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Rock Magnetic Investigations of Surface and sub-surface soil Samples from five Lake Catchments in Tropical Southern India

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ABSTRACT: Iron oxide minerals in soils provide valuable insights into pedogenic processes. A wealth of such information has been obtained by rock magnetic investigations on temperate soils but similar studies on *tropical* soils are rare. Here, we report rock magnetic data on pristine soil profiles and surficial soils from five catchments in the tropical southern India and throw light on the pedogenic processes. We ruled out contributions from greigite, bacterial magnetite and anthropogenic sources; hence, the magnetic signal is mainly from the catchment, principally pedogenic and, thus, has a climatic signature embedded in it. The Pookot profile from a high rainfall (~4000 mm/year) region does not exhibit any magnetic enhancement at the surface. In fact, there is hardly any difference between surface and sub-surface samples, which reflects on its deeply weathered nature as a result of the high rainfall. The Shantisagara profile exhibits lessivage of magnetic minerals, resulting in a thick magnetically enhanced zone. It shows the highest χ_{lf} values among the five profiles studied. The Thimmannanayakanakere (TK) and Ayyanakere (AK) soil profiles do not exhibit any magnetic enhancement of top-soil. In fact, χ_{lf} values increase towards the profile-bottom, suggesting top-soil erosion, besides contribution of magnetic minerals from parent rocks. In the TK profile, there is a clear distinction between surface and sub-surface samples, the former being magnetically coarser grained. The Kurburukere profile exhibits moderate to strong χ_{lf} values and a mild magnetic enhancement at the surface.The data would be useful for establishing soil-sediment linkages for paleoclimatic studies of lake sediments.

Key words: Rock magnetism, Magnetic enhancement, Tropical soils, Pedogenesis, Erosion, Lessivage

INTRODUCTION

Iron is one of the essential constituents of soils and an important plant nutrient. It exists in the form of iron oxide phases like magnetite, maghemite, hematite, goethite and limonite in soils depending upon the environmental conditions. Iron oxides are produced in soils as a result of chemical weathering/pedogenesis which, in turn, is influenced by climatic conditions prevalent in the area. Thus, fluctuations in climate may initiate changes in chemical weathering processes, leading to changes in the iron oxide concentration, magnetic grain size and/or mineralogy. Hence, the iron oxide minerals can be valuable pedogenic indicators (Cornell and Schwertmann, 2003; Schwertmann, 1988). Rock magnetic methods have the advantages of being simple, rapid, inexpensive, sensitive and non-destructive. Also, the changes in iron oxide mineralogy, grain size and concentration associated with pedogenesis may be appraised effectively using rock magnetic methods. Soil magnetic investigations are useful for the evaluation of pedo-environmental conditions and processes in soils (Jordanova *et al.,* 2011). Rock magnetic methods have been successfully used in studies of loess-paleosol sequences (Orgeira *et al.,* 2003; Bloemendal and Liu, 2005), lake sediments (Shankar *et al.,* 2006; Warrier and Shankar, 2009; Foster *et al.,* 2008) and archaeological sites to decipher the past climate (Warrier *et al.,* 2011).Considerable work has been carried out on magnetic enhancement of top-soils and its relation to climate (Fine *et al.,* 1989; Maher *et al.,* 2003; Maher and Taylor, 1988). Soil magnetic properties may also be influenced by parent rock type (Shenggao, 2000), bacterial magnetite (Fassbinder *et al.,* 1990) and anthropogenic activities (Gautam *et al.,* 2004; Blaha *et al.,* 2008).

Most of the soil magnetic investigations concerned the temperate soils (Blundell *et al.,* 2009), the Russian Steppe (Maher *et al.,* 2003), the loess-paleosol sequence from China (Wang *et al.,* 2006;

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Maher and Thompson, 1995) and modern soils and paleosols from the U.S.A. (Guyodo *et al.,* 2006; Geiss *et al.,* 2008). Only limited studies dealt with soils from the tropics (Ortega–Guerrero *et al.,* 2004; van Dam *et al.,* 2005) where the variations in temperature are insignificant whereas those of rainfall are profound. In the Indian context, there have been only a few soil magnetic studies. Sangode et al. (2008) and Sangode and Bloemendal (2004) studied the magnetic properties of loess-paleosols of the Himalayan region. Magnetic mapping of urban soils from cities like Delhi (Maiti *et al.,* 2005; Meena *et al.,* 2011) and Pune (Sangode *et al.,* 2010) was also carried out, but these studies mainly focused on pollution aspects. Priya (2009) carried out rock magnetic investigations of soils developed on different lithologies and under different rainfall regimes of Karnataka region in Southern India.

In this study, rock magnetic investigations of surface and sub-surface soil samples from the catchment areas of five lakes situated in different rainfall regimes in the tropical Southern India were studied. The main objectives of this work are: (a) to determine the concentration, grain size and mineralogy of magnetic minerals in the soils; (b) to document magnetic enhancement in top-soils, if present; (c) explore soil-related processes, and (d) to magnetically characterize the soils. These objectives would, in turn, help in understanding pedogenesis in *tropical* regions and in establishing soil-lake sediment linkages that will be useful in paleoclimatic studies of lake sediments.

We collected surface and sub-surface soil samples from the catchment areas of five lakes in tropical southern India: the Pookot Lake (PK), Thimmannanayakanakere (TK), Shantisagara (SS), Ayyanakere (AK) and Kurburkere (KK; Fig. 1). The soil profiles are located well away from industries and other pollution sources. Therefore, the data obtained should reflect natural pedogenic processes. The mean annual rainfall in these areas ranges from ~ 638 to ~ 4000 mm. A summary of the location, rainfall, climate, soil type and lithology of the five sites is given in Table 1.

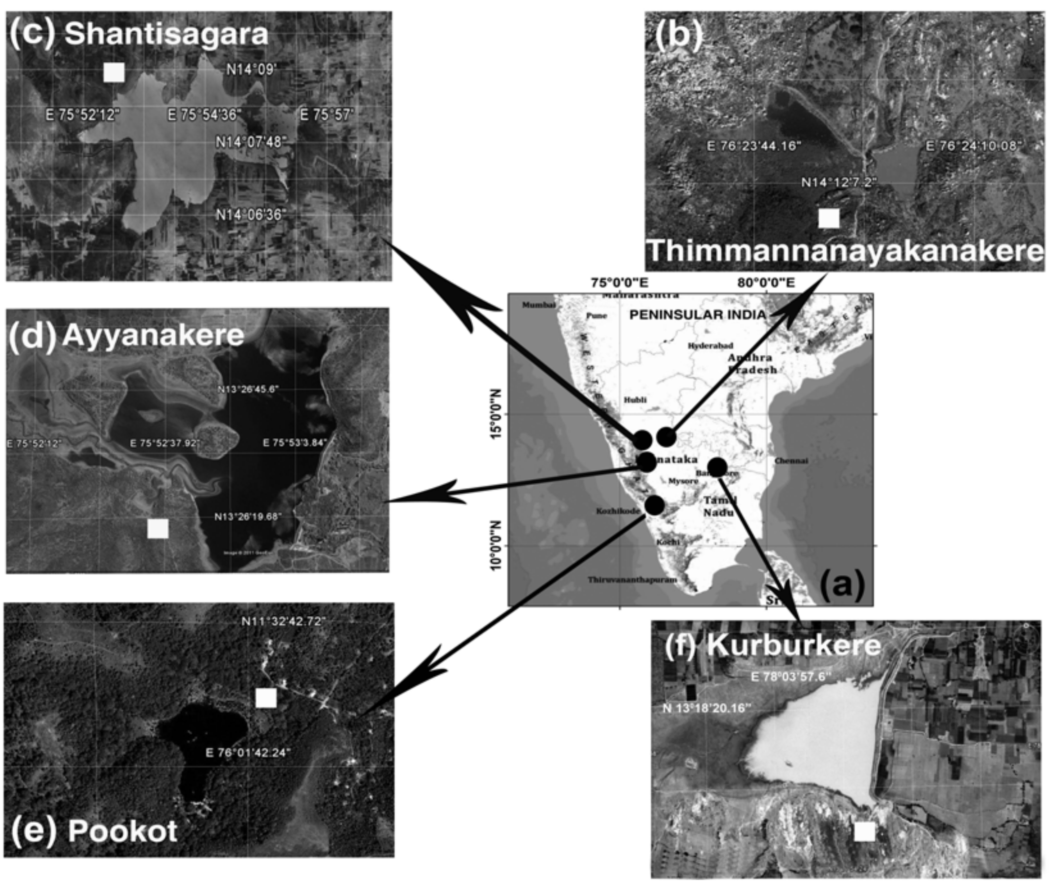

Fig. 1. Map showing the locations of Pookot, Shantisagara, Thimmannanayakanakere, Ayyanakere and Kurburkere lakes (a). Locations of soil profiles are shown by white squares (b, c, d, e and f)

Table 1. A summary of the geographical co-ordinates, rainfall, climate, soil type and lithology of the five soil profile locations. (India Meteorological Department, 2005, 2008; Kerala Forest Department, 2004; Soman, 1997; Radhakrishna and Vaidyanadhan, 1997; Gazetteer of India, 1965, 1985)

Sl. No.	Name of the lake catchment	Date of sampling	Geographic coordinates	Location	Mean annual rainfall (mm)	Mean annual temperature (^{0}C)	Soil type	Parent material
1	Pookot Lake (PK)	November 2007	11^{o}32'35"N 76^{o}01'40"E	Vythiri, Wayanad district, Kerala	~ 4000	Min = ~21 Max = ~ 38	Ferruginous forest loamy soil	Hornblende-biotite gneiss
2	Shantisagara (SS)	November 2007	14^{o}08'54"N 75^{o}53'11"E	Davanagere district, Karnataka	~ 795	Min = ~22.2 Max = ~ 35.8	Reddish brown clayey loam	Chlorite schist
3	Thimmannanayakanakere (TK)	July 2006	14°12'27"N 76°24'40"E	Chitradurga district, Karnataka	~ 638	Min = ~ 16.6 Max = ~ 41	Red loamy and sandy soil	Granitic gneiss
4	Ayyanakere (AK)	June 2007	13^{o}26'22"N 75^{o}52'34"E	Chikmagalur district, Karnataka	~ 1925	Min = ~ 12 Max = ~ 35	Red loamy and sandy soil	Hornblende gneiss
5	Kurburkere (KK)	May 2007	13^{o}18'22.16"N 78^{o}03'57.6"E	Chikkaballapur district, Karnataka	~ 740	Min = ~ 10 Max = ~ 40	Red loamy and sandy soil	Migmatite

MATERIALS & METHODS

Samples were collected from exposed soil profiles, using wooden knives to avoid contamination from iron and rust. Prior to sampling, the outer weathered portion of the surface was gently scraped to expose the fresh surface. Samples were collected at close intervals (2 cm) up to 20 cm depth, and at slightly sparser intervals thereafter. Besides this, samples of surface soil from additional locations were also collected. The samples were tightly packed in neatly labeled polythene covers and transported to the laboratory.

Standard techniques were used for sample preparation (Walden, 1999a). Soil 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-cm^3 non-magnetic plastic bottles. A range of magnetic parameters was determined on the samples (Dearing, 1999, Walden *et al.,* 1999; Thompson and Oldfield, 1986).

Magnetic susceptibility at low (0.47 kHz; χ_{lf}) and high (4.7 kHz; χ_{hf}) frequencies was determined on a Bartington Susceptibility Meter (Model MS2B) with a dual-frequency sensor. The sensor was calibrated by using the Fe_3O_4 (1%) standard supplied by the manufacturer. Frequency-dependent susceptibility (χ_{fd}-%) was calculated from the difference between low- and high-frequency susceptibilities (Dearing, 1999).

Anhysteretic remanent magnetisation (ARM) was induced in the samples using a Molspin AF demagnetiser (with an ARM attachment) set with a peak alternating field of 100 mT and a DC biasing field of 0.04 mT. The ARM induced was measured on a Molspin spinner fluxgate magnetometer. The susceptibility of ARM (χ_{ARM}) was calculated by dividing the mass-specific ARM by the size of the biasing field (0.04 mT = 31.84 Am^{-1}; Walden, 1999b).

Isothermal remanent magnetisation (IRM) was induced in the samples at different field strengths (20, 60, 100, 300, 500 and 1000 mT) using a Molspin pulse magnetiser. The isothermal remanence induced at 1T field (the maximum field attainable in the Environmental Magnetism Laboratory at Mangalore University) was considered as the saturation isothermal remanent magnetisation (SIRM). The remanence acquired was measured using the Molspin spinner fluxgate magnetometer. Inter-parametric ratios like S-ratio, χ_{ARM}/χ_{lf}, χ_{ARM}/SIRM and SIRM/χ_{lf} were calculated to determine the magnetic mineralogy and grain size (Walden, 1999b). The magnetic measurements, their interpretation and instrumentation are given in Table 2 (after Thompson and Oldfield, 1986; Maher, 1988; Oldfield, 1991).

RESULTS & DISCUSSION

Surface and sub-surface soil samples from the catchment area of Pookot Lake (PK)

The environmental magnetic parameters and inter-parametric ratios for the soil profile (n=24) from the catchment area of Pookot Lake are plotted in Fig . 2. This profile may be divided into three zones based on the values of concentration-dependent parameters, namely χ_{lf}, χ_{ARM} and SIRM (Fig. 2). Zone 3 (100-69 cm), the bottom most zone, has the lowest values for all the concentration-dependant parameters. In Zone 2 (69-5 cm), the values are slightly higher and do not exhibit noticeable fluctuations. Zone 1 (5-0 cm) has relatively high values that peak abruptly at the profile-top. Frequency-dependent susceptibility, which is proportional to the concentration of superparamagnetic grains (pedogenic component; Dearing *et al.*, 1996), and χ_{ARM}, which is proportional to the concentration of stable single domain (SSD) grains (Walden, 1999a), also exhibit trends similar to that of χ_{lf} (Fig. 2). Hence, it may be inferred that the concentrations of SP and SSD grains are higher in the profile-top sample compared to the sub-surface ones.

The top two samples exhibit an average χ_{lf} value of 463.8 x 10^{-8} m^3 kg^{-1} whereas the rest of the profile shows values in the range of 80.3 to 319.4 x 10^{-8} m^{3}kg^{-1} (average = 257.8 x 10^{-8} m^3 kg^{-1}). Similarly, the average χ_{fd} and χ_{ARM} values for the top two samples are 45.9 x 10^{-5} m^3 kg^{-1} and 2.9 x 10^{-8} m^3 kg^{-1} respectively, whereas the remainder of the profile shows χ_{fd} values ranging from 4.6 to 31.9 x 10^{-8} m^{3}kg^{-1} (average = 20.1 x 10^{-8} m^{3}kg^{-1}) and χ_{ARM} values ranging from 0.4 to 1.4 x 10^{-8} m^3 kg^{-1} (average = 0.95 x 10^{-8} m^3 kg^{-1}). The relatively high χ_{fd} and χ_{ARM} values for the top two samples are suggestive of magnetic enhancement of the surface soil. Besides, these parameters (χ_{ARM} and χ_{fd}) exhibit a statistically significant correlation coefficient of 0.84 ($p < 0.01$, n=12) with χ_{lf}, indicating that magnetic susceptibility is enhanced mainly by the ultra-fine pedogenic component in the samples.

What is the cause for such magnetic enhancement? The high values of concentration-dependant parameters may result from pedogenesis, the effect of fire, anthropogenic activities or the presence of bacterial magnetite. Natural fires or crop-burning may cause thermal transformation of weakly magnetic iron oxides, hydroxides and carbonates to ferrimagnetic magnetite or maghemite in the presence of organic matter (Le Borgne, 1955; Kletetschka and Banerjee, 1995). Burnt surface soils exhibit noticeably sharp peaks in susceptibility values compared to sub-surface samples. But in the PK soil profile, the enhancement is not remarkable (Fig. 2). The degree of magnetic enhancement is reported to be highly variable,

Table 2. Magnetic measurements, their interpretation and instrumentation (after Thompson and Oldfield, 1986; Maher, 1988; Oldfield, 1991)

Magnetic measurements and their units	Interpretation	Instruments used
Low- and high-frequency susceptibility χ_{lf} and χ_{hf} (10^{-8} m^3 kg^{-1})	Proportional to the concentration of magnetic minerals	Bartington susceptibility meter
Frequency-dependent susceptibility χ_{fd} (10^{-8} m^3 kg^{-1})	Proportional to the concentration of superparamagnetic grains	Susceptibility meter with a dual-frequency sensor
Susceptibility of Anhysteretic Remanent Magnetization (ARM) χ_{ARM} (10^{-5} m^3 kg^{-1})	Proportional to the concentration of magnetic minerals of stable single domain size range	AF-demagnetiser with ARM attachment and fluxgate magnetometer
Isothermal Remanent Magnetisation and Saturation Isothermal Remanent Magnetisation IRM and SIRM (10^{-5} A m^2 kg^{-1})	Proportional to the concentration of magnetic minerals	Pulse magnetizer and fluxgate magnetometer
Hard Isothermal Remanent Magnetisation HIRM (SIRM-IRM_{300mT}) (10^{-5} A m^2 kg^{-1})	Proportional to the concentration of magnetically 'hard' minerals like haematite and goethite	
χ_{ARM}/χ_{lf}	Indicative of magnetic grain size. A higher ratio indicates a finer grain size.	
χ_{ARM} /SIRM	Indicative of magnetic grain size with a higher ratio, suggesting a finer grain size.	
SIRM/χ_{lf}	Indicative of magnetic grain size with higher ratio, suggesting a coarser grain size.	
S-ratio (IRM_{300mT}/SIRM)	Relative proportions of ferrimagnetic and anti-ferromagnetic minerals (high ratio = A relatively higher proportion of magnetite).	

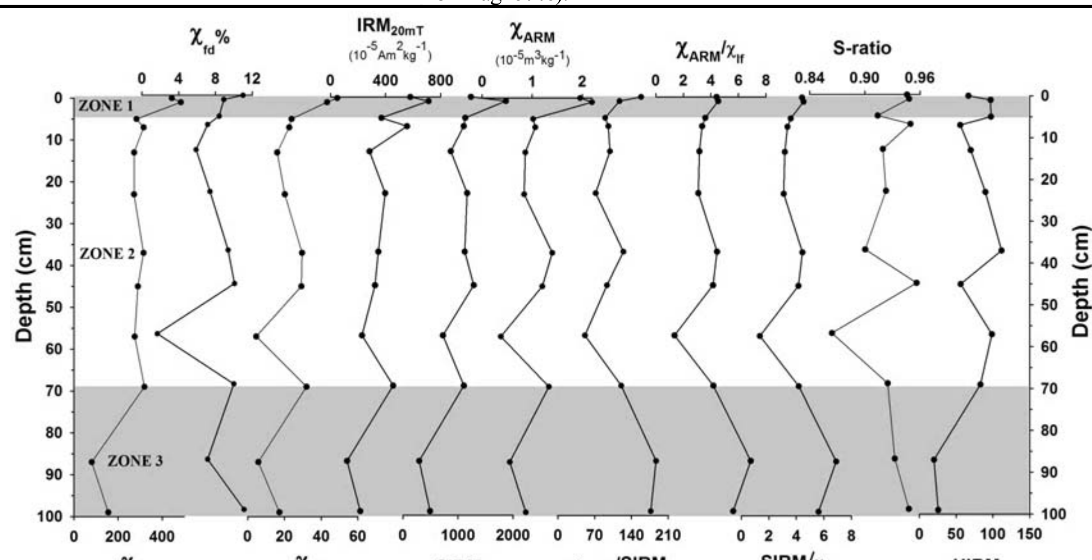

Fig. 2. Rock magnetic parameters and inter-parametric ratios for a soil profile developed on hornblende-biotite gneiss in the Pookot Lake (PK) catchment. ***Note:*** **The profile may be divided into three zones based on magnetic parameters: Zone 1 is a magnetically enhanced zone with higher values of concentration-dependent parameters (χ_{lf}, χ_{fd}, χ_{ARM} and SIRM) and a finer magnetic grain size (χ_{ARM}/SIRM and χ_{ARM}/χ_{lf}). Zones 2 and 3 are typified by relatively lower concentrations of magnetic minerals**

depending on the organic matter content, temperature of burning, availability of pre-existing iron minerals and soil porosity (Evans and Heller, 2003). Oldfield and Crowther (2007) documented a maximum susceptibility range of 1480-10700 x 10^{-8} SI units for burnt soils, which is highly variable. Fig. 3 is a biplot of χ_{ARM}/SIRM *vs.* χ_{fd} % (Dearing *et al.,* 1997) that shows the magnetic grain size distribution in soil samples from the five catchments. None of the PK soil samples plot in the MD/PSD envelope, indicating that the magnetic minerals are not anthropogenic (Fig. 3). Bacterial magnetite may influence the magnetic signal of soils. Its presence in natural materials may be detected principally by high-resolution SEM/TEM studies on magnetic mineral extracts. However, certain inter-parametric ratios like χ_{ARM}/χ_{lf} and χ_{ARM}/χ_{fd} have been used to detect the presence of bacterial magnetite (Oldfield, 1994). If the χ_{ARM}/χ_{lf} value is < 40 and the χ_{ARM}/χ_{fd} value < 1000, bacterial magnetite is absent (Oldfield, 1994, 2007). Oldfield (1994) proposed a biplot of χ_{ARM}/χ_{lf} *vs.* χ_{ARM}/χ_{fd} to distinguish between a variety of sources of magnetic minerals present in natural materials (Fig. 4). Almost all the PK soil samples fall in the envelope for "soil, paleosol and catchment-derived fine sediments" and none in the "bacterial magnetite" field. Based on the afore-mentioned reasons, the magnetic enhancement documented in the PK soil samples may be attributed to pedogenesis.As mentioned earlier, pedogenic enhancement of soils is governed principally by rainfall in the *tropics*. Thus, the climatic signal is imprinted in the pedogenic component of the catchment soil samples (Vidic *et al.,* 2000).The inter-parametric ratios, χ_{ARM}/SIRM and χ_{ARM}/χ_{lf}, are suggestive of magnetic grain size: higher values indicate finer magnetic grain size and *vice versa* (Fig. 2; Dearing *et al.,* 1997; King *et al.,* 1982). The ratio values exhibit considerable fluctuations in the profile. They peak at the profile-top, indicating a finer magnetic grain size in the top-soil, substantiating the interpretation based on concentration-dependent parameters.

The ratio of IRM_{300mT} to SIRM, commonly referred to as the S-ratio, is indicative of the relative proportions of the ferrimagnetic and antiferromagnetic components in a sample (Thompson and Oldfield, 1986; Heslop, 2009). Ferrimagnetic minerals like magnetite have an S-ratio value close to unity because they acquire most of the remanence at field strengths < 300mT. Antiferromagnetic minerals like hematite and goethite exhibit lower values because they would not have saturated at 300mT field strength. The S-ratio values of the PK soil profile vary between 0.86 and 0.95, indicating the predominance of magnetically "soft" minerals like magnetite. The top two samples exhibit the highest value of 0.95, confirming the presence of magnetically "soft" minerals like magnetite at the profile-top. The parameter HIRM is proportional to the concentration of magnetically "hard" minerals like hematite and goethite (Thompson and Oldfield, 1986; Walden, 1999b). Hence, the down-profile variations of S-ratio and HIRM exhibit opposite trends (Fig. 2), with slightly lower HIRM values for the top samples. IRM acquisition curves (Fig. 5) show that the samples (except a few) saturate at a field of ~ 300 mT, again indicating the soft magnetic mineralogy.

Samples of surface soil (n=12) from the catchment area too exhibit χ_{lf} values in the range of 107 to 726 x $10^{-8}m^3kg^{-1}$. Frequency-dependent susceptibility ranges from 5.3 to 59.4 x $10^{-8}m^3kg^{-1}$. The very high values of the two concentration-dependent parameters also bear testimony to the magnetic enhancement of top soil in the lake catchment.The surface soil samples were collected during November 2007, barely two months after the southwest monsoon. Despite this, they still bear the imprint of magnetic enhancement although considerable erosion (and subsequent deposition on the lake bed) would have taken place because of heavy rainfall (~ 4000 mm / year) prior to sample collection. This shows that a short time is enough for the formation of pedogenic magnetite and magnetic enhancement of surface soil. Maher and Thompson (1995), from their studies of the Chinese loess and palaeosol sequence, reported that pedogenic susceptibility is a rapidly formed soil property. Taylor et al. (1987) synthesized fine and ultra-fine grained magnetite (of SP and SD size) under pH and temperature conditions which are analogous to the natural soil environment. They reported that the time taken for magnetite formation varied from 36 to 2720 minutes depending upon pH, temperature, airflow and initial Fe^{2+} and Fe^{3+} concentrations. Our soil magnetic studies in the Pookot Lake catchment confirm that magnetic enhancement and formation of pedogenic magnetite are rapid.

Surface and sub-surface soil samples from the catchment area of Shantisagara (SS)

The environmental magnetic data for the soil profile (n=23) from the Shatisagara catchment are plotted in Fig. 6. The profile may be divided into two zones based on the magnetic data: Zone 1 (0-35 cm) where the concentration-dependent parameters (χ_{lf}, χ_{ARM} and SIRM) exhibit relatively high values and Zone 2 (39-102 cm) where these parameters exhibit relatively low values. Samples from Zone 1 exhibit χ_{lf} values varying from 455 to 732 x $10^{-8}m^3kg^{-1}$ (average = 583.7 x $10^{-8}m^3kg^{-1}$); Zone 2 has χ_{lf} values in the range of 92.5 to 452.4 x $10^{-8}m^3kg^{-1}$ (average = 272.5 x $10^{-8}m^3kg^{-1}$). Similarly, the average χ_{fd} values for Zone 1 and Zone 2 are 56.2 and 29.2 x $10^{-8}m^3kg^{-1}$ respectively. The average χ_{ARM} values

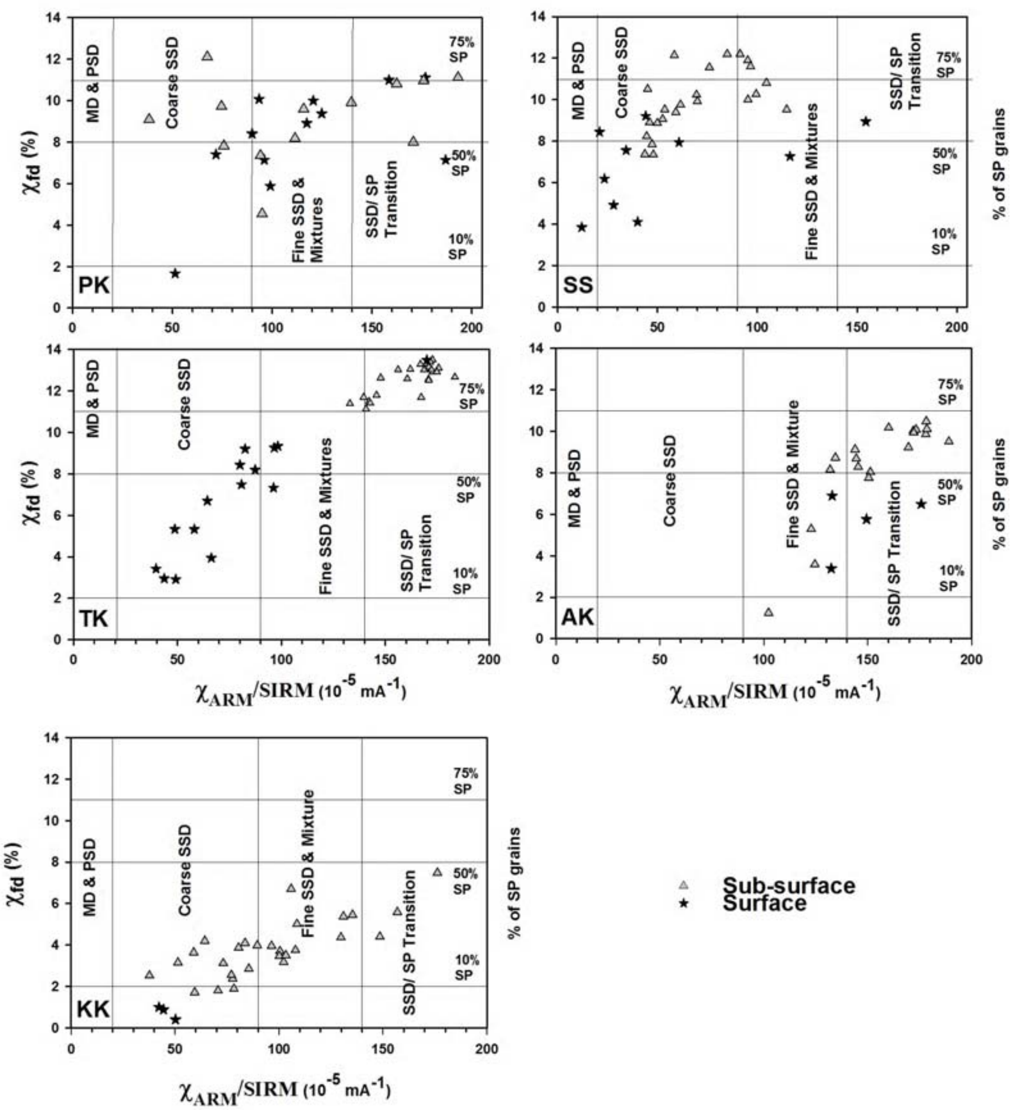

Fig. 3. The biplot of χ_{ARM}/SIRM *vs.* χ_{fd} % for soil samples from Pookot (PK), Shantisagara (SS), Thimmannanayakanakere (TK), Ayyanakere (AK) and Kurburkere (KK). *Note:* The magnetic grain size of surface and sub-surface samples of PK is not significantly different (a). MD+PSD grains characteristic of anthropogenic activity are absent except in a lone sample (b). Although both surface and sub-surface samples exhibit grain size in the coarse SSD range, the former are slightly coarser and the latter finer (SSD/SP transition range) with a higher concentration of SP grains in TK samples (c). The AK surface and sub-surface samples have a similar grain size (fine SSD & mixtures and SSD/SP transition; d). The KK surface and sub-surface samples have similar grain size (coarse SSD and fine SSD & mixtures), however, the surface soil samples from the catchment have < 10 % contribution from SP grains

are 2.8 and 1.4 x 10^{-5} $m^3 kg^{-1}$ for Zone 1 and Zone 2 respectively.

The grain size plot of χ_{fd} % *vs.* χ_{ARM}/SIRM (Fig. 3) indicates that MD+PSD grains are absent in SS soils. Hence, the presence of anthropogenic magnetite may be ruled out. χ_{ARM}/χ_{lf} values of < 40 and χ_{ARM}/χ_{fd} values of < 1000 indicate the absence of bacterial magnetite in the soil samples (Fig. 4).

Although the concentration-dependent parameter values increase at the profile-top, they do not register a sharp peak as in the Pookot soil profile. There may be two reasons for this. 1) Due to lessivage, the newly formed magnetic minerals may have percolated to deeper horizons, creating a thick, magnetically enhanced profile (Fine *et al.*, 1989). Hence, the entire Zone 1 may be considered as magnetically enhanced.

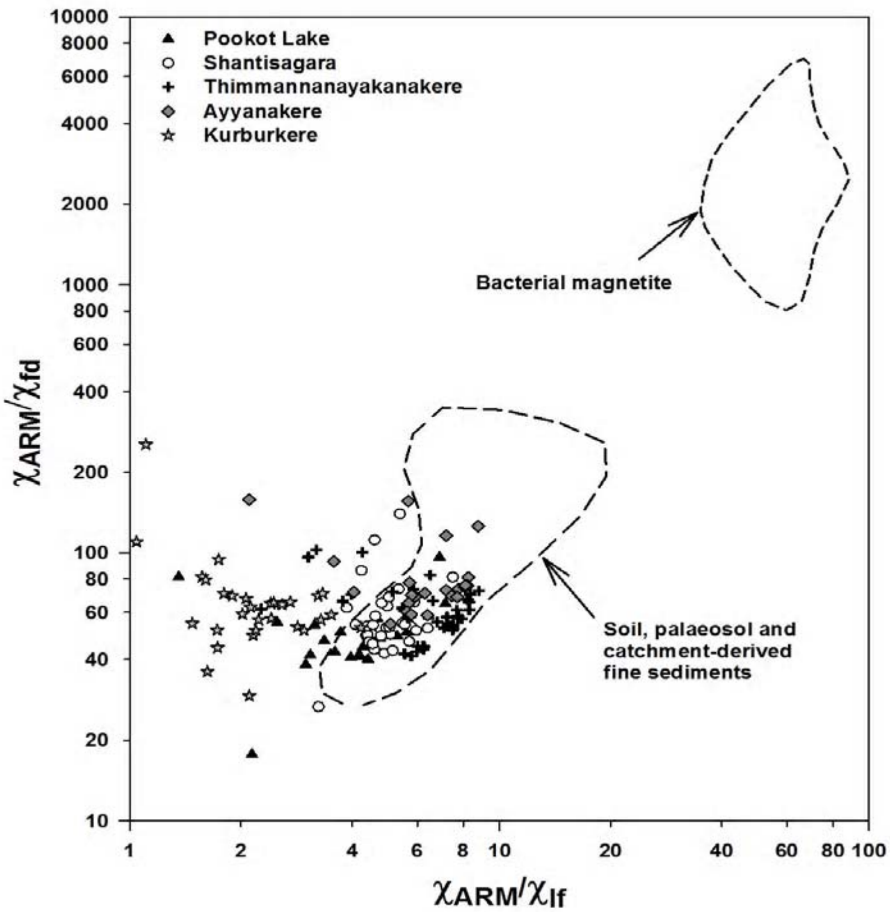

Fig. 4. The biplot of χ_{ARM}/χ_{lf} *vs.* χ_{ARM}/χ_{fd} for soil samples from the five locations. *Note:* χ_{ARM}/χ_{lf} values of < 40 and χ_{ARM}/χ_{fd} values of < 1000 indicate the absence of bacterial magnetite

2) Erosion of the magnetically enhanced top-soil. The χ_{ARM} and χ_{fd} values also exhibit similar trends and show statistically significant correlation coefficients of 0.92 and 0.93 ($p < 0.001$; n= 23) respectively with χ_{lf}, indicating that magnetic susceptibility is mainly controlled by the ultra-fine, pedogenic component.

The inter-parametric ratios, χ_{ARM}/SIRM and χ_{ARM}/χ_{lf}, which indicate magnetic grain size, do not vary markedly between the two zones. In fact, the former exhibits a decreasing trend towards the profile-top. This situation may arise due to significant lessivage of fine magnetic minerals. Values of S-ratio vary between 0.89 and 0.96, indicating the predominance of magnetically soft minerals. This is confirmed by IRM acquisition curves, which demonstrate that the samples get saturated at a field of ~ 300 mT (Fig. 5). But there is no significant difference in the S-ratio values for Zone 1 and Zone 2. HIRM ranges from 26.4 to 519.2 x 10^{-8} m^3 kg^{-1} and exhibits slightly higher values in Zone 1.

Other surface soil samples (n=10) from the catchment area exhibit χ_{lf} values in the range of 66-502.4 x 10^{-8} m^3 kg^{-1} (average = 282.4 x 10^{-8} m^3 kg^{-1}). Values of χ_{fd} range from 2.6 to 44.9 x 10^{-8} m^3 kg^{-1} (average = 20.9 x 10^{-8} m^3 kg^{-1}). The high values of both the parameters demonstrate magnetic enhancement of the top-soil (Maher and Taylor, 1988).

Surface and sub-surface soil samples from the catchment of Thimmannanayakanakere (TK)

The 1-m deep soil profile (n=24) developed on gneissic lithology in the TK catchment is moderate to strongly magnetic, with χ_{lf} values ranging between 93.08 and 592.83 x $10^{-8}m^3kg^{-1}$, χ_{fd} between 11.09 and 82.65 x $10^{-8}m^3kg^{-1}$, χ_{ARM} between 0.78 and 3.70 x $10^{-5}m^3kg^{-1}$ and SIRM between 551.51 and 2195.66 x $10^{-5}Am^2kg^{-1}$ (Fig. 7). The magnetic minerals are magnetically "soft", as suggested by the S-ratio values (close to 0.94; Fig.7) and by IRM acquisition curves (IRM's getting almost saturated at 300 mT field; Fig. 5c). However, the presence of small amounts of goethite or hematite is also indicated, as the IRM values continue to increase even at 1 T field for a few samples (Fig. 5). The high χ_{fd} % (> 11) suggests a high concentration of SP grains. MD + PSD magnetic grains characteristic of

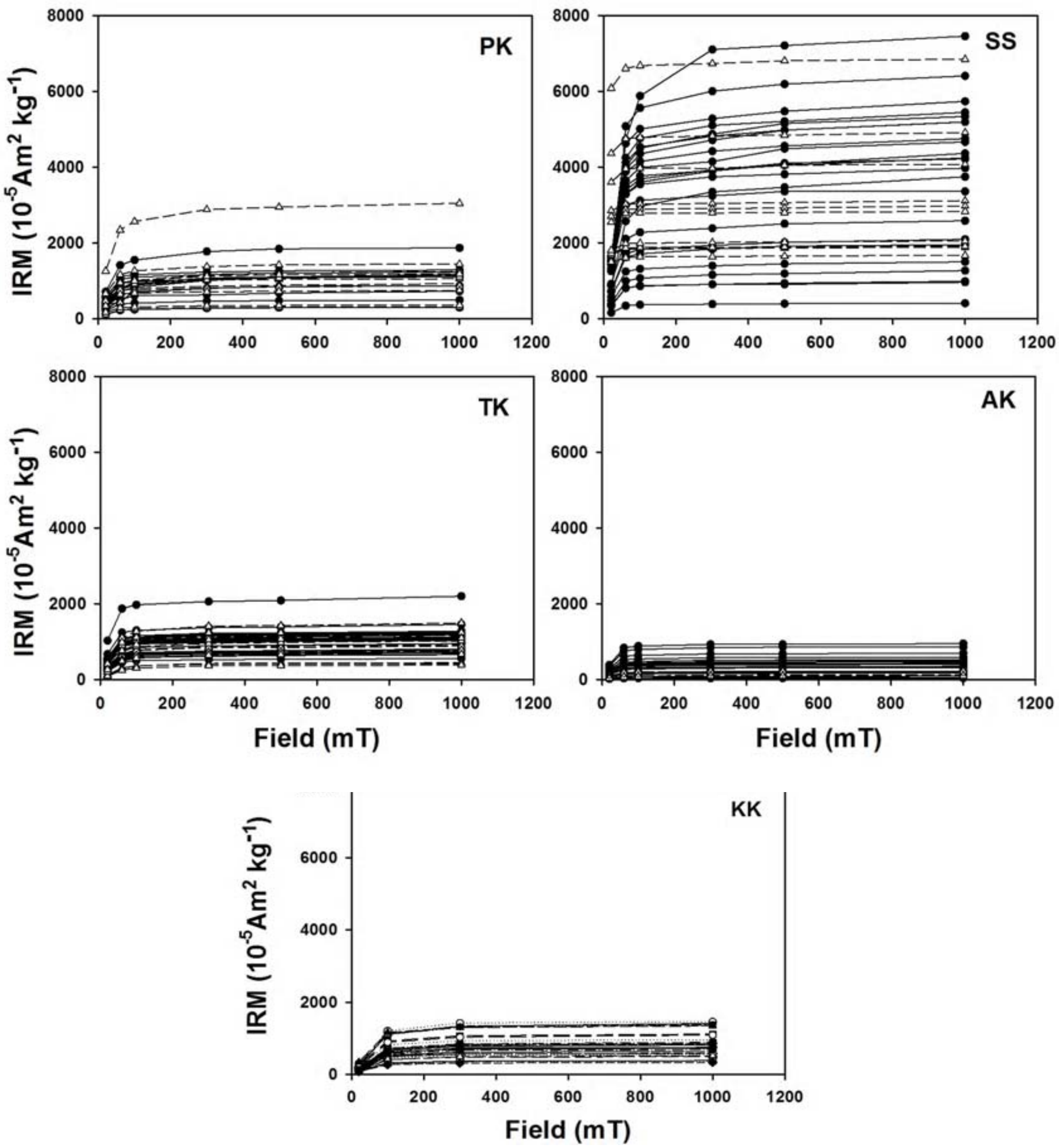

Fig. 5. Isothermal remanent magnetization (IRM) acquisition curves for soil samples from Pookot Lake; Shantisagara; Thimmannanayakanakere; Ayyannakere; and Kurburkere. *Note:* Most of the samples saturate at a field of ~ 300 mT, indicating a magnetically soft mineralogy. However, IRM values continue to increase even at 1T field for a few samples, indicating the presence of hematite/goethite in them

anthropogenic magnetite are absent (Fig. 3). χ_{ARM}/χ_{lf} values of < 40 and χ_{ARM}/χ_{fd} values of < 1000 indicate that bacterial magnetite is absent (Fig. 4). Sub-surface soil samples have SSD/SP grains with > 75 % contribution from ultra-fine SP grains, whereas surface soil samples plot in the "coarse SSD" envelope with > 50 % contribution from SP grains. These fine magnetic grains must have formed during pedogenesis, which was accelerated by high rainfall and the high organic matter content resulting from the thick vegetative cover (Maher, 1986, 1998; Zhou *et al.,* 1990).

All the concentration-dependent parameters show a decreasing trend towards the profile-top (Fig. 7), suggesting the removal of fine magnetic minerals from the top-soil by erosion because of rainfall (Maher and Thompson, 1995). Top-soil erosion is further confirmed by the down-profile distribution of magnetic granulometric ratios - SIRM/χ_{lf} and χ_{ARM}/SIRM (Fig. 7). The SIRM/χ_{lf} ratio is high in the top 20 cm of the profile when compared to the lower part (20-100 cm). This indicates the predominance of coarse grains of magnetic minerals in the top 20 cm. Similarly, the χ_{ARM}/

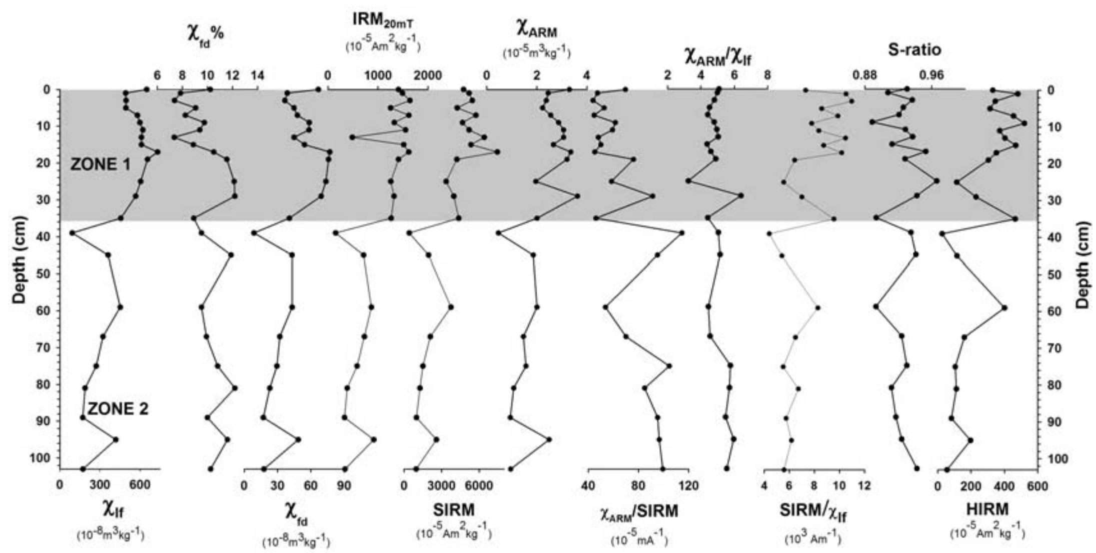

Fig. 6. Rock magnetic parameters and inter-parametric ratios for a soil profile developed on chlorite schist in the Shantisagara Lake (SS) catchment. *Note:* The profile may be divided into two zones based on magnetic parameters. Zone 1 is typified by relatively higher values of concentration-dependent parameters (χ_{lf}, χ_{fd}, χ_{ARM} and SIRM) and Zone 2 by lower values

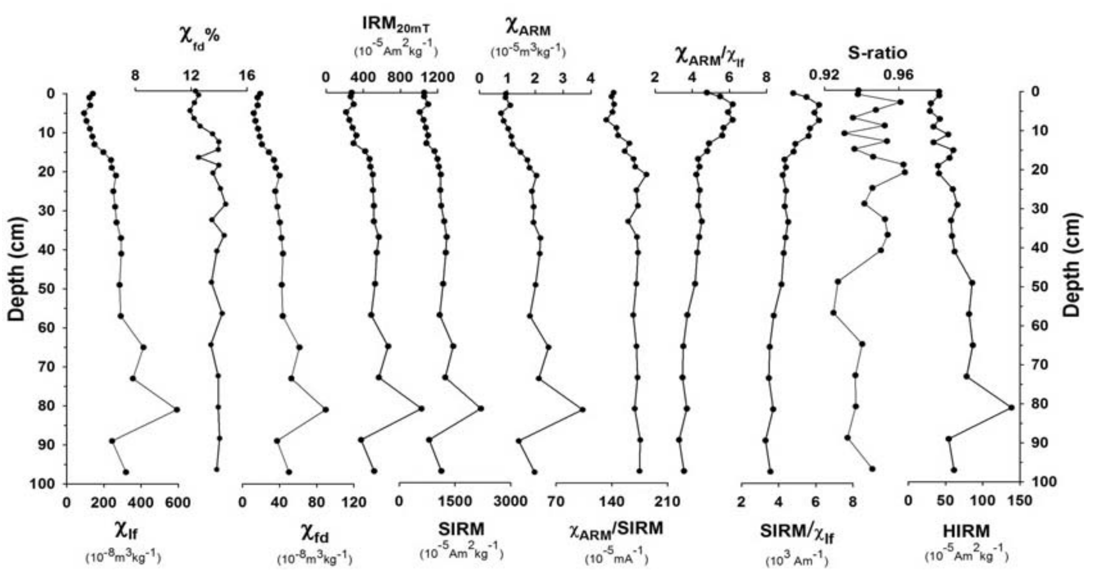

Fig. 7. Rock magnetic parameters and inter-parametric ratios for a soil profile developed on granite gneiss in the Thimmannanayakanakere (TK) catchment. *Note:* The data do not indicate any magnetic enhancement at the surface, which may be due to soil erosion. It appears that the increasing values of concentration dependent parameters towards the profile-bottom is an artifact of soil erosion

SIRM ratio is low in the top 20 cm, suggesting coarser magnetic grains. During periods of high rainfall, fine grained magnetic minerals would have been washed away, while the soil profile itself was enriched in magnetic minerals of coarser grain size. The TK surface and sub-surface soil samples were collected in early July 2006, when the southwest monsoonal rainfall was active, which would have washed away the fine magnetic minerals from the catchment to the lake-bed. The increase in susceptibility values at deeper horizons of the soil profile may be due to two reasons: i) presence of magnetite/maghemite which may have been inherited from the weathered parent rock (Jordanova *et al.*, 2011); ii) lessivage of fine-grained magnetic minerals formed during pedogenesis. The first reason can be ruled out as the soil profile is hosted on a granitic gneiss rock and it does not contribute much magnetic minerals. The increase in susceptibility values at the profile-bottom could be an artifact of soil erosion during which fine grained magnetic minerals may be vertically transported towards the profile-bottom which can be seen from the high values of concentration and grain size dependent parameters (Fig. 7).

The average magnetic values for surficial soil samples (n=16) from the catchment are: χ_{lf} = ~ 142.48 x 10^{-8} $m^3 kg^{-1}$; χ_{fd} = ~ 12.47 x $10^{-8} m^3 kg^{-1}$; χ_{ARM} = ~ 0.76 x $10^{-5} m^3 kg^{-1}$; SIRM = ~ 876.58 x $10^{-5} Am^2 kg^{-1}$; S-ratio = ~ 0.95 and HIRM = ~ 45.37 x $10^{-5} Am^2 kg^{-1}$.

Surface and sub-surface soil samples from the catchment area of Ayyanakere (AK)

Rock magnetic investigations were carried out on a 65-cm deep soil profile (n=19) developed on hornblende gneiss along with surficial soil samples from five sites. Fig. 8 shows the rock magnetic parameters and inter-parametric ratios for the soil profile samples. The soil profile is weakly to moderately magnetic as the magnetic susceptibility (χ_{lf}) values vary between 16.47 and 201.35 x $10^{-8} m^3 kg^{-1}$, χ_{ARM} between 0.034 and 1.62 x $10^{-5} m^3 kg^{-1}$, and SIRM between 34 and 944 x$10^{-5} Am^2 kg^{-1}$ (Fig. 8).

These parameters (χ_{lf}, χ_{fd}, χ_{ARM}, SIRM and HIRM) exhibit a decreasing trend towards the profile-top. The high χ_{fd} % of the soil profile, barring the top 8 cm (~ 8-10 %), suggests the presence of ultra-fine SP grains, probably due to pedogenic magnetite that forms *in situ* (Maher, 1988; Oldfield and Crowther, 2007). However, χ_{fd} % is low at the profile-top (0-8 cm, ~ 3%), which may be attributed to top-soil erosion during periods of high rainfall when fine-grained magnetic minerals in the top-soil are eroded and transported to Ayyanakere. The hypothesis of top-soil erosion may be justified by the χ_{ARM}/SIRM ratio data. The ratio value is low in the top 8 cm, suggesting a coarser magnetic grain size and implying that fine grained magnetic minerals were selectively removed from the top-soil. Sampling of the AK catchment soils was done during June 2007, when the southwest monsoon had just commenced, resulting in the erosion of fine grained magnetic minerals. The χ_{fd} % *vs.* χ_{ARM}/SIRM biplot (Fig. 3) shows that all the soil samples have SSD-SP grains, with > 50 % contribution from ultra-fine SP grains. This characteristic also indicates the presence of pedogenic magnetite. Besides, MD + PSD grains that are characteristic of anthropogenic magnetite are absent. χ_{ARM}/χ_{lf} values of < 40 and χ_{ARM}/χ_{fd} values of < 1000 indicate the absence of bacterial magnetite (Fig. 4). The S-ratio for the sub-surface soil samples varies from 0.90 to 0.97, suggesting the presence of magnetically "soft" minerals like magnetite, which is also supported by IRM acquisition curves (Fig. 5). Most of the samples in the soil profile acquire their remanence at ~300 mT. Susceptibility values increase slightly towards the profile- bottom, indicating the presence of fine-grained magnetite/maghemite which may be derived from the weathering of the parent rock (Jordanova *et al.*, 2011).

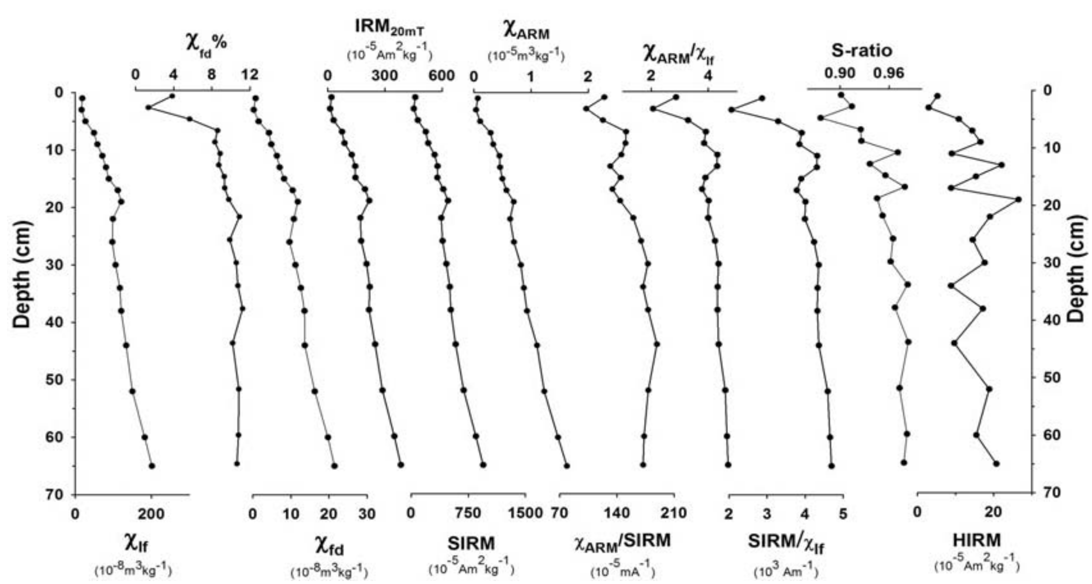

Fig. 8.Rock magnetic parameters and inter-parametric ratios for a soil profile developed on hornblende gneiss in the AK catchment. *Note:* No magnetic enhancement is indicated at the surface, which may be due to soil erosion. The concentration-dependent parameters increase slightly towards the profile-bottom, indicating the effect of the parent rock

As the parent rock is hornblende gneiss, it contributes some ferromagnesian minerals due to weathering processes.

The average magnetic values for the surficial soil samples (n=4) are: χ_{lf} = ~ 31 x $10^{-8}m^3kg^{-1}$; χ_{fd} % = ~ 6; χ_{ARM} = ~ 0.22 x 10^{-5} m^3kg^{-1}; SIRM = ~ 148 x 10^{-5} Am^2kg^{-1}; S-ratio = ~ 0.94 and HIRM = ~ 8.59 x 10^{-5} Am^2kg^{-1}. Unlike subsurface samples, the surficial samples do not saturate at 300 mT but show an increasing trend at high magnetic fields as well (Fig. 5), indicating the presence of magnetically "hard" minerals like hematite and goethite. Besides, they exhibit low SIRM values too as hematite and goethite are not as strongly magnetic as magnetite (Walden *et al.,* 1999).

Surface and sub-surface soil samples from the catchment area of Kurburkere (KK)

Rock magnetic investigations were carried out on a 130-cm deep soil profile (n=28) developed on migmatite, besides three samples of surficial soil from the lake catchment. Fig. 9 displays the down-profile variations of rock magnetic parameters and inter-parametric ratios for the KK soil profile. The soil profile is moderately magnetic as the magnetic susceptibility (χ_{lf}) values vary between 62.12 and 285.68 x $10^{-8}m^3kg^{-1}$, χ_{ARM} between 0.107 and 0.493 x $10^{-5}m^3kg^{-1}$, and SIRM between 332 and 1361 x$10^{-5}Am^2kg^{-1}$ (Fig. 9).

Based on the magnetic data, the KK profile may be divided into two zones. The lower zone (Zone 1; 130 to 50 cm) shows upwardly increasing values of χ_{fd}, χ_{ARM}, IRM_{20mT} and SIRM indicating a slight magnetic enhancement. However, χ_{lf} does not show any notable variations. Further, this zone exhibits a slightly higher χ_{fd}% (~ 4.6 %) compared to the upper zone (Zone 2; 50 to 0 cm; χ_{fd}% ~ 3.8 %), suggesting a marginally higher content of ultrafine SP grains. Similarly, the grain size related ratios - χ_{ARM}/SIRM and χ_{ARM}/χ_{lf} also register an upward gradual increase, suggesting a fining of the magnetic grain size. The afore-said features of upwardly increasing magnetic mineral concentration and decreasing magnetic grain size demonstrate the effect of pedogenesis.

The upper zone (50 to 0 cm) also shows upwardly increasing χ_{lf}, IRM_{20mT}, SIRM and HIRM values, suggesting magnetic enhancement of top-soil. However, χ_{fd} and χ_{ARM} values decrease towards the surface. Therefore, it appears that the magnetic enhancement here is because of coarse SD grains and "hard" magnetic minerals like haematite and goethite. Erosion of fine magnetic grains from the top-soil is indicated by upwardly decreasing values of χ_{fd} and χ_{ARM}. The interpretations presented above are reinforced by Fig. 3. A majority of the subsurface samples have coarse and fine SSD grain size, with <50 % contribution from ultra-fine SP grains. By contrast, the surface samples have a coarse SSD grain size, with only <10 % contribution coming from SP grains, owing to erosion of fine magnetic grains from the catchment. MD + PSD grains that are characteristic of

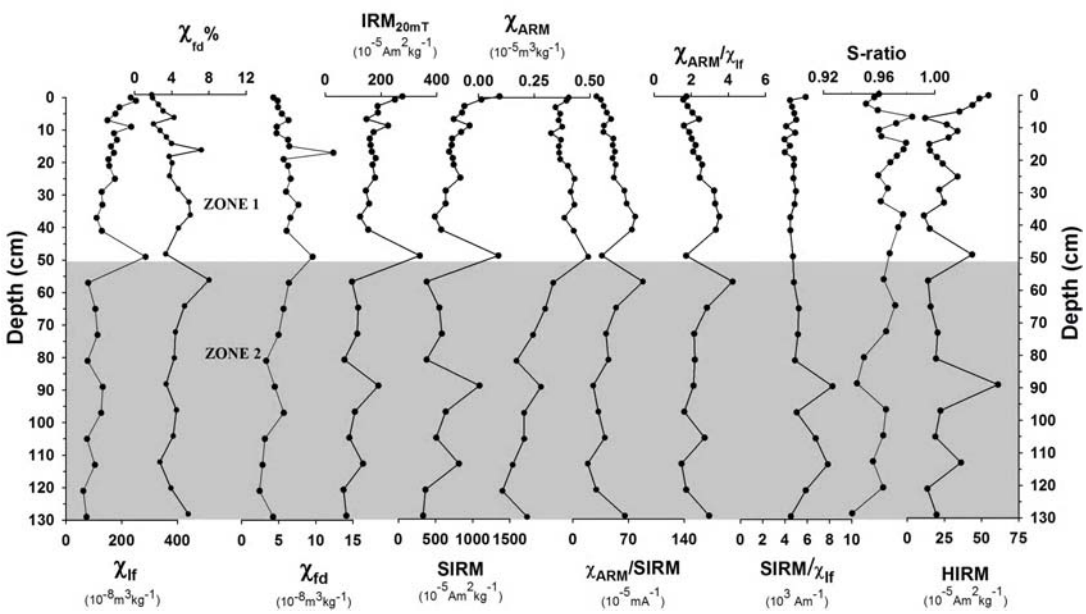

Fig. 9. Rock magnetic parameters and inter-parametric ratios for a soil profile developed on migmatite in the KK catchment. *Note:* The values of concentration-dependent parameters increase slightly towards the profile-top, suggesting only a weak magnetic enhancement

anthropogenic magnetite are absent in the KK soil samples. χ_{ARM}/χ_{lf} values of < 40 and χ_{ARM}/χ_{fd} values of < 1000 indicate the absence of bacterial magnetite (Fig. 4). The S-ratio for the sub-surface soil samples varies from 0.94 to 0.98, indicating a magnetically "soft" mineralogy, which is corroborated by IRM acquisition curves (Fig. 5). Almost all the samples in the soil profile as well as the surficial soil samples from the catchment acquire their remanence at ~300 mT. The average magnetic values for the three surficial soil samples are: χ_{lf} = ~ 313 x $10^{-8}m^3kg^{-1}$; χ_{fd} % = ~ 1; χ_{ARM} = ~ 0.32 x 10^{-5} m^3kg^{-1}; SIRM = ~ 1421 x 10^{-5} Am^2kg^{-1}; S-ratio = ~ 0.96 and HIRM = ~ 55.06 x 10^{-5} Am^2kg^{-1}.

A comparison of the magnetic properties of surface and sub-surface soil samples from the five catchments

Fig. 10 is a plot of the magnetic susceptibility of the five soil profiles studied. The AK soil profile (parent rock: hornblende gneiss; mean annual rainfall: ~ 1925 mm) has the lowest χ_{lf} values. The TK, PK and KK profiles developed on granitic gneiss, hornblende-biotite gneiss and migmatite respectively have similar χ_{lf} values, except the top part where the PK soil profile has slightly higher values. This is surprising because PK catchment receives a much higher mean annual rainfall (~ 4000 mm) compared to TK (~ 638 mm) and KK (~ 770 mm). The SS profile from a rainfall regime of ~ 795 mm exhibits the highest susceptibility values among the five profiles. In the TK profile, and to a lesser degree AK profile, the susceptibility values increase towards the profile-bottom. As discussed in Sections 3.3 and 3.4, this may be due to the derivation of magnetic minerals from the weathering of parent rocks. The concentration-dependent parameters like χ_{lf} and SIRM do not exhibit any remarkable difference between PK surface and sub-surface samples. The biplot of χ_{lf} *vs*. SIRM (Fig. 11) shows that the values for surface and subsurface samples overlap. Similarly, there is no notable difference in the magnetic grain size of surface and sub-surface samples of PK. They are mainly in the range of fine SSD & mixtures and SSD/SP transition (Fig. 3). Only a few samples have coarse SSD grain size. This indicates the deeply weathered nature of the PK soil profile, resulting in no appreciable difference in the magnetic grain size between surface and sub-surface soils. The S-ratio *vs*. χ_{lf} biplot (Fig. 12) indicates that there is no profound difference in terms of magnetic mineralogy as well. But when samples from a single profile are considered, the two surface samples exhibit higher values for concentration-dependent parameters and hence have a fine magnetic grain size and a soft magnetic mineralogy as discussed in Section 3.1.

The SS surface soil samples plot separately in comparison with sub-surface ones, with relatively lower χ_{lf}, but higher SIRM values (Fig. 11). Both surface and sub-surface samples exhibit a grain size in the coarse SSD range (Fig. 3), with the former displaying a slightly coarser magnetic grain size (with a lower χ_{fd} %, indicating a lower concentration of SP grains). As no sample plots in the SSD/SP transition, it may be assumed that the finer grains have been eroded away or have percolated downwards due to lessivage as discussed in Section 3.2. Their magnetic mineralogy is also distinct, with surface soil samples having a softer magnetic mineralogy (S-ratio > 0.96) and the sub-surface ones having a relatively higher contribution from magnetically hard minerals.

The TK surface and subsurface soil samples, can not be distinguished on the basis of either the χ_{lf} *vs*. SIRM plot (Fig. 11) or down-profile variations of magnetic concentration (Fig. 10). But there is a clear distinction in their magnetic grain size. The surface samples display a relatively coarse magnetic grain size (coarse SSD range) with a low concentration of SP grains (low χ_{fd} %; Fig. 3). The sub-surface samples, on the other hand, exhibit a finer magnetic grain size (SSD/SP transition range) with a higher concentration of SP grains (higher χ_{fd} %). The presence of coarse magnetic grains may be indicative of top-soil erosion. The surface and sub-surface soil samples do not exhibit notable differences in their magnetic mineralogy (Fig. 12).

The AK surface soil samples exhibit lower values for concentration-dependent parameters compared to the sub-surface ones (Fig. 11). All the AK soil samples are magnetically weak compared to those from the other four locations. The magnetic grain size of the surface and sub-surface soil samples is similar (fine SSD & mixtures and SSD/SP transition; Fig. 3). Also, there is no significant difference in magnetic mineralogy (Fig. 12).

The KK soil samples are magnetically strong in comparison with those from AK, but weak in comparison with those from PK, SS and TK. The three KK surface soil samples exhibit higher values for concentration-dependent parameters compared to the sub-surface ones (Fig. 11). The magnetic grain size of the surface and sub-surface soil samples is similar (coarse SSD and fine SSD & mixtures; Fig. 3). However, the contribution of SP grains in the surface soil samples is less than 10 %, which could be due to the erosion of the fine SP grains during periods of high rainfall. The magnetic mineralogy of the surface and sub-surface soil samples of KK is not different (Fig. 12) and is similar to that of TK soil samples.

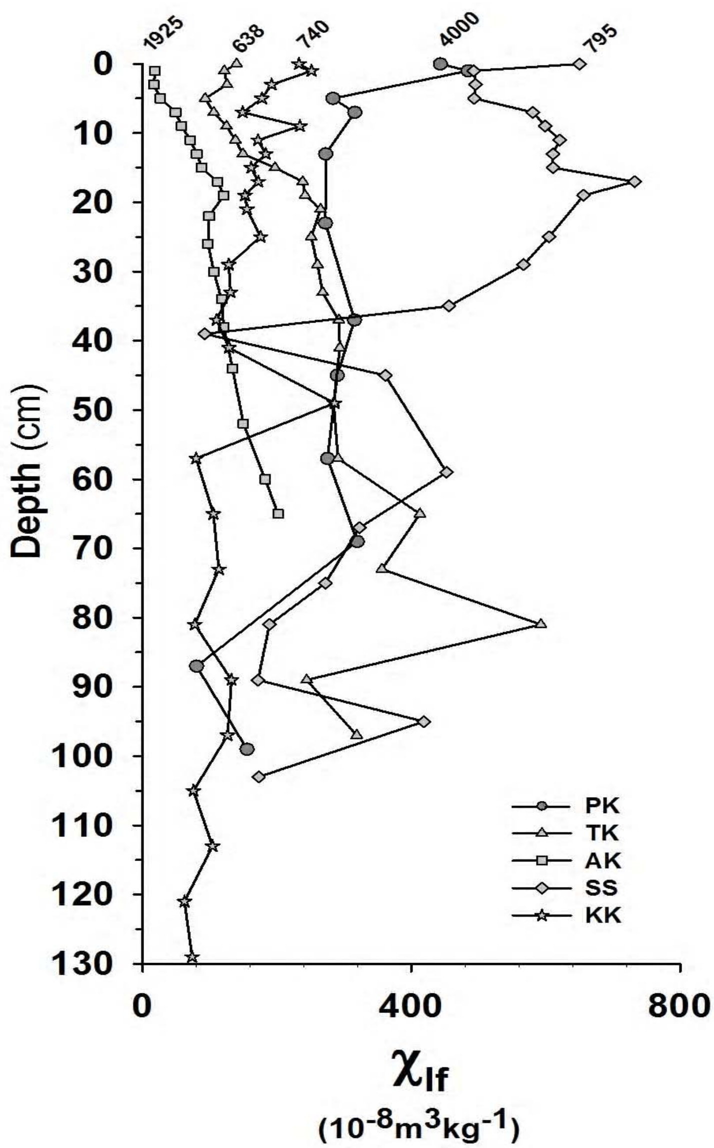

Fig. 10. A comparison of the down-profile variations of χ_{lf} values for the five soil profiles from PK, SS, TK, AK and KK catchments. *Note:* The number above each curve is the mean annual rainfall. TK and PK samples exhibit similar χ_{lf} values, except for the top part where the latter shows slightly higher values. SS samples generally exhibit the highest χ_{lf} values among the five profiles

CONCLUSIONS

We draw the following conclusions based on rock magnetic investigations of surface and sub-surface soil samples from the catchments of five lakes in Southern India: Pookot (PK), Shantisagara (SS), Thimmannanayakanakere (TK), Ayyanakere (AK) and Kurburkere (KK):

1.Soil samples from the five profiles do not have any contributions from bacterial magnetite, greigite and anthropogenic sources. The magnetic minerals are catchment-derived and hence bearing a climate-related signal; they are mainly pedogenic and to a smaller extent lithogenic. In view of this, the soils show prospects of use in palaeoclimatic studies through soil-lake sediment linkages.

2.The PK soil profile exhibits magnetic enhancement of the top-soil even though the samples were collected in November 2007, hardly two months after the SW monsoon, indicating that pedogenic magnetite can form rapidly.

3.The SS soil profile indicates lessivage of magnetic minerals, producing a thick magnetically enhanced

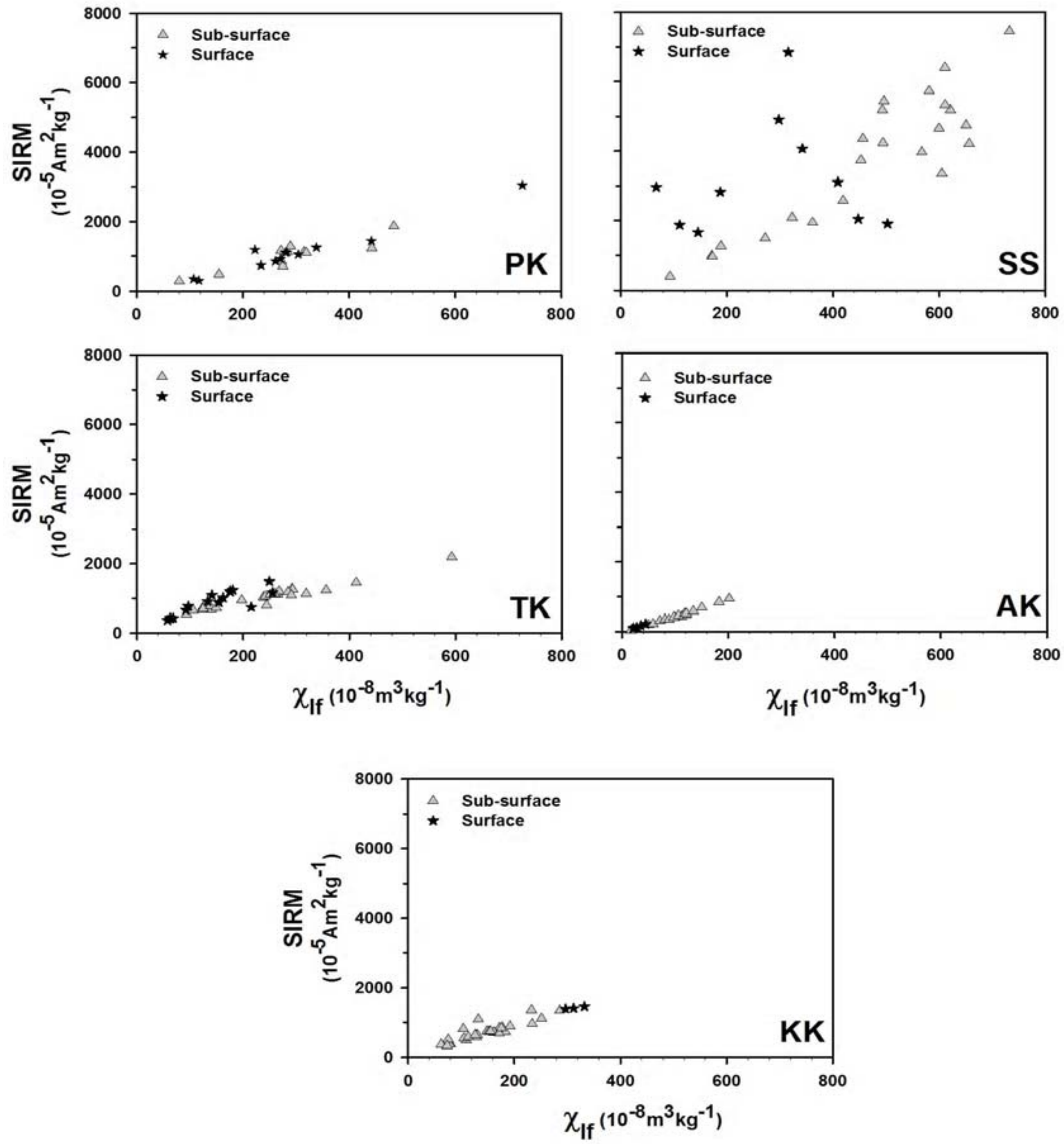

Fig. 11. The χ_{lf} *vs.* SIRM biplot for surface and sub-surface soil samples from the catchments of Pookot Lake; Shantisagara; Thimmannanayakanakere; Ayyannakere; and Kurburkere. *Note:* In PK, the surface and sub-surface samples overlap with no clear distinction between them. In SS, they plot separately, with sub-surface samples having relatively lower χ_{lf} values but higher SIRM values. In TK, there is no notable difference in magnetic concentration between the surface and sub-surface samples though the latter show somewhat higher χ_{lf} values. In AK, the surface soils exhibit lower values for concentration-dependent parameters compared to sub-surface ones. In KK samples, the surface samples display higher values for concentration-dependent parameters in comparison with the sub-surface samples

zone. Susceptibility values are the highest for this profile among the five.

4.The TK and AK soil profiles indicate neither high χ_{lf} values nor fine magnetic grain size at the profile-top, indicating a possible erosion of the top-soil. The χ_{lf} values of AK samples are the lowest among the five profiles. Increase in susceptibility values towards the profile-bottom in the TK soil profile probably indicates lessivage of fine magnetic minerals during soil erosion, whereas in the case of AK soil profile, the increase in clf values towards the profile-bottom is probably due to the presence of magnetite/ maghemite which may have been derived from the weathering of the parent rock which is hornblende gneiss. Besides, they are relatively less weathered compared to PK and SS.

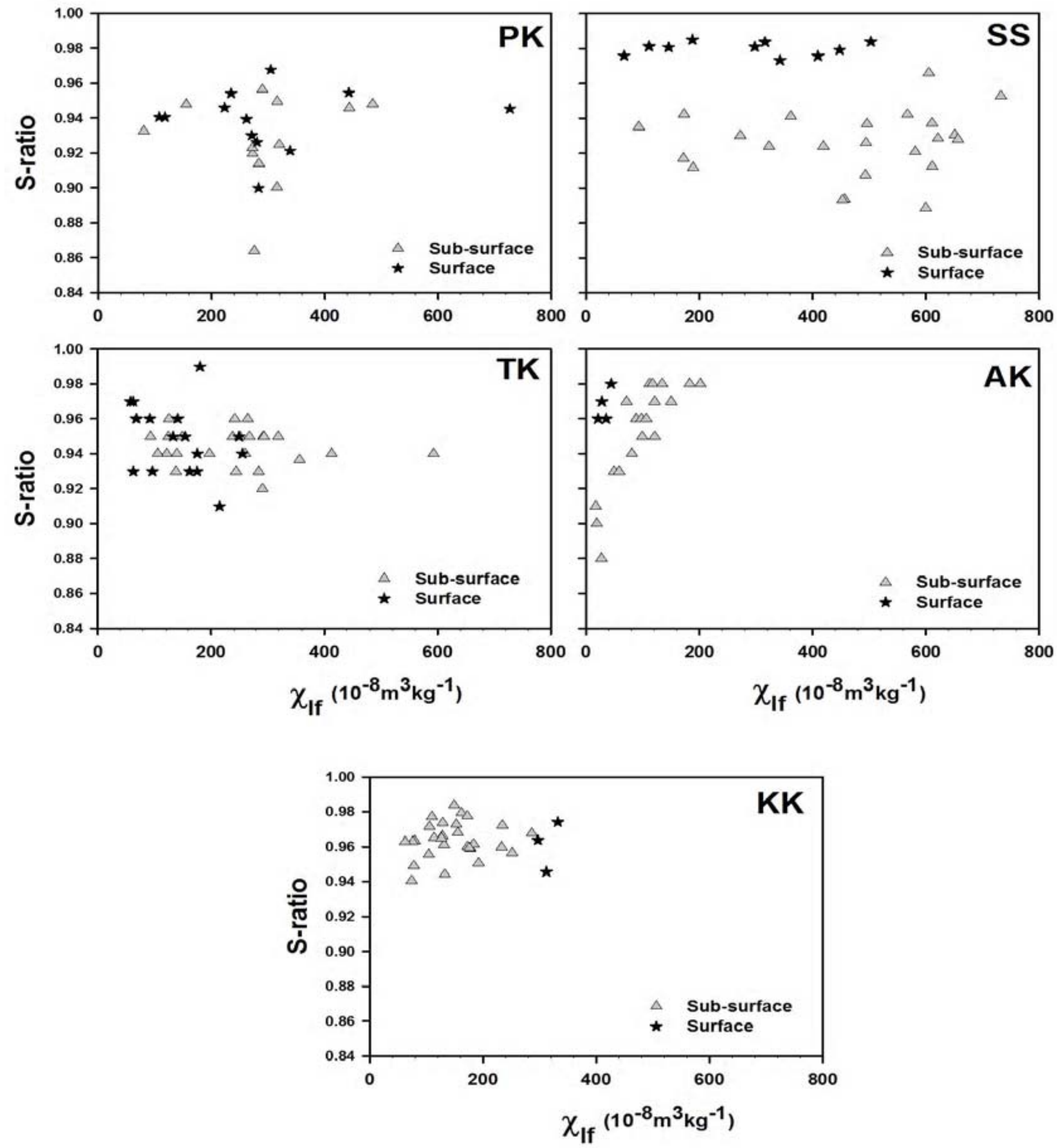

Fig. 12. S-ratio *vs.* χ_{lf} for soil samples from the catchments of Pookot Lake; Shantisagara; Thimmannanayakanakere; Ayyannakere; and Kurburkere. Samples from PK, TK, AK and KK do not have profound differences in their magnetic mineralogy. In SS, the magnetic mineralogy is distinct, with the surface soil samples having a soft magnetic mineralogy (S-ratio > 0.96), and the sub-surface ones having a relatively higher contribution from hard magnetic minerals

5.There is no remarkable difference between surface and sub-surface soil samples of PK in terms of mineralogy, grain size and concentration of magnetic minerals, indicating the deeply weathered nature of the profile as a result of heavy rainfall.

6.The TK and PK soil samples exhibit similar χ_{lf} values despite differences in rainfall in the respective catchments.

7.Like SS samples, the KK soil samples also show lessivage of magnetic minerals, albeit to a lesser extent.

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