia*	0.33	0.04
17	*Holigarna arnottiana*	30.72	3.76
18	*Hopea parviflora*	5.00	0.61
19	*Lagerstroemia lanceolata*	1.33	0.16
20	*Machilus macarantha*	0.19	0.02
21	*Mangifera indica*	1.26	0.15
22	*Melia azedarach*	1.18	0.14
23	*Mesua ferrea*	14.66	1.79
24	*Myristica attenuata*	38.46	4.71
25	*Poinciana regia*	25.43	3.11
26	*Pterocarpus marsupium*	1.22	0.15
27	*Scheichera Oleosa*	21.95	2.69
28	*Terminalia paniculata*	1.52	0.19
29	*Tetrameles mudiflora*	3.81	0.47
30	*Toona ciliate*	40.53	4.96
31	*Vateria indica*	187.87	22.99
32	*Vitex altissima*	1.89	0.23
33	*Xylia xylocarpa*	3.00	0.37
34	*Deciduous miscellaneous*	119.36	14.61
35	*Evergreen miscellaneous*	182.66	22.35

Pollen analysis

Standard procedures were followed to extract pollen and spores from the sediment samples (Erdtman 1943; Fageri and Iversen 1975). The samples were treated with mild alkali (10 % potassium hydroxide), 40 % hydrofluoric acid, followed by acetolysis (9:1 acetic anhydride and

Table 2 AMS ^{14}C dates for Pookot Lake sediment cores PK1 and PK2

Core no.	Sample no.	Xi'an lab ID	Depth (cm)	δ ^{13}C (‰)	^{14}C age (years)	Weighted mean of calibrated age (years)	Calibrated age (cal. years BP) 2-σ
PK1	PKA1	XA3591	44–45	−32.30 ± 0.28	125 ± 20	133.3	269–13
	PKA2	XA3567	108–109	−33.97 ± 0.27	399 ± 20	468.1	507–335
	PKA3	XA3568	153–154	−32.31 ± 0.39	698 ± 24	650.4	683–567
	PKA4	XA3570	194–194.5	−25.95 ± 0.27	2003 ± 28	1952.1	203–1884
PKB2	PKB2	XA2996	52–53	−30.11 ± 0.44	420 ± 20	492.07	514–464
	PKB3	XA2997	90–91	−30.41 ± 0.38	430 ± 20	Date not used in the age-depth model	
	PKB4	XA2998	143–144	−31.31 ± 0.35	734 ± 19	676.8	691–663
	PKB5	XA2999	193–194	−23.32 ± 0.37	1630 ± 22	1515.4	1595–1418
	PKB6	XA3000	214–215	−18.11 ± 0.45	2641 ± 21	2758.1	2777–2743
	PKB7	XA3001	235–236	−17.43 ± 0.80	2891 ± 26	3026.37	3142–2946

The radiocarbon dates were calibrated using the code clam (Blaauw, 2010) which runs on open source software 'R' (R Development Core Team 2010) and using the IntCal09.14C calibration curve (Reimer et al. 2009). Sample PKB3 (depth = 90–91 cm, ^{14}C age = 430 ± 20 years) of core PK2 was not considered for the age-depth model as its age is nearly the same as that of the adjoining sample PKB2 (depth = 52–53 cm, ^{14}C age = 420 ± 20 years)

sulphuric acid). The samples were later prepared in 50 % glycerine solution for microscopic examination. The pollen recovered from the sediments were identified by comparing them with (1) pollen slides of plants growing in coastal regions of India; (2) reference slides available at the BSIP herbarium; (3) photographs of pollen/spores of tropical taxa. Palynomorphs identified were counted and quantitatively analyzed using Tilia software. In the calculation of pollen percentage, aquatic taxa, ferns and algal spores were excluded from the total pollen count to get the "pollen sum". Percentages of other pollen taxa were calculated in terms of pollen sum to avoid their masking by the over-representation of ferns, aquatic taxa and algal or fungal spores, which are calculated in relation to the total pollen count.

Particle size analysis

About 4 g of the sediment sample was used for particle size analysis. As a 0.5 cm thick sub-sample of the core did not yield sufficient sample quantity, three to four adjacent samples were clubbed. Organic matter and carbonate contents were removed by treating the samples with 30 % H_2O_2 and 10 % acetic acid, respectively. The sand fraction was separated by wet sieving through an ASTM test sieve no. 230 (62 μm pore diameter). After removing the sand content, the silt + clay fraction was transferred to a 1000 ml measuring cylinder. One gram of sodium hexametaphosphate was added to prevent flocculation. After making it up to 1000 ml volume with double distilled water, the silt + clay fraction was determined by pipette analysis (Carver 1971). The column containing silt and clay was stirred vigorously for about 1 min using a long stirring rod. Twenty-seconds after stirring, 20 ml of the liquid was pipetted out from 20 cm depth which contains the silt + clay fraction. After 3 h and 10 min, 20 ml of the liquid was pipetted out from 5 cm depth which contains only the clay fraction. The total weight of the clay fraction was calculated by multiplying the weight of clay by 50. A value of 1 g was subtracted from the value obtained to account for the weight of sodium hexametaphosphate added. The total weight of the silt + clay fraction was also similarly calculated. From these values, the total weight of the silt fraction was determined. The three fractions (sand, silt and clay) are expressed as percentages.

Magnetic susceptibility (χ_{lf}) measurements

Standard techniques were used for sample preparation (Walden 1999). Sediment samples were dried in a hot air oven at 35 °C and gently disaggregated using an agate mortar and a pestle. They were filled in polythene covers and tightly packed in 8-cc non-magnetic plastic bottles. Magnetic susceptibility at low frequency (0.47 kHz; χ_{lf}) was determined on a Bartington susceptibility meter (Model MS2). Magnetic susceptibility (χ_{lf}) was determined for 51 samples, i.e., samples selected for both pollen and particle size analyses.

Results

Pollen data and vegetational history

Based on the changes in the pollen/spore assemblage during the past 3100 years, two distinct phases may be recognised (Fig. 2a, b). Most samples from the lower half of the profile (i.e., <153.5 cm depth) are either poor or

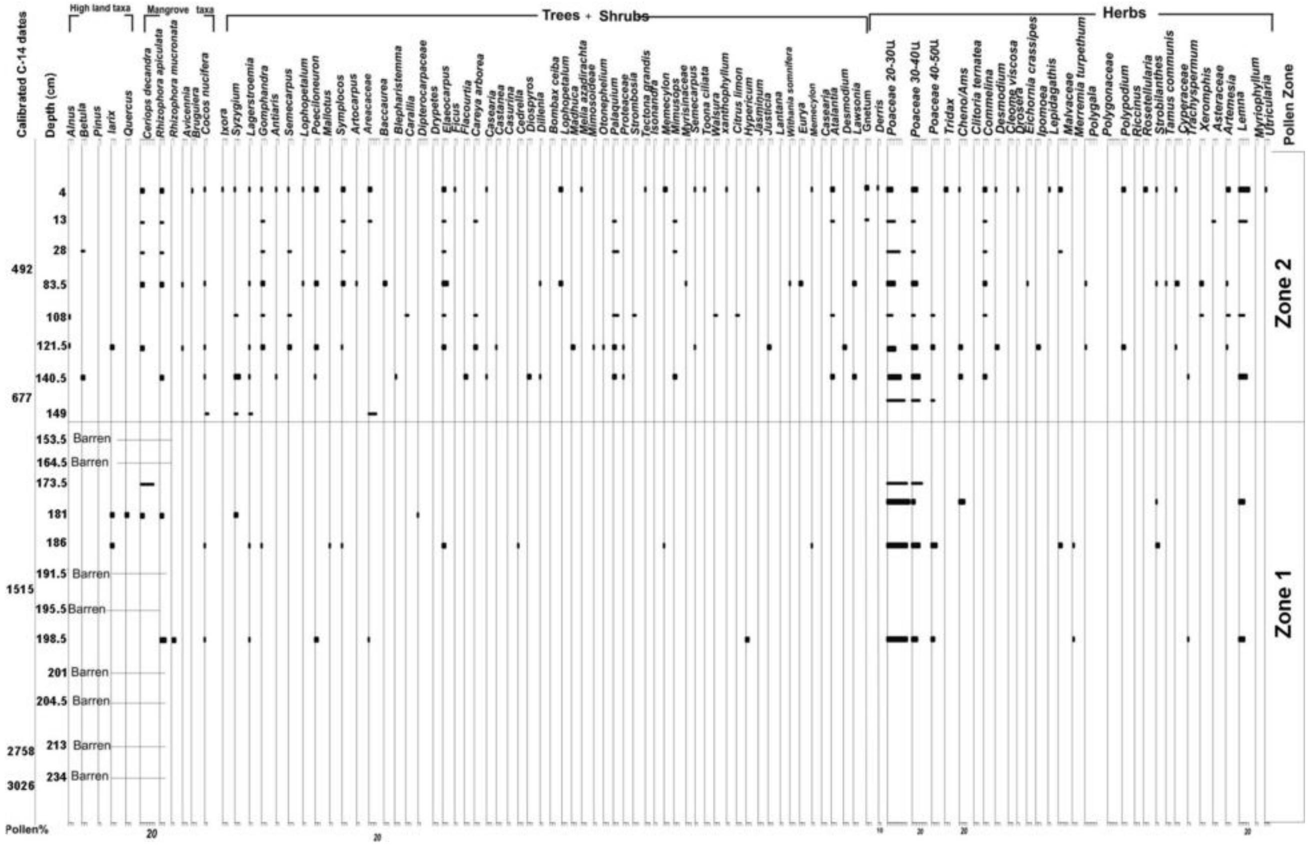

Fig. 2 **a**, **b** Pollen diagrams for Pookot Lake sediments. Based on the changes in pollen assemblage during the past 3100 years, two pollen zones—Zone 1 (>153.5 cm) and Zone 2 (0–153.5 cm)—may be recognised. Zone 1 possesses no/hardly any spores/pollen. Zone 2 contains spores/pollen of diverse taxa and in good amounts at that

almost devoid of pollen/spores. Samples from the upper part of the profile, however, yielded good numbers of pollen/spores of diversified taxa. Photomicrographs of some pollen/spores found in Pookot Lake sediments are displayed in Fig. 3. Pollen spectra for the two sediment cores are shown in Fig. 2a, b. For convenience of interpretation, the pollen diagram is divided into two pollen zones: Zones 1 and 2. Zone 1 (153.5–236 cm depth) comprises 12 samples covering the time span of 3100–1000 cal. years BP and Zone 2 (153.5 to core-top) eight samples spanning the past 1000 cal. years BP

Zone 1

Zone 1 (153.5–236 cm depth) spans the period 310–1000 cal. years BP (Fig. 2a). As stated earlier, this zone is not much promising from a palynological point of view. Most samples exhibit an insignificant or no pollen count. Such samples are labelled as "barren" in Fig. 2a. At depths of 198 cm, (~2200 cal. years BP) and around 171–182 cm (~1400–1200 cal. years BP), coastal vegetation like mangrove is represented by pollen grains of *Ceriops decandra*, which comprise 28 % of the total whereas pollen grains of *Rhizophora apiculata* and *R. mucronata* comprise <10 %. The other arboreal taxa represented are *Quercus* and *Poeciloneuron* (6 %), *Syzygium*, *Lagerstroemia*, Dipterocarpaceae, Rosaceae, *Cocos nucifera*, *Gomphandra*, *Symplocos*, Arecaceae, *Elaeocarpus* and *Memecylon* (<5 % each). *Mallotus* and *Cedrella* constitute <1 %. Herbs are represented mostly by members of *Poaceae* (>50 %). The other non-arboreal taxa are Cheno/Ams (>10 %) whereas *Malvaceae* and *Strobilanthes* are <10 %. *Merremia* and *Trachyspermum* constitute <2 % of the total assemblage. Fern spores of both monolete and trilete are ~35 % each. Various fungal spores are found too in this zone: *Glomus* is >45 %; *Meliola*, *Neurospora*, *Nigrospora* and Pestalotia are >20 % whereas *Tetraploa* and *Torula* are <5 %. Fungal remains (hyphae) represent >25 %. *Pseudoschizaea* algal remains constitute >10 % of the total assemblage. Protozoans, represented by *Thecaamoeboids* (3 %), are also prominent in Zone 1.

Zone 2

Zone 2 (153.5 cm to the core-top) represents the past ~1000 years (from 1000 cal years BP to the Present).

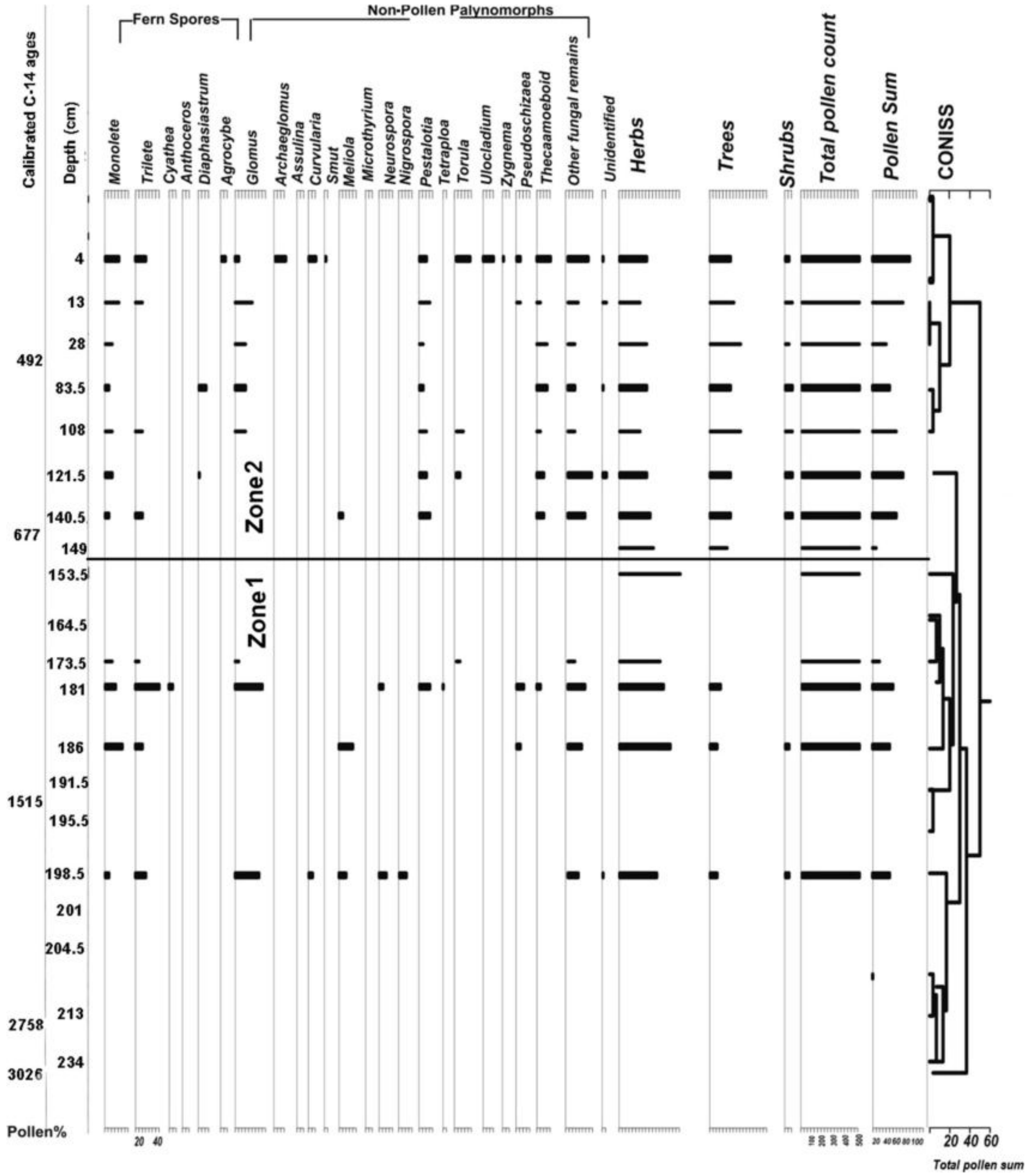

Fig. 2 continued

Being rich in pollen/spores, this zone appears promising from a palynological viewpoint. Coastal vegetation (i.e., mangroves) of *Ceriops decandra*, *Rhizophora apiculata* and *C. nucifera* represent <10 % each and other mangrove taxa like *Avicennia* and *Bruguiera* <5 %. Some high land taxa like *Alnus* and *Betula* are present (<5 % each); *Pinus* and *Quercus* too are represented albeit at low levels (<1 and 10 %, respectively). Other tropical forest taxa like *Lagerstroemia*, *Gomphandra*, *Semecarpus*, *Poeciloneuron*, *Artocarpus*, *Carallia*, *Ficus*, *Flacourtia*, *Careya*, *Madhuca*, *Otonephelium*, *Isonandra*, *Memecylon*, *Semecarpus*, *Toona ciliata*, *Citrus limon*, *Justicia*, *Withania*, *Eurya*, *Atalantia*, *Desmodium*, *Syzygium*, *Symplocos*, Arecaceae, *Elaeocarpus*, *Palaquium* and *Mimusop* are <5 % each; Even less abundant are *Ixora*, *Lophopetalum*, *Mallotus*, *Baccaurea*, *Blephasristemma*, *Cedrella*, *Diospyros*, *Dillenia*, *Bombax ceiba*, *Proteaceae*, *Strombosia*, *Drypetes*, *Myrisinaceae*, *Walsura*, *Xanthophyllum*, *Lantana* and *Lawsonia* (<2 % each). Taxa present at <1 % include *Lophopetalum*, *Jasminum*, *Melia azadirachta*, *Mimosoideae* and *Tectona*.


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◀**Fig. 3** Photomicrographs of selected pollen grains from Pookot Lake sediments. **A** *Syzygium*; **B** *Rostellularia*; **C** Melastomataceae; **D** Sapotaceae; **E** *Myriophyllum*; **F** Asteraceae; **G** *Bruguiera*; **H**, **I** *Avicennia*; **J** *Acanthus*; **K**, **L** *Excoecaria*; **M**, **N** *Rhizophora apiculata*; **O** *Rhizophora lamarckii*; **P** *Excoecaria agallocha*; **Q** *Scyphiphora*; **R** *Cocos nucifera*; **S** *Kandelia*; **T** *Rhizophora apiculata*; **U** *Meliaceae*; **V** Chenopodiaceae; **W** Poaceae; **X** Cyperaceae; **Y** Monolete; **Z**, **Aa** Trilete; **Bb** *Urticularia*; **Cc**, **Dd** Dinoflagellates; **Ee**, **Ff and Gg** fungal spores; **Hh** *Glomus*

Taxa like *Antiaris* represent <10 %. Non-arboreal taxa are represented mostly by members of Poaceae (>50 μ) and Cyperaceae, which constitute <5 % of the total assemblage. Other herbaceous taxa present (<5 % each) are *Gnetum*, *Cheno/Ams*, *Ipomoea*, Malvaceae, *Rosetellularia*, *Strobilanthes*, *Xeromphis* and *Artemesia*. There are some taxa represented by <1 % each (*Derris*, *Tridax*, *Drosera*, *Lepidagathis*, *Merremia*, *Ricinnus*, *Trachyspermum* and Asteraceae). *Clitoria*, *Commelina*, *Eichornia*, *Polygala* and *Tamus* are <2 %. Aquatic taxa are represented by *Lemna* by >15 % whereas *Myriophyllum* and *Utricularia* are <5 %. Ferns are represented by both monolete (<25 %) and trilete (<20 %). Besides, various fungal spores are present: e.g. *Agrocybe*, *Assulina* and *Smut* are <5 % whereas *Curvularia* and *Meliola* are <10 % and others like *Pestalotia*, *Torula* and *Glomus* are <30 %; also present are algal remains like *Zygnema* and *Pseudoschizaea* representing <5 %, *Thecaamoeboids* accounting for <15 % and fungal remains representing ∼40 %.

Based on the spore/pollen data, the vegetational history *vis a vis* climate of the Pookot Lake area may be reconstructed for the past 3100 cal. years BP Pollen data suggest that the area was covered by upland tropical vegetation and wetland mangrove in the vicinity in variable frequencies for a considerable part of the time span studied. The presence of montane taxa viz., *Betula, Pinus*, *Alnus* etc. point to the long distance dispersal of their pollen grains from nearby high altitude sites. Our study reveals that during the 3100 cal. years BP, neither tropical upland taxa nor mangrove taxa are recorded. Thus, this phase represents an arid environment, though the preservation of biota also plays a role in the presence/absence of pollen in sediments cannot be ruled out. Subsequently, around 2200 cal. years BP and around 1400–1200 cal. years BP, climate got ameliorated for a short while as evident from the growth of tropical vegetation along with mangroves in the vicinity of the lake. Subsequently, ∼1000 cal. years BP, climatic conditions became favourable for the growth of various trees/shrubs along with mangrove taxa, indicating a shift towards a warm and humid climate that continues up to the Present.

Magnetic susceptibility (χ_{lf}) data

The 236–203 cm depth (3100–2500 cal. years BP; Fig. 4) is characterised by relatively high χ_{lf} values Thereafter, there is a sudden decrease; this trend persists up to 155 cm depth (∼1000 cal. years BP). However, this zone is interspersed with small peaks. After ∼1000 cal. years BP, χ_{lf} values are relatively high and exhibit an increasing trend. But this period is interrupted by a low-χ_{lf} sample at ∼566.5 cal. years BP (81–86 cm depth).

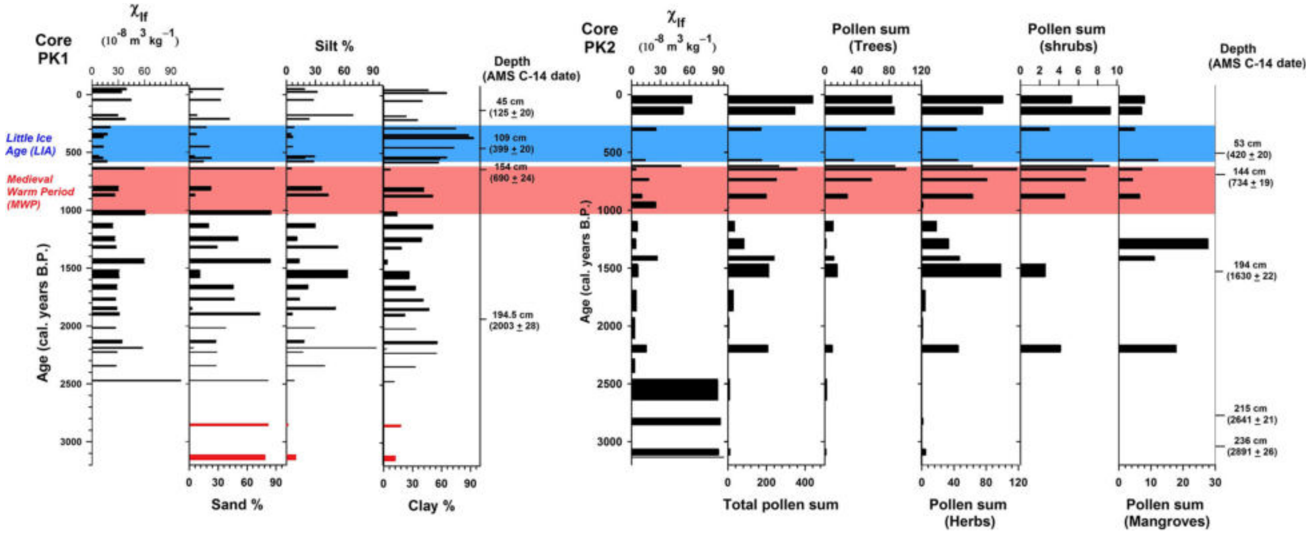

Fig. 4 Variations of magnetic susceptibility values, total pollen count, total counts of trees, herbs, shrubs and mangroves, and percentages of sand, silt and clay in cores PK1 and PK2 during the past 3100 years. (1) There is synchronicity between magnetic susceptibility data and total pollen sum, and total counts of trees, shrubs, and herbs except at the core bottom. (2) The high sand % in the core bottom might have led to the poor preservation of pollen grains. (3) Sand % exhibits a high positive correlation with χ_{lf}, but a negative correlation with clay %. (4) Variations in the aforementioned parameters indicate the two widely recognised global climatic events: the Medieval Warm Period (MWP) and the Little Ice Age (LIA)

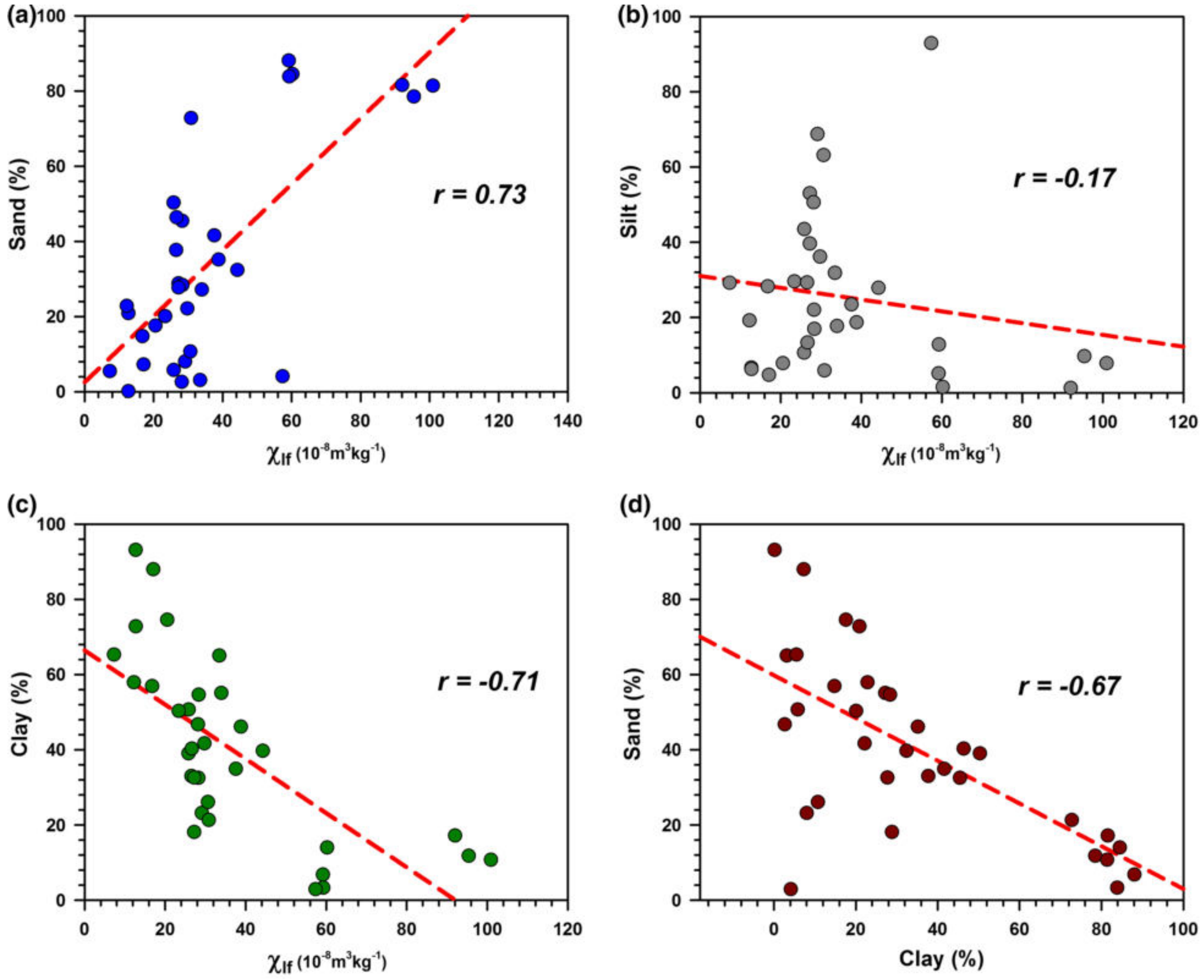

Fig. 5 Scatter plots of particle size and magnetic susceptibility data for representative samples of Pookot Lake sediments: **a** sand % vs. χ_{lf}; **b** silt % vs. χ_{lf}; **c** clay % vs. χ_{lf} and **d** sand % vs. clay %. The high χ_{lf} values are accompanied by high sand % and low clay %, indicating high-energy conditions due to high rainfall when coarse particles were transported to the lake

Particle size data

The three particle size classes (sand, silt and clay) exhibit considerable variability in the Pookot Lake sediment record (Fig. 4). The % sand, % silt and % clay range from 0.2 to 88, 1.2 to 93 and 3 to 93, respectively.

Particle size data reveal that the period 3100–2500 cal. years BP is characterised by a remarkably high sand content (78–81 %) but low silt (1.2–9.7 %) and clay (10.8–17.2 %) contents. This period is also characterised by high χ_{lf} values (89 to 89.7×10^{-8} m^3 kg^{-1}). Thereafter, there is a sudden decrease in sand % but an increase in clay %. The sand and clay fractions exhibit fluctuations but the peaks in χ_{lf} values correspond to peaks in sand % and troughs in clay %. There is a sudden decrease in the sand content and increase in the clay content during the period 600–150 cal. years BP when χ_{lf} values are also low. Sand content exhibits a good correlation with χ_{lf} data ($r = 0.73$; $n = 33$; $p < 0.01$; Fig. 5a). Silt % exhibits an insignificant correlation with χ_{lf} ($r = -0.17$; $p = 0.01$; $n = 33$; Fig. 5b), whereas clay % is negatively correlated with χ_{lf} ($r = -0.71$; $n = 33$; $p < 0.01$; Fig. 5c). Therefore, % sand is a mirror image of % clay ($r = -0.67$, $p = 0.01$; $n = 33$; Fig. 5d), which is also apparent from the down-core variation diagram (Fig. 4). It is interesting that % silt is only weakly correlated with χ_{lf}, although several studies have documented the occurrence of magnetic minerals in the silt fraction of sediments/soils (Walden and Addison 1995; Colman et al. 1990).

Discussion

Considering the palynological, magnetic and particle size data for the Pookot Lake sediment record, the palaeoenvironmental history of the region may be divided into three periods: (1) 3100–2500 cal. years BP), (2) 2500–1000 cal. years BP, and (3) 1000 cal. years BP to the Present.

The ~3100–2500 cal. years BP period

There is no mangrove or peripheral mangrove pollen recorded during this period. Therefore, this climatic zone probably experienced comparatively dry environmental conditions. However, the χ_{lf} values are profoundly high. In fact, they are the highest for the entire core (PK2). This is due to the large amount of pedogenic magnetite produced in the catchment as a result of high rainfall and a good number of wetting/drying cycles (Thompson and Oldfield 1986; Maher and Thompson 1995; Maher and Taylor 1988; Maher 2009). The formation of pedogenic magnetite is attributed to the mediation of iron-reducing bacteria in soils. During wetting, the soil environment becomes depleted in oxygen. The iron-reducing bacteria present in the soil become active and release Fe^{2+} ions which, on drying (re-oxidation), react with Fe^{3+} oxides to form magnetite (Maher 2009). Hence, iron in non-ferrimagnetic forms is converted to ferrimagnetic forms during the oxidation–reduction cycles that occur during pedogenic processes (Thompson and Oldfield 1986). Thus, the high amounts of pedogenic magnetite in soils (during high rainfall periods) are responsible for the high susceptibility values and vice versa. A good correlation between instrumental rainfall record and χ_{lf} data was documented for lake sediments of Thimmannanayakanakere (TK), Karnataka, southern India, based on which the climatic history of the region was reconstructed for the past 3700 years (Shankar et al. 2006). The reconstruction is bolstered by palaeoclimatic data from the Indian sub-continent and the adjacent Arabian Sea. Shankar et al.'s (2006) study and the geochemical studies by Warrier and Shankar (2009) showed that magnetic susceptibility may be used as a proxy for rainfall in the tropics. In view of this, we interpret the significantly high χ_{lf} values in this zone as an indicator of high rainfall compared to the Present.

Our interpretation of the Pookot Lake sediment data is further corroborated by the high % sand and the low % clay during 3100–2500 cal. year BP period. Based on high-resolution studies, Chen et al. (2004) proposed that on shorter time-scales (1 or 10 a), a larger particle size reflects a higher rainfall and a wetter climate and vice versa. They proposed that in tropical and sub-tropical regions, it is rainfall, and not lake level variation, that principally determines the particle size of lacustrine sediments. With a higher rainfall, coarser particles are transported to the centre of the lake due to the higher runoff, increased erosive power and greater transport capacity. However, during low-rainfall periods, only fine particles are transported to deep water regions of a lake due to the lower runoff, decreased erosive power and decreased transport capacity (Chen et al. 2004; Kashiwaya et al. 1987; Conroy et al. 2008; Peng et al. 2005). Hence, a coarser particle size reflects higher rainfall conditions and vice versa. In lakes situated in a hilly and mountainous region, an increase in precipitation would increase the transport capacity of surface runoff, which can then carry coarser particles and deposit them in the lake basin (Meyers et al. 1993; Schmidt et al. 2002). According to Morgan (2006), the prevalence of sand suggests high-energy depositional conditions, because larger particles may be entrained in the runoff. Such a model was used by many workers (Chen et al. 2004; Conroy et al. 2008; Peng et al. 2005; Schmidt et al. 2002). The extremely high % sand (average = 80.4) in this climatic zone must have resulted in the poor preservation of pollen grains as sediments dominated by coarse sand size fraction are not suitable for pollen preservation (Smith et al. 2012). This probably explains the queer association of high χ_{lf} values with low pollen content in this climatic zone. The near absence of pollen during 3100–2500 cal. years BP in the Pookot Lake sediment record is in agreement with Farooqui and Vaz's (2000) observations from the Pulicat lagoon.

Chauhan et al. (2010b) also documented an enhanced SW monsoon during this period (Fig. 6). According to Prasad et al. (1997), the overall climate was wetter than the Present during the period 3–2 ka, but the trend towards aridity had begun by 3 ka. However, Shankar et al. (2006) documented a very low rainfall prior to 2.5 cal. years BP based on the magnetic susceptibility data from Thimmannanayakanakere (TK) in Chitradurga, Karnataka (Fig. 6). This is because the two lakes experience entirely different climatic conditions at the Present: TK being situated in a semi-arid area has an average annual rainfall of 638 mm whereas PK is situated in the Sahyadri (the Western Ghat) with an average annual rainfall of ~4200 mm. Similarly, Kumaran et al. (2005) documented drying up of many of the marginal marine mangrove ecosystems since around 4000 $^{14}\mathrm{C}$ year BP, which is attributed to the gradual reduction in the monsoon strength. Caratini et al. (1991) inferred increasing aridity since 3500 $^{14}\mathrm{C}$ year BP from their studies of marine sediment cores off Karwar, Western India.

The 2500–1000 cal. years BP period

Rainfall was low during this period as evident from the relatively low χ_{lf} values. However, this period was interspersed with brief spells of strong monsoon as indicated by the small peaks in χ_{lf} values with corresponding peaks in %

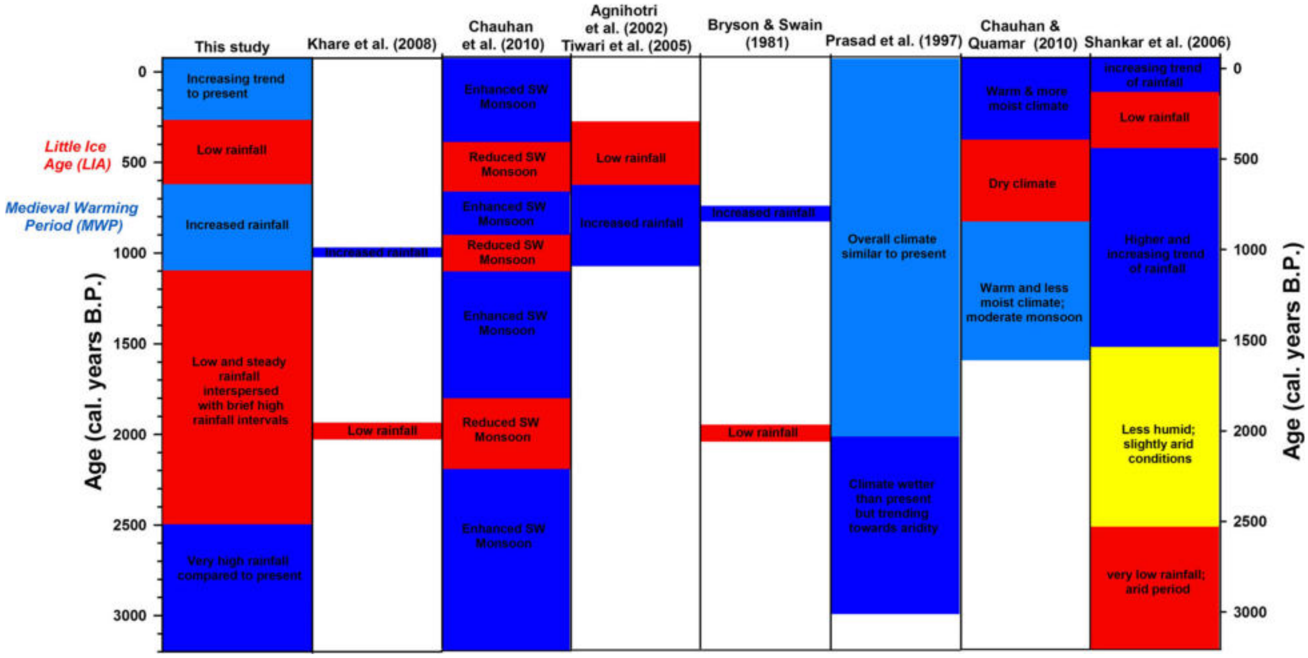

Fig. 6 Schematic diagram of climate variability during the Late Holocene from a few continental and marine records in the region

sand and troughs in % clay. This period is barren from a palynological point of view. Around 2000 cal. years BP, climatic conditions were not favourable as no pollen is recorded during this time. Around 2200 cal. years BP and 1500–1200 cal. years BP, the climate was moist for short periods, supporting the growth of mangrove in the vicinity of the lake. These periods were also characterised by a slight increase in χ_{lf} values. However, around 2200 cal. years BP % sand does not exhibit a corresponding increase; instead, % silt displays a sharp peak. Between 1500 and 1200 cal. years BP, % sand exhibits a sharp peak (Fig. 4). Earlier palynological studies from different parts of southern India also documented lower pollen contents during the periods 2599–2250 and 3100–2799 cal. years BP (Farooqui and Vaz 2000) and decline in mangrove trees (Khandelwal et al. 2006). The dry and wet conditions were recorded at around 2000 and 1000 cal. years BP, respectively (Khare et al. 2008) from the sedimentological and foraminiferal proxies of Arabian Sea sediment cores (Fig. 6). Chauhan et al. (2010a) documented arid periods around 450–650, 1000 and 2200–1800 cal. years BP Bryson and Swain (1981) documented scanty rainfall around 2000 cal. years BP.

The 1000 cal. years BP to the Present period

After 1000 cal. years BP, the climatic conditions became favourable for the growth of various types of trees/shrubs along with mangrove vegetation, indicating warm and humid climatic conditions (Fig. 4). The high-rainfall conditions favoured the growth of vegetation in the catchment area of the Pookot Lake which, in turn, led to greater pollen production and preservation. Such conditions persisted up to 600 cal. years BP; this time slice may probably be the Medieval Warm Period (MWP). However, this moist period is interspersed by a low-rainfall spell during 600–300 cal. years BP when vegetation growth was low as indicated by the low pollen percentages. The 600–300 cal. years BP period is also characterised by low χ_{lf} values, indicating a low rainfall. Hence, this time bracket is probably showing the generally cold and arid climate of the Little Ice Age (LIA) after which the southwest monsoon got intensified. The relatively high rainfall during the MWP and low rainfall during the LIA are also documented in other palaeomonsoon records from the region (Agnihotri et al. 2002; Tiwari et al. 2005; Chauhan et al. 2010a; Fig. 6). The varve thickness record from a sediment core off Pakistan (von Rad et al. 1999) also exhibits a similar pattern, with an increased runoff from the Indus River recorded during 1000–700 cal. years BP and a decreased runoff during 700–400 cal. years BP Chauhan and Quamar (2010) documented an increase in tropical sal deciduous forests during the period 1600–700 cal. years BP, which indicates warm and moist conditions. From 700 to 350 cal. years BP, tropical mixed deciduous forests registered an increase, which indicates warm and relatively less moist (weak monsoon) conditions. However, during 350 cal. years BP to the Present, deciduous sal forests increased again, indicating the predominance of warm and moist (strong monsoon) conditions once more.

Table 3 A summary of the behaviour of different proxies used in this investigation and their palaeoenvironmental and palaeomonsoonal interpretation

Period	Proxies			Palaeoclimatic interpretation
	Magnetic susceptibility (χ_{lf})	Particle size	Pollen	
1000 cal. years BP to the Present	Fluctuating χ_{lf} values. High values during ~1000–600 cal. years BP but low values during ~600–300 cal. years BP	Fluctuating % sand and % clay values. Average values of % sand high (50.1 %) and % clay low (43.7 %) during ~1000–600 cal. years BP but average % sand low (23 %) and average % clay high (47.3 %) during ~600–300 cal. years BP	Abundant in pollen when compared to earlier periods. High pollen % during ~1000–600 cal. years BP, but high pollen % during ~600–300 cal. years BP	Monsoon got strengthened compared to earlier periods. Rainfall was relatively low during the Little Ice Age and high during the Medieval Warm Period. Increasing trend of rainfall towards the Present
2500–1000 cal. years BP	Low χ_{lf} values interspersed with small peaks	Fluctuating % sand and % clay values. However, the average values of % sand decreased (36.4 %) and % clay increased (32.9 %) compared to earlier period	Devoid of pollen except during 1500–1200 cal. years BP when some mangrove pollen recorded	Low rainfall interspersed with brief spells of strong monsoon
3100–2500 cal. years BP	High χ_{lf} values	High % sand (average = 80.3 %) and low % clay (average = 13.7 %)	Devoid of pollen except around 2200 cal. years BP when some mangrove pollen recorded	Very high rainfall compared to the Present

An interesting observation made during this investigation is the good correspondence between pollen and χ_{lf} data, except a few samples. Pollen percentages of trees, shrubs and herbs are in tandem with magnetic susceptibility data (Fig. 4). For instance, a high representation of trees in the Pookot Lake region is well correlated with high magnetic susceptibility values. The periods characterised by high % sand are typified by high χ_{lf} values and vice versa. On the other hand, high % clay is associated with periods of low χ_{lf} values and vice versa (Fig. 4). Shankar et al. (2006) proposed χ_{lf} as a proxy for rainfall in tropical regions; geochemical (Warrier and Shankar 2009) and sedimentological (Warrier et al. 2014) lines of evidence were presented in support of the proposition. The pollen, magnetic and particle size data obtained in this study lend support to the proposition that χ_{lf} may be used as a proxy for rainfall even in high-rainfall areas (like the Pookot Lake region with a mean annual rainfall of 4200 mm) of tropical regions.

Reconstruction of the environmental and palaeomonsoonal changes in the Pookot Lake area based on a multi-proxy approach is summarised in Table 3.

Conclusions

Based on the pollen, magnetic susceptibility and particle size data, we present here an account of the vegetation history and climate for the past ~3100 years in the Pookot Lake region, southern India:

1. The vegetation and climate of Pookot Lake area have varied significantly during the past 3100 years.
2. The period ~3100–2500 cal. years BP was characterized by a significantly high rainfall compared to the Present. However, pollen grains of this period are poorly preserved due to the high sand content.
3. During ~2500–1000 cal. years BP, vegetation was sparse and the rainfall low. However, this period was interspersed by spells of relatively high rainfall when there was abundance of mangroves.
4. After 1000 cal. years BP, the monsoon got intensified, leading to the growth of various trees/shrubs along with mangrove taxa. The signatures of the Medieval Warm Period and the Little Ice Age are embedded in the pollen data for this period. Rainfall exhibits an increasing trend during the recent years.
5. The synchronicity between the pollen and magnetic susceptibility data lend credence to Shankar et al. (2006) proposition that magnetic susceptibility may be used as a proxy for rainfall in tropical regions, and in high-rainfall areas at that.

However, further studies based on multi-proxy data from long, continuous, undisturbed cores from many lakes are required to unravel the long-term palaeoclimatic and palaeoenvironmental history of southern India.

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