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Magnetic Susceptibility as a Proxy for Rainfall in the Tropics : New Data from Hirekolale Lake Sediments, Southern India

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ABSTRACT

In this paper, we present the environmental magnetic record of a sediment core from Hirekolale (HK) Lake situated in tropical Southern India and decipher the paleorainfall conditions of the region. We determined environmental magnetic properties and inter-parametric ratios for subsamples from a 1.1 m-long sediment core. Accelerator mass spectrometer ^{14}C dates, obtained on sedimentary organic matter, suggest that the core spans the past ~ 1250 years. The environmental magnetic data suggest the absence of greigite, biogenic and anthropogenic magnetite and of dissolution of magnetic minerals in the samples. Magnetic susceptibility is positively correlated with rainfall data for Peninsular India, All-India, Karnataka, and Chikkamagalur Station. Hence, magnetic susceptibility may be used as a proxy for rainfall in tropical regions. During the past ~ 1250 years, rainfall has varied significantly in the study area. During 1.25-0.79 cal. ka B.P., rainfall was profoundly low (= low χ_{lf} values). During 0.79-0.37 cal. ka B.P., it was relatively high (= relatively high χ_{lf} values). Rainfall was comparatively high (= significantly high χ_{lf} values) during 0.36 cal. ka B.P. to Present. Many high- and low-rainfall events documented in the HK χ_{lf} record are correlatable with similar ones in recorded in proxy climate data from different parts of India.

Keywords: Paleorainfall, Environmental magnetism, Proxy, Hirekolale, Southern India

I. INTRODUCTION

Rainfall and temperature are important components of the Earth's climate system that influence life on Earth. Extreme climatic events like floods and droughts, resulting from human-induced climate change, are reported from many parts of the world [1]. Through high-resolution paleoclimatic data, it is possible to understand the causes and mechanisms of climate change. By determining the past climatic changes quantitatively, it would be possible to model the future climatic scenario and the impact of anthropogenic activities on climate[2].

Lake sediments are a valuable archive of paleoclimatic data. They are more sensitive to climatic and environmental changes when compared to marine sediments because of their higher sedimentation rate and smaller areal extent. Hence, lake sediment data are of fine temporal resolution, which can be compared with instrumental data and historical records of climate [3] [4]. Lake sediments also have the potential to record regional as well as global climatic signals. Several proxies like organic and inorganic geochemistry [5] [6], particle size [7], stable isotopes of oxygen and carbon [8] [9], diatoms [10] [11] and pollen [12] have been used to determine the past climatic conditions. Many have attempted to estimate rainfall using magnetic susceptibility as a proxy. However, the focus has primarily been on lakes from temperate regions [13] [14] and on the Chinese loess plateau [15] [16] [17]. Such studies for tropical regions are limited. Based on the positive correlation between magnetic susceptibility of Thimmannanayakanakere (TK) Lake sediments and instrumental rainfall data, Shankar et al. (2006) proposed magnetic susceptibility as a proxy for rainfall in TK area in tropical Southern India (average annual rainfall = 638 mm yr^{-1}) [3]. They backed up their proposition with historical and proxy climate data from many diverse geographic locations. In addition, they put forth geochemical [5] and sedimentological [7] lines of evidence in support of the proposition. Sandeep et al. (2015) confirmed that magnetic susceptibility may be used as a rainfall proxy in tropical regions with high average annual rainfall (4200 mm/year) as well [18].

Here, we have investigated the environmental magnetic properties of a sediment core from Hirekolale Lake from tropical Southern India with the following objectives: to test Shankar et al.'s (2006) proposition in a tropical area with medium rainfall (1925 mm/year); and to reconstruct paleorainfall variations in HK area using high-resolution magnetic susceptibility data.

A. Study Area

For the present study, Hirekolale Lake (13°21'34''N; 75°42'30''E), Chikkamagalur District, Karnataka, Southern India, was selected (Figure 1). The lake is situated at an elevation of 1138 m. It covers an area of ~ 1.09 x 10^5 m^2. The average water depth is ~ 6 m. According to an inscription at the lake site, a dam was constructed in AD 1967. The lake is surrounded by the Bababudan Range of hills in the north. The main source of water and sediment to the lake is the small streams that drain the surrounding hills. Anthropogenic perturbations may be ruled out as the lake is situated away from human settlements, industries and pollution sources. Agriculture is being carried out to the east of the lake; as this area has a relatively low elevation (~1120 m), agricultural activity here may not have an influence on sedimentation in HK lake. There is no record of deforestation near the study area.

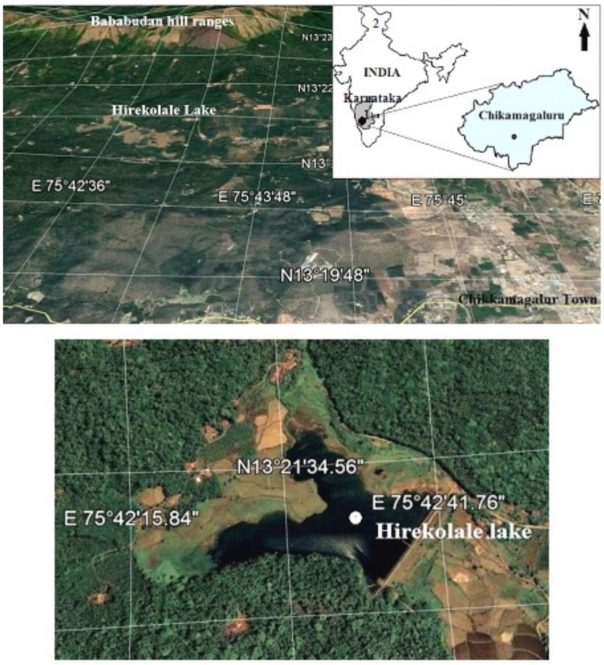

Figure 1. Location of Hirekolale Lake in Chikkamagalur District, Karnataka, southern India. Sample location is shown by a white dot. Location of the Chikkamagalur meteorological station is marked by a red star in the inset map. Location of the Thimmannanayakanakere, Chitradurga and Tsokar Lake, Ladakh is marked as 1 and 2 respectively.

No large river contributes sediments to the lake; hence, the climate signal is not brought from afar but principally derived from the lake catchment. Because of the small size of the lake, it is reasonable to expect that local / regional climate is recorded by the HK sediments. The catchment rocks come under the Bababudan Group of the Dharwar Supergroup with granitic gneisses, schists and banded iron formations [19]. Black soil occurs around the Bababudan Hill range whereas red loamy and sandy soils are seen in the southern part of Chikkamagalur District. The temperature varies from 11 °C to 20 °C during winter and from 25 °C to 32 °C during summer. The annual average rainfall is 1925 mm that is received mainly during the southwest monsoon (http://chickmagalur.nic.in/htmls/dic_main.htm).

II. MATERIALS AND METHODS

A. Sample Collection

A 1.1 m-long sediment core was collected from the centre of Hirekolale Lake (~ 6 m water depth) by driving a PVC pipe (0.064 m diameter) into the sediment bed. After the sediment had entered the PVC pipe, it was retrieved carefully and the overlying water removed. The core was stored in a freezer until it was sampled to prevent microbial activity. The core was sub-sampled using a stainless steel knife at 0.3-m interval to obtain high-resolution paleoclimatic data. Care was taken throughout to avoid contamination from iron and rust particles.

B. Geochronology

To obtain a timeframe for the HK sediment core, carbon-14 dating by accelerator mass spectrometry was carried out on the organic matter of bulk sediment samples at the Xi'an Accelerator Mass Spectrometer Center, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China. The ^{14}C ages were calibrated using the code clam [20], which runs on the open source software 'R' (R Development Core Team 2010) and uses the IntCal09.14C calibration curve [21] [22]. Based on the dates obtained, an age-depth model (Figure 2) was constructed and the age for each sample depth calculated using the linear interpolation model. The sedimentation rate was calculated using the age-depth model.

C. Environmental Magnetic Measurements

Standard techniques outlined by Walden (1999) were adopted for environmental magnetic measurements [23]. Approximately 3 to 6 g of sediment sample each was tightly packed in pre-weighed, 8-cm^3, cylindrical, non-magnetic plastic bottles. The samples were tightly packed to avoid movement of particles within the bottle, which would affect remanence measurements. After the magnetic measurements, the samples were oven-dried at ~ 35 °C. A range of magnetic parameters was determined on the samples (Table 1). The dry weight of the samples was used for expressing the magnetic parameters on a mass-specific basis. All the magnetic parameters are expressed in Standards International (SI) units.

Low- and high-frequency magnetic susceptibility (χ_{lf} and χ_{hf} at 0.47 and 4.7 kHz) were determined on a Bartington susceptibility meter (Model MS2B) with a dual frequency sensor. The sensor was calibrated using the standard (1 % Fe_3O_4) provided by the manufacturer. Mass-specific magnetic susceptibility (χ_{lf}) was calculated from the data obtained with the MS2B meter. Frequency-dependent susceptibility (χ_{fd}) was calculated from the difference between low- and high-frequency susceptibility values.

An anhysteretic remanent magnetisation (ARM) was induced in the samples using a Molspin demagnetizer with an ARM attachment. The demagnetizer produces an alternating magnetic field of 100 milli Tesla (mT). While the alternating field was reduced at the rate of 0.016 mT/ cycle, a small, constant direct current (DC) magnetic field (0.04 mT) was superimposed on the sample [24]). A Molspin spinner fluxgate magnetometer was used to measure the ARM. Susceptibility of ARM (χ_{ARM}) was obtained by dividing the mass-specific ARM by the size of the biasing field [23].

A Molspin pulse magnetiser was used to induce an isothermal remanent magnetisation (IRM) in the samples at different field strengths: initially at 20 mT, followed by progressively larger fields (100, 300 and 600 mT), culminating with the maximum field (1000 mT) attainable at the Environmental Magnetism Laboratory of Mangalore University. The remanence acquired by the sample was measured using the Molspin spinner fluxgate magnetometer [24]. The isothermal remanence induced at 1T field was considered as the saturation isothermal remanent magnetisation (SIRM).

Table 1. Rock Magnetic Parameters And Inter-Parametric Ratios, Their Units And Interpretation [24] [25]

Parameter or ratio and its units	Indicative of
Mass-specific magnetic susceptibility (χ_{lf}) (10^{-8} m^3 kg^{-1})	Concentration of magnetic minerals
Frequency-dependent susceptibility (χ_{fd}) (10^{-8} m^3 kg^{-1})	Concentration of superparamagnetic (SP) grains
Percentage frequency-dependent susceptibility (χ_{fd}) (%)	Concentration of SP grains
Susceptibility of anhysteretic remanent magnetisation (χ_{ARM}) (10^{-5} m^3 kg^{-1})	Concentration of single domain (SD) ferrimagnetic minerals
Saturation isothermal remanent magnetisation (SIRM) (10^{-5}A m^2 kg^{-1})	Concentration and grain size of remanence-carrying minerals
SIRM/χ_{lf} (10^3 A m^{-1})	Magnetic grain size and mineralogy. The higher the ratio, the coarser the grain size. But values > 40 indicate greigite
χ_{ARM}/SIRM (10^{-5} m A^{-1})	Magnetic grain size and concentration of remanence-carrying SD minerals. The higher the ratio, the finer the grain size
χ_{ARM}/χ_{lf}	Magnetic grain size. The higher the ratio, the finer the grain size
χ_{ARM}/χ_{fd}	Magnetic grain size. The higher the ratio, the finer the grain size
S-ratio	Magnetic mineralogy (relative proportions of ferrimagnetic and anti-ferromagnetic minerals)
"Hard" isothermal remanent magnetisation (HIRM) (10^{-5} A m^2 kg^{-1})	Concentration of magnetically "hard" minerals like hematite and goethite

Table 2. Radiocarbon Ages And Calibrated Ages Of Hirekolale Lake Sediment Samples

Depth (cm)	Laboratory code	δ^{13}C (‰)	^{14}C age	Calibrated age (Cal. yr. B.P.)	Calibrated age range (Cal. yr. B.P.)
0-0.9	XA14021	-28.70	Modern sample	-	-
81.6-82.2	XA14025	-23.74	1047 ± 28	960	941-978
109.8-110.4	XA14026	-24.49	1329 ± 28	1264	1237-1291

Inter-parametric ratios like χ_{ARM}/χ_{lf}, χ_{ARM}/χ_{fd}, χ_{ARM}/SIRM, SIRM/χ_{lf}, and S-ratio (IRM_{300mT} / SIRM) were calculated to determine magnetic mineralogy and magnetic grain size (Table 1) [26] [27]. An S-ratio value close to 1 signifies the dominance of magnetically "soft" minerals like magnetite and maghemite whereas profoundly low values indicate the dominance of magnetically "hard" minerals like hematite and goethite. "Hard" isothermal remanent magnetisation (HIRM) is a measure of the concentration of anti-ferromagnetic minerals; it was calculated by subtracting the IRM_{300mT} value from the SIRM value (Evans and Heller 1994). The magnetic parameter and inter-parametric ratio values obtained for the samples were plotted against their respective ages using SIGMAPLOT v. 11.

III. RESULTS & DISCUSSION

A. Chronology

The chronology of the HK Lake sediment core is provided by three AMS ^{14}C dates from depths of 0-0.09 m, 0.816-0.822 m and 1.098-1.104 m (Table 2). The ^{14}C dates indicate that the core spans the past 1.25 cal. ka B.P.

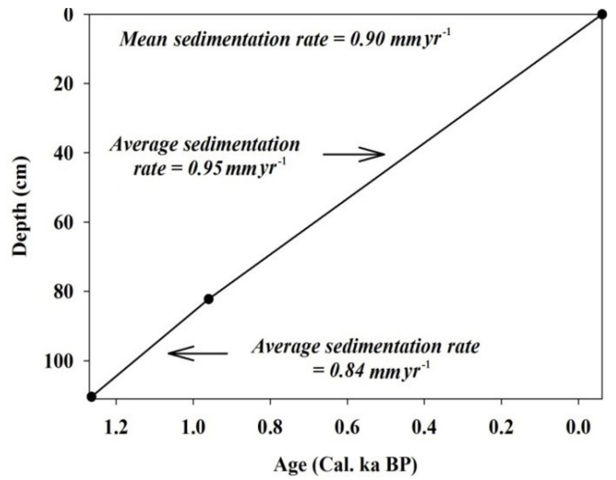

Figure 2. Age-depth model for the Hirekolale Lake sediment core.

We agree that only three radiocarbon dates are available for the HK core, which are insufficient to provide a secure chronological framework for the 1.1-m long core. In the absence of more C-14 dates, the age-depth model (Figure 2) presumes that there was no slumping or bioturbation of sediments and there was conformable deposition at HK with no episodes of fast sedimentation. The average sedimentation rate is 0.84 mm yr^{-1} for the period 1.26-0.96 cal. ka B.P. and 0.95 mm yr^{-1} for the period 0.96 cal. ka B.P.-Present. The mean sedimentation rate for the entire sediment column is 0.90 mm yr^{-1}, which is comparable with 0.99 mm $yr^{-1}$for Thimmannanayakanakere, Chitradurga [3] and 0.95 mm yr^{-1} for Tsokar Lake, Ladakh [28].

B. Origin of Magnetic Minerals

Depending on their origin, catchment-derived magnetic minerals may be primary or secondary. Primary magnetic minerals are inherited from parent rocks whereas secondary magnetic minerals form during pedogenesis. During chemical weathering, the iron contained in ferromagnesian minerals is leached out. The ferrous ions are oxidised under suitable Eh-pH conditions to form magnetite [29]. This magnetite is, therefore, secondary and may be termed pedogenic. High rainfall and temperature accentuate pedogenesis. As temperature is more or less constant in tropical regions over time scales of a few millennia, rainfall becomes the dominant factor governing pedogenic magnetite formation. Thus, high (low) rainfall would produce a high (low) amount of pedogenic magnetite/ maghemite (high χ_{lf} and SIRM) [3]. As pedogenic magnetite/ maghemite is ultrafine grained and superparamagnetic (SP), a high (low) amount of pedogenic magnetite would give rise to high (low) values of χ_{fd} [24].

It appears that pedogenic magnetic minerals can form relatively rapidly. Our earlier study of a soil profile from HK catchment documented magnetic enhancement in the top-soil [30]. Post-monsoon sampling of the soil profile in October also documented magnetic enhancement. One would normally expect obliteration of the magnetic enhancement signal due to top-soil erosion, resulting from rainfall during the monsoon season (~ 1925 mm yr^{-1}). The fact that the soil profile was magnetically enhanced again after the monsoon season is proof enough for the rapid formation of pedogenic magnetite. Sandeep et al. (2012) too reported pedogenic magnetite formation and magnetic enhancement of top-soil in the catchment of Pookot Lake in Southwestern India in a relatively short period [31]. The Pookot catchment soil magnetic data are even more convincing because pedogenic magnetite formed within two months after the heavy monsoonal rains (~ 4000 mm yr^{-1}) had washed out all the previously formed pedogenic magnetite. Maher and Thompson's (1995) study of the Chinese loess and paleosol deposits documented that pedogenic susceptibility is a rapidly formed soil property [29]. Taylor et al. (1987) also reported that pedogenic magnetite can be synthesised in the laboratory in 36 to 2720 minutes under pH and temperature conditions similar to the natural soil environment [32].

In the following paragraphs, we discuss and evaluate our data for the presence of bacterial magnetite, greigite and anthropogenic magnetite in the HK sediments.

The bi-logarithmic plot of χ_{ARM}/χ_{lf} *vs.* χ_{ARM}/χ_{fd} [33] for HK Lake sediments is displayed in Figure 3. It is used for differentiating the sources of sediments. When bacterial magnetite is present, χ_{ARM}/χ_{lf} and χ_{ARM}/χ_{fd} ratios exhibit considerably high values, i.e., > 40 and > 1000 respectively [33] [34] and plot in a distinct envelope in the bi-plot of the two ratios [33] [35].

The average χ_{ARM}/χ_{lf} ratio value of HK sediments is 3.62 (range: 0.15 to 7.49). The lowest χ_{ARM}/χ_{lf} value was recorded around 1.09 cal. ka B.P. and the highest around 0.45 cal. ka B.P. The average value of χ_{ARM}/χ_{fd} is 55.97 (range: 2.27 to 174.78). The lowest χ_{ARM}/χ_{fd} ratio value was recorded about 0.98 cal. ka B.P. and the highest about 1.00 cal. ka B.P. A χ_{ARM}/SIRM ratio value of > 200 x 10^{-5} m A^{-1} also indicates the presence of bacterial magnetite [36].

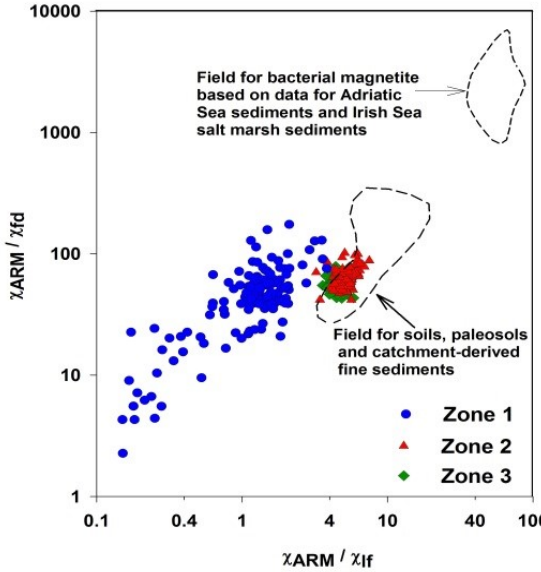

Figure 3. Bi-logarithmic plot of $\chi_{ARM}/\ \chi_{lf}$ *vs.* $\chi_{ARM}/\ \chi_{fd}$ for Hirekolale Lake sediments [33].

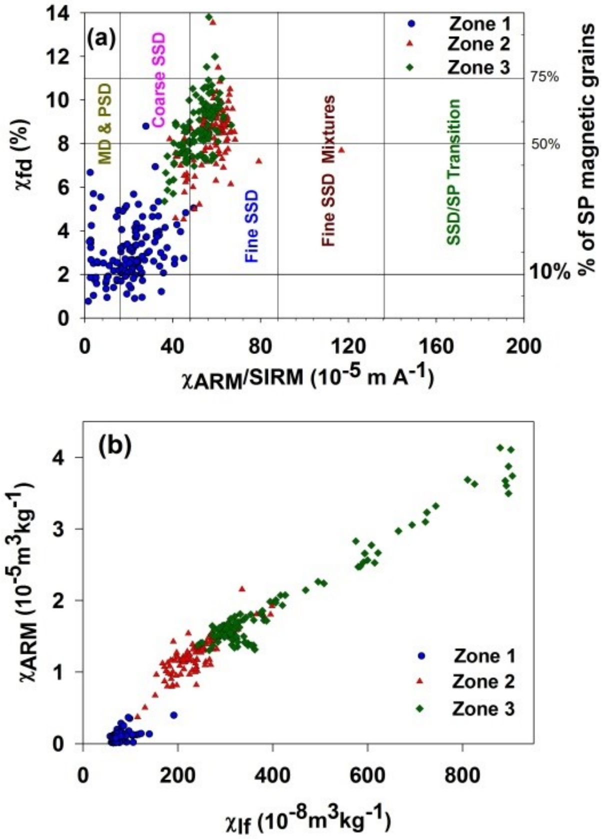

Figure 4. Bi-plots of magnetic parameters and inter-parametric ratios indicating the magnetic grain size of HK lake sediment samples. (a) Scatter plot of X_{ARM}/SIRM *Vs.* X_{fd} [39] [40], and (b) Bi-plot of X_{lf} *Vs.* X_{ARM} (King's Plot) [41].

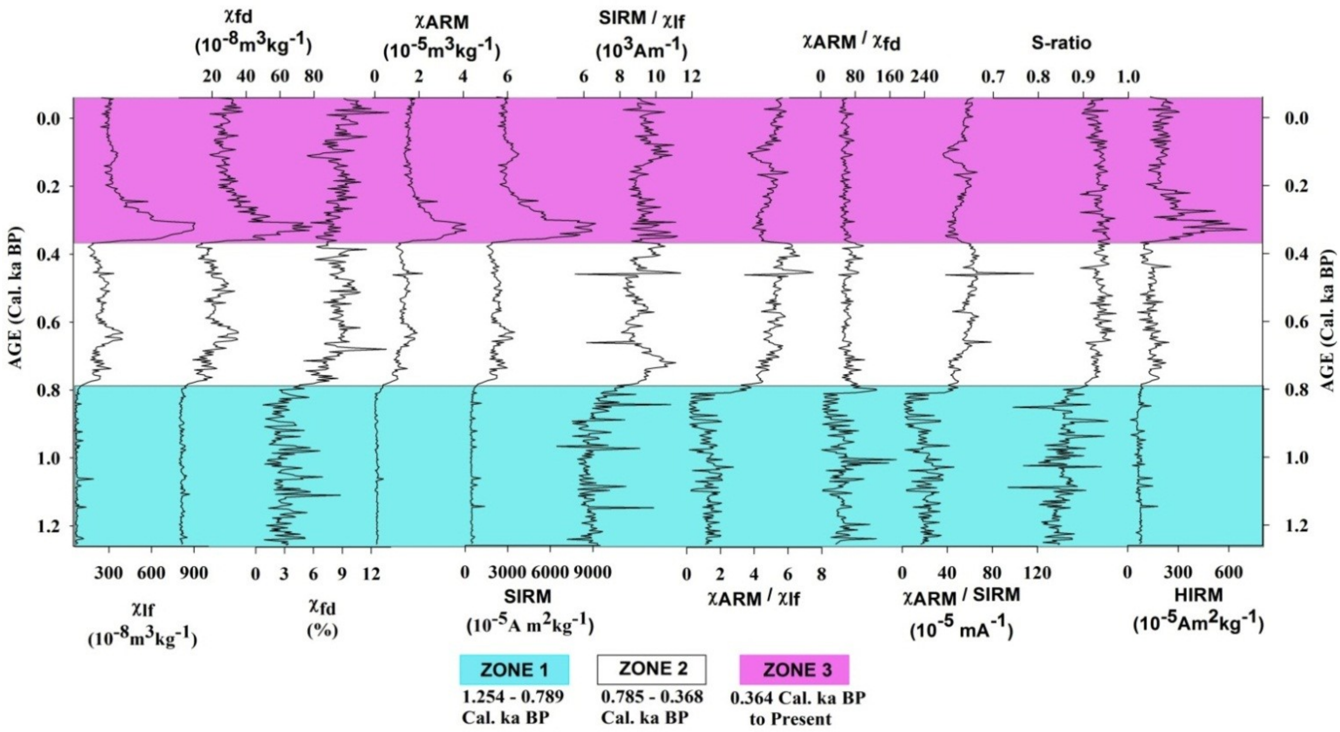

Figure 5. Down-core variations of rock magnetic parameters and inter-parametric ratios for the Hirekolale lake sediment core. Note: Three zones have been differentiated based on variations in χlf.

But the average χ_{ARM}/SIRM ratio value of HK is < 200 x 10^{-5} m A^{-1} in all the three zones. This indicates the absence of bacterial magnetite in HK sediment samples. An SIRM/χ_{lf} value of > 40 x 10^3 A m^{-1} indicates the presence of greigite, which forms under reducing conditions [25] [37] [38] [24]. However, the SIRM/χ_{lf} values of < 40 x 10^3 A m^{-1} indicate the absence of greigite in HK sediments (Figure 5). Hence, the possibility of greigite contributing to the HK magnetic signal may be ruled out. There is no coarsening of magnetic grain size (= no steep increase in magnetic grain size ratio values). Hence, dissolution of magnetic minerals in HK sediments may be discounted.

A scatter plot of χ_{ARM}/SIRM *vs.* χ_{fd} % [39] [40] for the HK sediment samples is shown in Figure 4a. It helps one decipher the magnetic grain size and also the contribution from superparamagnetic (SP) grains. The magnetic properties of anthropogenic magnetic minerals differ from those of naturally produced ones [42] in having a coarse magnetic grain size like multi-domain and pseudo-single domain (MD and PSD) [43] [44]. Values of χ_{ARM}/SIRM indicate magnetic grain size: < 16 x 10^{-5} m A^{-1} - Multi-domain and pseudo-single domain (MD+PSD); 16 to 48 x 10^{-5} m A^{-1} - Coarse stable single domain (coarse SSD); 48 to 88 x 10^{-5} m A^{-1} - Fine SSD; 88 to 136 x 10^{-5} m A^{-1} - Fine SSD mixture; and 136 to 200 x 10^{-5} m A^{-1} - SSD/Superparamagnetic (SSD/SP) transition. Samples having relatively high χ_{fd} % values have a higher % of SP grains.

Most of the samples from Zone 1 (Figure 4a) have coarse SSD grain size; but a few have MD + PSD grain size. The SP grain percentage is < 50. Such magnetic minerals may be lithogenous [45] [46] [47]. The possibility of their anthropogenic origin may be ruled out as the lake is situated away from industries and pollution sources. Samples from Zones 2 and 3 plot in the fine SSD region whereas a few do so in the coarse SSD region (Figure 4) and have ~ 50 % contribution from SP grains. These data indicate that the magnetic minerals present in these zones formed during pedogenesis [27] [35]. This contention is also supported by high values of χ_{fd} % in Zone 2 (average = 8.37) and Zone 3 (average = 8.67).

The χ_{ARM} *vs.* χ_{lf} bi-plot, also known as the King's plot (Figure 4b) [41], is used to decipher both the concentration and the (magnetic) grain size of magnetic minerals [6] [43] [48] [49] [50]. The King's plot for samples of HK sediments suggests that Zone 1 has a lower concentration of magnetic minerals when compared to Zones 2 and 3. Figure 5 also indicates that Zone 1 is made up of magnetically coarse grained minerals whereas Zones 2 and 3 contain fine grained magnetic minerals.

Zone 1 contains a higher proportion of magnetically 'hard' minerals like hematite and goethite as evident from the relatively low S-ratio values (average = 0.85) compared to Zones 2 (average = 0.93) and 3 (average = 0.94; Figure 5) [37] [51]. Peaks in HIRM values at some depths indicate the presence of high-coercivity magnetic minerals like hematite and goethite in the samples (Figure 3). The relatively high S-ratio value of HK sediments (average = 0.90) indicates that the HK sediments are dominated by magnetically "soft" minerals. Besides, the statistically significant correlation between χ_{lf} and χ_{fd} (r = 0.97, n = 367, 1% level of significance) indicates that the HK magnetic signal is controlled by pedogenic magnetite. Based on the above discussion, it is evident that HK sediments constitute a natural archive of paleoclimatic data.

C. Relationship between Magnetic Susceptibility and Instrumental Rainfall Data

In spite of the uncertainty in the age-depth model and variations in sedimentation rate, we attempted correlation between χ_{lf} and instrumental rainfall data (Figure 6). Magnetic susceptibility data were correlated with annual rainfall data (4-year moving average) for the AD 1930 to AD 2011 period for Peninsular India, All-India, Karnataka (http://www.tropmet.res.in; Indian Institute of Tropical Meteorology), and Chikkamagalur Station (India Meteorological Department and Karnataka State Natural Disaster Monitoring Centre).

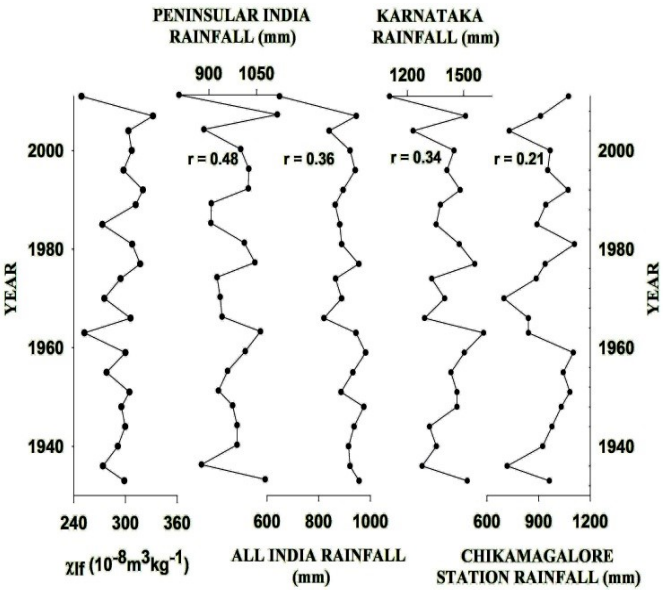

Figure 6. Correlation of magnetic susceptibility (χ_{lf}) of HK sediments with instrumental rainfall data (4-year moving average) for peninsular India, All-India, Karnataka and Chikkamagalur Station.

Magnetic susceptibility is positively correlated with rainfall data (n = 22) for Peninsular India (r = 0.48, p = 0.023), All-India (r = 0.36, p = 0.10), Karnataka (r = 0.34, p = 0.11) and Chikkamagalur Station (r = 0.21, p = 0.23). It may be noted that dam construction in AD 1967 may have had some effect on the sedimentation rate and hence on the χ_{lf}-rainfall correlation. The lowest rainfall (4-year moving average) of Peninsular India (805.97 mm), All-India (648.39 mm) and Karnataka (1105.51 mm) was recorded for AD 2011, which corresponds to the lowest χ_{lf} value (248.98 x10^{-8} $m^3\,kg^{-1}$).

The lowest rainfall (698.55 mm) of Chikkamagalur Station also corresponds to a trough (275.49 x 10^{-8} m^3 kg^{-1}) in χ_{lf} values. The highest χ_{lf} value (331.92 x 10^{-8} $m^3\,kg^{-1}$) corresponds to the highest rainfall of 1115.16 mm for Peninsular India during AD 2007. The highest rainfall of 981.52 mm for All-India during AD 1959 corresponds to a peak (299.97 x 10^{-8} $m^3\,kg^{-1}$) in the χ_{lf} curve. However, the highest rainfall (1605.81 mm) of Karnataka during AD 1963 corresponds to a trough in χ_{lf} (252.35 x 10^{-8} m^3 kg^{-1}). This may be because Chikkamagalur Station received a relatively low rainfall (841.05 mm) during AD 1963. Another possible reason for the mismatch could be uncertainty in the chronology, and the comparison of χ_{lf} data with 4-year moving average rainfall data. The highest rainfall of 1108.03 mm for Chikkamagalur Station corresponds to a peak in the χ_{lf} curve (307.82 x 10^{-8} m^3 kg^{-1}). Based on the statistically significant positive correlation of χ_{lf} with instrumental rainfall data, we suggest that χ_{lf} may be used as a proxy for rainfall in a tropical region like HK with medium rainfall (1925 mm yr^{-1}).

D. Paleorainfall Variations during the Past ~ 1250 Years

From the foregoing discussion, it is apparent that the HK sediment magnetic signal is catchment-derived and not attributable to anthropogenic magnetite, biogenic magnetite and greigite or to dissolution of magnetic minerals. This is borne out by the presence of pedogenic SP magnetite (high χ_{fd} % values) in the HK sediments, and magnetic enhancement of top-soil from HK catchment [30]. Further, HK χ_{lf} is positively correlated with instrumental rainfall data for the past 80 years. Therefore, it appears reasonable to suggest that χ_{lf} variations in the HK sediment core are related to paleorainfall variations. Based on this premise, we reconstructed paleorainfall variations in the study area. In doing so, we presume that there was no slumping or bioturbation of sediments and there was conformable deposition at HK with no episodes of rapid sedimentation. The dam construction in AD 1967 may have subsequently increased the sedimentation rate in the lake; to that extent, dates younger than AD 1967 would be affected.

Down-core variations of rock magnetic parameters for the HK sediment core are displayed in Figure 5 and the Pearson's correlation matrices for concentration-dependant environmental magnetic parameters given in Table 3. Based on the variation in χ_{lf}, HK core may be divided into three zones: Zone 1 (1.25 – 0.79 cal. ka B.P.), Zone 2 (0.78 – 0.37 cal. ka B.P.*)* and Zone 3 (0.36 cal. ka B.P. – Present).

In Zone 1, magnetic susceptibility (χ_{lf}) exhibits low values, ranging from 57.18 to 191.40 x 10^{-8} m^3 kg^{-1}. The average χ_{lf} value is 75.85 x 10^{-8} m^3 kg^{-1}. Other concentration-dependant magnetic parameters like χ_{fd}, χ_{ARM} and SIRM also display similar trends. The ranges of these values are from 0.63 to 6.76 x 10^{-8} m^3 kg^{-1}, from 0.010 to 0.39 x 10^{-5} m^3 kg^{-1} and from 355.71 to 1380.94 x 10^{-5} A m^2 kg^{-1} respectively (Figure 5). The average values of χ_{fd}, χ_{ARM} and SIRM respectively are 2.20 x 10^{-8} m^3 kg^{-1}, 0.10 x 10^{-5} m^3 kg^{-1} and 496 x 10^{-5} A m^2 kg^{-1}. The % frequency-dependent susceptibility value (χ_{fd} %) ranges between 0.63 and 6.76 and the average χ_{fd} % value is 3.03. A relatively low concentration of magnetic minerals, as indicated by the low values of χ_{lf} and other concentration-dependant parameters, indicates a relatively low rainfall.

Magnetic susceptibility is correlated weakly with χ_{fd} (r = 0.27, p = 00), moderately with χ_{ARM} (r = 0.48, p = 00) and strongly with SIRM (r = 0.83, p = 00) (Table 3a; n = 140) suggests a low concentration of pedogenic magnetic minerals. The ranges (average value in parentheses) of magnetic grain size ratio values are: SIRM/χ_{lf} = 6.51 to 10.82 x 10^3A m^{-1} (6.5 x 10^3 A m^{-1}), χ_{ARM}/χ_{lf} = 0.15 to 3.82 (1.32), χ_{ARM}/χ_{fd} = 2.27 to 174.78 (49.05), and χ_{ARM}/SIRM = 1.59 to 49.53 x 10^{-5} m A^{-1} (20.64 x 10^{-5} m A^{-1}). Low values of magnetic grain size-related ratios (χ_{ARM}/χ_{lf}, χ_{ARM}/χ_{fd}, and χ_{ARM}/SIRM) indicate a coarser magnetic grain size. This is suggestive of low rainfall and weak chemical weathering and weak pedogenesis in the catchment. As a result, the production of pedogenic magnetic minerals was low. A relatively high rainfall was recorded around 1.06, 1.15 and 1.24 cal. ka B.P. Rainfall was deficient about 0.87 and 0.92 cal. ka B.P.

The sediments of Zone 2 register a two-fold increase in χ_{lf}, χ_{fd}, χ_{ARM} and SIRM values (Figure 5), indicating a relatively high rainfall. Magnetic susceptibility values range between114.88 and 398.54 x 10^{-8} m^3 kg^{-1} and the average value is 242.33 x 10^{-8} m^3 kg^{-1}. The χ_{fd}, χ_{ARM} and SIRM values range respectively from 5.2 to 35.39 x 10^{-8} m^3 kg^{-1} (average = 20.59 x 10^{-8} m^3 kg^{-1}), from 0.37 to 2.15 x 10^{-5} m^3 kg^{-1} (average = 1.26 x 10^{-5} m^3 kg^{-1}) and from 901.92 to 3502.44 x 10^{-5} A m^2 kg^{-1}(average = 2194.09 x 10^{-5} A m^2 kg^{-1}.

Relatively high χ_{fd} % values compared to Zone 1 are documented in this zone and they range between 4.52 and 13.55 (average = 8.38). Relatively high values of magnetic grain size-related inter-parametric ratios (χ_{ARM}/χ_{lf}, χ_{ARM}/χ_{fd}, and χ_{ARM}/SIRM) indicate a finer magnetic grain size. Their ranges (average values in parentheses) are: χ_{ARM}/χ_{lf} = between 3.23 and 3.82 (average = 5.22), χ_{ARM}/χ_{fd} = between 41.62 and 101.53 (average = 63.74), and χ_{ARM}/SIRM = between 38.49 and 116.76 x 10^{-5} m A^{-1} (average = 57.59 x 10^{-5} m A^{-1}).

The relatively high values of concentration-dependant parameters and the strong positive correlation (n = 114) of magnetic susceptibility with χ_{fd} (r = 0.90, p = 00), χ_{ARM} (r = 0.86, p = 00) and SIRM (r = 0.90, p = 00) (Table 3b) indicate that the magnetic signal is dominated by pedogenic magnetic minerals. This is suggestive of a relatively high rainfall and relatively strong chemical weathering and pedogenesis in the catchment.

Zone 3 samples exhibit very high values of concentration-dependant magnetic parameters during the beginning of this period; however, they decrease and remain steady afterwards (Figure 5). Magnetic susceptibility values range from 242.98 to 905.89 x 10^{-8} m^3 kg^{-1} and the average value is 408.99 x 10^{-8} m^3 kg^{-1}. The χ_{fd}, χ_{ARM} and SIRM values range respectively from 18.64 to 78.86 x 10^{-8} m^3 kg^{-1} (average = 34.54 x 10^{-8} m^3 kg^{-1}), from 1.35 to 4.13 x 10^{-5} m^3 kg^{-1} (average = 1.99 x 10^{-5} m^3 kg^{-1}) and from 2236.21 to 9196.22 x 10^{-5} A m^2 kg^{-1} (average = 3881.35 x 10^{-5} A m^2 kg^{-1}). The χ_{fd}% value ranges between 5.35 and 13.81 (average = 8.67). All the high values indicate a significantly high rainfall during 0.36 cal. ka B.P. – Present.

Table 3. Pearson's Correlation Matrices For Concentration-Dependant Rock Magnetic Parameters For The Three Zones In The Hirekolale Lake Sediment Core

(a) Zone 1 samples (1254 -789 cal. yr. B.P.) (n = 140)				
	χ_{lf}	χ_{fd}	χ_{ARM}	SIRM
χ_{lf}	1			
χ_{fd}	0.27	1		
χ_{ARM}	0.48	0.35	1	
SIRM	0.83	0.16	0.32	1
(b) Zone 2 samples (782-368 cal. yr. B.P) (n = 114)				
	χ_{lf}	χ_{fd}	χ_{ARM}	SIRM
χ_{lf}	1			
χ_{fd}	0.90	1		
χ_{ARM}	0.86	0.85	1	
SIRM	0.90	0.80	0.73	1
(c) Zone 3 samples (364 cal. yr. B.P. - Present) (n = 116)				
	χ_{lf}	χ_{fd}	χ_{ARM}	SIRM
χ_{lf}	1.00			
χ_{fd}	0.94	1.00		
χ_{ARM}	0.98	0.94	1.00	
SIRM	0.99	0.90	0.97	1.00

Magnetic susceptibility is significantly correlated (n = 116) with χ_{fd} (r = 0.94, p = 00), χ_{ARM} (r = 0.98, p = 00) and SIRM (r = 0.99, p = 00) (Table 3c). The statistically significant positive correlation between χ_{lf} and χ_{fd} suggests that the magnetic signal is dominantly controlled by pedogenically formed magnetic minerals. It is reasonable to surmise that a high concentration of pedogenic magnetic minerals formed due to the intense chemical weathering and strong pedogenesis induced by high rainfall. The average values of SIRM /χ_{lf}, χ_{ARM}/χ_{lf}, χ_{ARM}/χ_{fd} and χ_{ARM}/SIRM ratios are 9.44 x 10^3A m^{-1}, 4.85, 56.71 and 51.66 x 10^{-5} m A^{-1} respectively. The fine magnetic grain size (= high values of magnetic grain size-related ratios like χ_{ARM}/χ_{lf}, χ_{ARM}/χ_{fd} and χ_{ARM}/SIRM) suggest high rainfall conditions during this period. Considerably high concentrations of magnetic minerals are recorded during the period 0.36-0.28 cal. ka B.P. A significantly high rainfall was recorded around 0.31 cal. ka B.P (significantly high χ_{lf} value of 905.89 x 10^{-8} m^3 kg^{-1}) and low rainfall during 0.03 cal. ka B.P. (low χ_{lf} value of 242.49 x 10^{-8} m^3 kg^{-1}).

E. Comparison of χ_{lf} Data with Incoming Solar Radiation (Insolation)

We compared the incoming solar radiation (insolation) (at 14° N latitude, June 21; Figure 7) for the past 1200 years with HK χ_{lf} data to check whether insolation has any control on HK rainfall [52].

We are aware, in this context, of the uncertainty in our C-14 dates and possible variations in sedimentation rate. A moderate correspondence may be seen between insolation and HK χ_{lf} data (Figure 7). A lower rainfall during 1.25-0.79 cal. ka B.P. corresponds to low insolation during this period. The relatively high rainfall during 0.79-0.37 cal. ka B.P further corresponds to an increase in insolation. From 0.36 cal. ka B.P. to Present, HK received an even higher rainfall with an increase in insolation.

However, there is no corresponding peak in insolation for the χ_{lf} peak around 330 cal. yr. B.P. This χ_{lf} peak is also documented in other paleoclimatic records (Figure 8 b, c and f), for example in the Thimmannanayakanakere (TK) χ_{lf} record, Pookot χ_{lf} record and Gupteshwar speleothem δ^{18}O record. Considering the correspondence between insolation and χ_{lf} data, we interpret that insolation seems to have had an influence on monsoonal rainfall. Shankar et al. (2006) too demonstrated that insolation had an influence on the southwest monsoon during the past 3700 years [3]. Bhattacharyya and Narasimha (2005) analysed the relationship between four solar indices and seven regional Indian Monsoon rainfall time series between AD 1871 and AD 1990, and concluded that the Indian monsoon rainfall is controlled by solar activity [53].

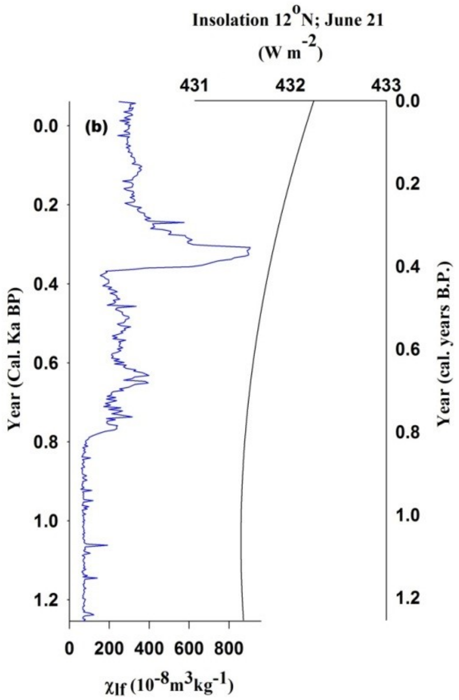

Figure 7. Comparison of HK χ_{lf} data with insolation data (14° N latitude, June 21) [52].

F. Comparison with Other Paleoclimatic Records from the Region

We compared the HK Lake sediment χ_{lf} record (Figure 8a) with the χ_{lf} record from Thimmannanayakanakere, Chitradurga (Figure 8b) [3], χ_{lf} record from Pookot Lake, Wayanad (Figure 8c) [18], δ^{18}O of Akalagavi speleothem (Figure 8d) [54], ring-width index of a teak tree from Kerala (Figure 8e) [55] and δ^{18}O of Gupteshwar speleothem (Figure 8f) [56].

Again, we are aware of the limitations imposed by the uncertainty in geochronology and the possible variations in sedimentation rate while comparing the data. Hirekolale catchment recorded a high rainfall (=

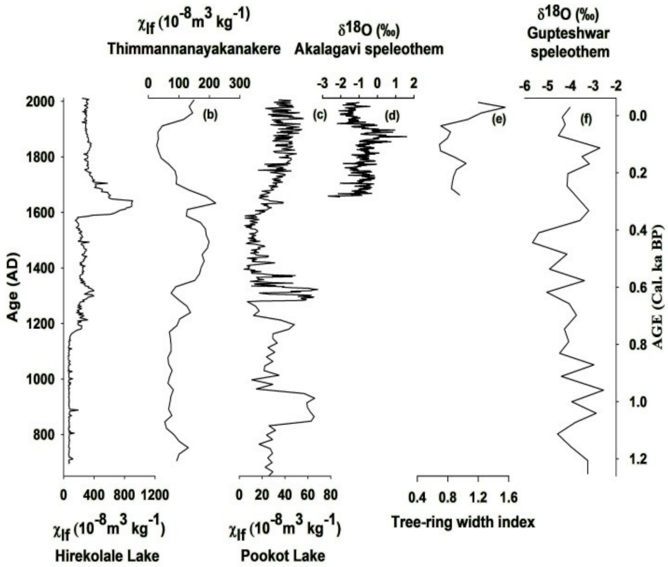

Figure 8. Comparison of **(a)** HK sediment χ_{lf} record with **(b)** Sediment χ_{lf} record from Thimmannanayakanakere, Chitradurga [3]; **(c)** Sediment χ_{lf} record from Pookot Lake, Wayanad District [18]; **(d)** δ^{18}O of Akalagavi speleothem [54]; **(e)** Ring-width index of a teak tree from Kerala [55] and **(f)** δ^{18}O of Gupteshwar speleothem [56].

high χ_{lf} values) during AD 1642. This high-rainfall event corresponds to the small maximum between the Maunder and Spörer Minima. Shankar et al. (2006) too reported high rainfall during AD 1642 for Chitradurga region from Thimmannanayakanakere sediment χ_{lf} data (Figure 8b) [3]. Yadava et al. (2004) suggested that the Akalagavi speleothem growth started around 1666 AD (ER1) when rainfall was high (Figure 8d) [54]. Borgaonkar et al. (2010) too documented a high rainfall during AD 1665 in a tree-ring from Southern India (Figure 8d) [55].

During AD 1650 Pookot Lake catchment (Figure 8c) was also characterised by high rainfall as suggested by the small peak in the Pookot χ_{lf} record [18]. It appears that this high-rainfall event is widespread across the Indian subcontinent. The relatively high rainfall record of HK during AD 1493 may be correlated with the high rainfall of AD 1505 recorded by Shankar et al. (2006) [3] and Borgaonkar et al. (2010) [55] after allowing a margin for dating errors. Hirekolale Lake received a relatively low rainfall during 1.25 -0.79 cal. ka B.P. A similar trend is also documented in the TK χ_{lf} record during this period. Sandeep et al. (2015) too recorded a relatively low rainfall during 1.25-0.79 cal. ka B.P. [18].

The AD 1876-1877 drought recorded in the proxy data of TK χ_{lf}, Akalagavi speleothem δ^{18}O and Kerala tree-ring width record is not documented in the HK sediment χ_{lf} record. The AD 1777 drought recorded by Yadava et al. (2004) too is not documented in the HK χ_{lf} data but the AD 1796 drought appears as a small trough in χ_{lf} during AD 1791 in the HK data. The AD 1675 and AD 1695 drought years documented by Yadava et al. (2004) [54] are not seen in the HK χ_{lf} record. These drought years are also recorded by Borgaonkar et al. (2010) [55]. Such inconsistencies would have arisen from dating uncertainties or from the spatial variability of the Indian monsoon [57]. A relatively high rainfall recorded during AD 1165-1351 coincides with the Medieval Warm Period (MWP; AD 1100 - AD 1400). Magnetic susceptibility data of Pookot Lake [18] and Thimmannanayakanakere [3] have also documented a relatively high rainfall during MWP. Reconstructed rainfall data using the Gupteshwar speleothem record suggest a relatively high rainfall during MWP [58] [59].

III. CONCLUSIONS

We draw the following conclusions based on the environmental magnetic investigations of the Hirekolale Lake sediment core:

1. The HK sediment magnetic signal is mainly catchment-derived and not attributable to anthropogenic magnetite, biogenic magnetite and greigite or dissolution of magnetic minerals.

2. Magnetic susceptibility is positively correlated with rainfall (n = 22) for Peninsular India (r = 0.48,

p = 0.023), All-India (r = 0.36, p = 0.10), Karnataka (r = 0.34, p = 0.11) and Chikkamagalur Station (r = 0.21, p = 0.23).

3. Paleorainfall has been reconstructed for the HK region for the past ~ 1250 years, which has many similarities with instrumental rainfall data and other published paleorainfall reconstructions for Southern India.
4. Moderate correspondence of the HK χ_{lf} data with insolation for the past 1200 years underscores the Sun's influence on the southwest monsoon.

5. Many of the high- and low-rainfall events discerned in this study are correlatable with published proxy climate data from different parts of India; for e.g., lake sediment χ_{lf} records, speleothem $\delta^{18}O$ data and tree ring-width index.

6. Magnetic susceptibility may be used as a rainfall proxy in tropical regions even with a moderate rainfall regime (1925 mm yr^{-1}).

7. Thus, this study shows that the HK lake sediments constitute a natural archive of paleorainfall data, and that magnetic susceptibility can be used as a proxy for rainfall in tropical regions with moderate rainfall. The study demonstrates the potential for application in other tropical regions.

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