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Rock Magnetic Characterisation of Tropical Soils From Southern India: Implications to Pedogenesis and Soil Erosion

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ABSTRACT: In this study we report the rock magnetic properties of surface soil samples and their spatial variability from the northernmost district of Kerala to understand pedogenic processes and soil erosion. The magnetic signal is mainly from fine grained pedogenic magnetite as other sources like anthropogenic and lithogenic magnetite, bacterial magnetite and greigite are absent. The surface soil samples were collected from four locations (Aribail, Kodlamogaru, Miyapadavu and Seethangoli). Magnetic properties (c_{lf}, $c_{fd,}$ $c_{ARM,}$ IRM's at different field strengths) determined on these samples exhibit significant variations for the four locations. Aribail samples contain a lower concentration of magnetic minerals whereas Miyapadavu samples exhibit higher values. The magnetic mineralogy is softer and the magnetic grain size finer in Miyapadavu samples whereas it is harder and coarser in Aribail samples. The magnetic properties of samples from other locations (Kodlamogaru and Seethangoli) exhibit wide variations. In general, the magnetic concentration increases, grain size decreases and mineralogy become softer as one traverses from NW to SE in the study area. Such variations in soil magnetic properties may be due to the geographical location of sampling sites and vulnerability to erosion, as other factors like parent rock, rainfall, temperature and vegetation are almost similar in all the four locations. Our study also indicates that higher production of pedogenic magnetite occurs in the monsoon season and the time lag between erosion of magnetite during heavy rains and production of 'new magnetite' is not very large. This data would also serve as primary database for future pollution studies.

Key words: Monsoon,Super paramagnetic, Contour plots, Top soil, Hematite

INTRODUCTION

Soil is the weathered and unconsolidated material on top of the bed-rock that contains organic matter and is capable of supporting plant life (Carlson *et al.,* 2008). The nature, properties and genesis of soils are dependent on factors like parent rock, climate, vegetation, topography and time (Jenny, 1946). There have been studies on the organic carbon content (Torn *et al.,* 1997; Bhattacharya *et al.,* 2008), hydraulic conductivity (Durner, 1994), colour (Melville and Atkinson, 1985), engineering properties (Phani Kumar and Sharma, 2004), geochemistry (Manjunatha *et al.,* 2001), microbial properties (Goyal *et al.,* 1999) and texture (Shirazi and Boersma, 1984) of soils. Recently, an environmental magnetic approach has been extensively applied to the study of European soils, but similar studies for the tropics are limited. Evans and Heller (2003), Maher and Thompson (1999) and Thompson and Oldfield (1986) have discussed various aspects like magnetic properties of soil magnetic minerals, impact of weathering on magnetic properties, magnetic enhancement of surface soils and impact of slope process on soil magnetism.

Soil magnetic properties have been widely employed to study Quaternary loess-paleosol deposits (Maher, 1998; Maher and Thompson, 1991), heavy metal loadings (Hanesch and Scholger, 2002), top-soil pollution (Gautam *et al.,* 2004; Blaha *et al.,* 2008; Petrovsky and Ellwood,1999), pedo-environmental conditions and climatic signature (Maher *et al.,* 2003; Maher and Taylor, 1988), detection of burnt soils in the context of archaeology (Oldfield and Crowther, 2007), spatial variability of soil magnetic properties in

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relation to climate (Blundell *et al.,* 2009; Geiss *et al.,* 2008),weathering of basaltic rocks (Chevrier *et al.,* 2006) etc. There have been some studies which have dealt with the mineralmagnetic characterisation of soils (Maher, 1986, Jordanova and Jordanova, 1999; Dearing *et al.,* 1997). Most soil magnetic studies have dealt with temperate soils (Blundell *et al.,* 2009, Maher *et al.,* 2003) except a few from tropical regions (Ortega–Guerrero *et al.,* 2004; van Dam *et al.,* 2005). In India soil magnetic studies are limited to loess-paleosol sequences of the Himalaya and the Siwaliks (Sangode *et al.,* 2004, 2008) and delineation of polluted areas in metropolitan cities like Delhi (Maiti*et al.,* 2005; Meena*et al.,* 2011) and Pune (Sangode *et al.,* 2010). Sandeep et al. (2012) have investigated the surface and sub-surface soil samples from the catchment areas of five lakes in southern India.

The objectives of the present study are to document the rock magnetic properties of surface soils from a tropical region, which is free of anthropogenic influences, and to determine the spatial variability of soil magnetic properties in relation to topography, slope and geology. The area chosen for the present study is Kasaragod District, the northern most part of Kerala State, southern India (Figs. 1 and 2). The area receives an annual average rainfall of ~ 3500 mm. The geology of the area is predominantly hornblende-biotite gneiss and charnockites of Archaean Era (Geological and Mineral Map of Kerala, 1995) which, upon weathering, give rise to thick lateritic profiles. The soils are classified as inceptisols and belong to the Edanad Series (SSO, 2000).

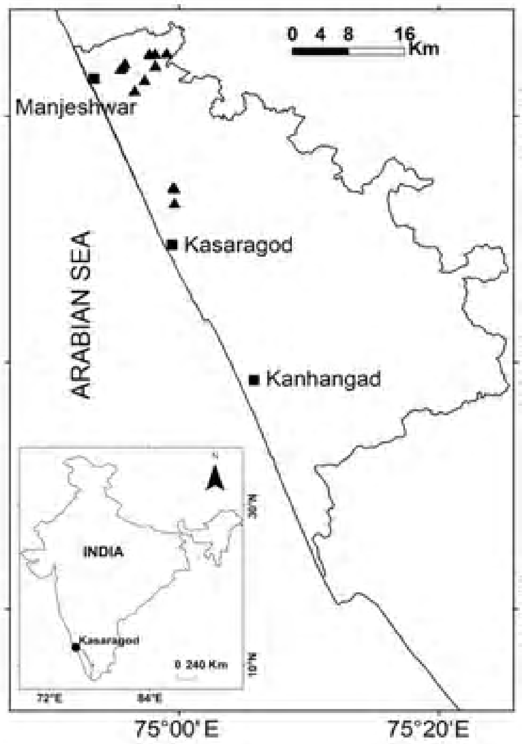

Fig. 1. Map showing the area of study and the locations (marked as triangles) of surface soil samples

MATERIALS & METHODS

Fifty pre-monsoon samples of surface soils were collected during May 2007 from Aribail, Kodlamogaru, Miyapadavu and Seethangoli and eight post-monsoon surface soil samples during September 2007 from Aribail (Fig. 1). In Miyapadavu, samples were collected from the slopes of three isolated, low lateritic mounds within an elevation of 80-120 m. Hence, these three discrete sample groups in the Miyapadavu area are designated as Miyapadavu-1, Miyapadavu-2 and Miyapadavu-3. All the samples were collected using a plastic knife to avoid contamination from iron and rust particles. The samples were tightly packed in labelled polythene covers and transported to the laboratory.

Standard techniques were used for sample preparation (Walden, 1999a). The soil samples were air-dried and gently disaggregated using an agate mortar and a pestle. About 7 g each of the samples were refilled in polythene covers and tightly packed in 8-cm^3 non-magnetic plastic bottles. A range of magnetic parameters (Table 1) was determined on the samples (Dearing, 1999, Walden *et al.,* 1999; Thompson and Oldfield, 1986). A Bartington Susceptibility Meter (model MS2B) with a dual-frequency sensor was used to measure magnetic susceptibility at low-(0.47 kHz; χ_{lf}) and high-(4.7 kHz; χ_{hf}) frequencies. The sensor was calibrated by using the Fe_3O_4 (1%) standard provided by the manufacturer. Frequency-dependent susceptibility (χ_{fd}%) was calculated from the difference between low- and high-frequency susceptibility values (Dearing, 1999). A Molspin AF demagnetiser (with an ARM attachment) was used to induce an anhysteretic remanent magnetisation (ARM) in the samples. It was set with a peak alternating field of 100 mT and a DC biasing field of 0.04 mT. A Molspin spinner fluxgate magnetometer was used to measure the ARM thus induced. The susceptibility of ARM (χ_{ARM}) was obtained by dividing the mass-specific ARM by the size of the biasing field (Walden, 1999b). Isothermal remnant magnetisation (IRM) was induced in the samples at different field strengths (20, 60, 100, 300, 500, 600 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

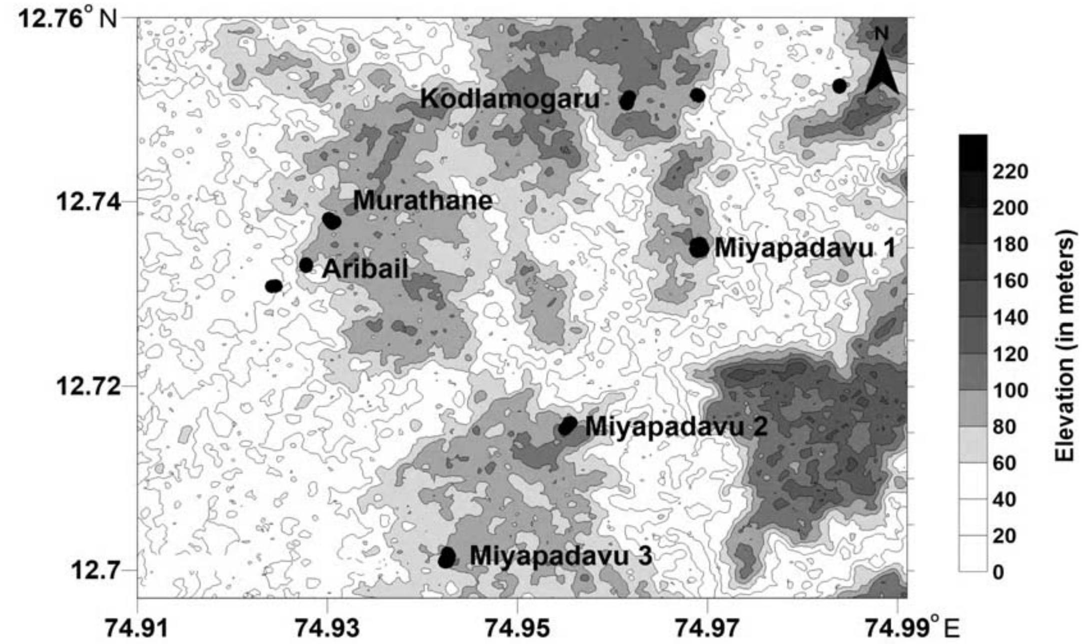

Fig. 2. Topographic map of the study area. The area comprises of dissected lateritic hills and valleys. Surface soil samples (shown as Ï%) were collected from slightly elevated lateritic hills. Note: Topographic contours were prepared using the ASTER Global Digital Elevation Model (GDEM) data provided by Japan's Ministry of Economy, Trade and industry (METI) and NASA. Thedatawere obtained from http:// gdem.ersdac.jspacesystems.or.jp/index.jsp

magnetisation (SIRM). The remanences acquired were 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 topographic contours of the study area were prepared using the ASTER (Advanced Space-borne Thermal Emission and Reflection Radiometer) Global Digital Elevation Model (GDEM) data provided by Japan's Ministry of Economy, Trade and industry (METI) and NASA. Thedata were obtained from the site http:// gdem.ersdac.jspacesystems.or.jp/index.jsp. The contour maps of $\chi_{lf,}$ χ_{fd}, S-ratio, χ_{ARM}/SIRM and topographic elevation were prepared using SURFER 9.0.

RESULTS & DISCUSSION

The sources of magnetic minerals in soils include bacterial magnetite, greigite (Fe_3S_4), anthropogenic magnetite and pedogenic magnetite. The various interparametric ratios may effectively be used to identify their origin. The biplot of χ_{ARM}/χ_{lf} *vs.* χ_{ARM}/χ_{fd} (Oldfield, 1994) was used to ascertain the source of magnetite in the soil samples (Fig. 3). Most of the samples plot near or in the envelope for "soils, paleosols and catchment-derived fine sediments" with χ_{ARM}/χ_{lf} values of < 40 and χ_{ARM}/χ_{fd} values of< 1000. These values are much lower than the threshold values prescribed for bacterial magnetite (Oldfield, 1994, 2007). As none of the samples falls in the "bacterial magnetite" field, the presence of bacterial magnetite may be ruled out (Oldfield, 1994, 2007). Greigite in soils can be identified using inter-parametric ratio SIRM/χ_{lf}. The samples dominated by greigite exhibits high values of SIRM/χ_{lf}, usually > 40 x 10^3 A/m which peak at ~ 70 x 10^3 A/m (Snowball and Thompson, 1990; Snowball, 1991; Oldfield *et al.*, 2010). But all the soil samples investigated display SIRM/χ_{lf} values < 40 x 10^{-3} A/m (average value = 14.29 x 10^{-3} A/m) which indicate the absence of greigite.

Another source of magnetic minerals is anthropogenic activities. The magnetic properties of anthropogenic magnetic minerals differ from those of naturally produced magnetic minerals (Oldfield *et al.*, 1985) in having a coarser magnetic grain size (MD and PSD; Yang *et al.*, 2007; Shen *et al.*, 2008; Gautam *et al.*, 2004). Magnetic grain size of samples may be determined from the biplot of χ_{ARM}/SIRM *vs.* χ_{fd} % (Dearing *et al.*, 1997). Except a few, the samples plot in the coarse SSD field (Fig. 4), indicating that there is no contribution from anthropogenic sources to the magnetic signal. A few samples which plot in the

MD+PSD range may be lithogenic as they have a coarse magnetic grain size). Besides, the sampling sites are situated well away from industries and pollution sources.

There is an overall good correlation between χ_{lf} and χ_{fd} ($r = 0.81$, $p < 0.01$, $n = 50$; Fig. 5). This indicates that the magnetic signal present in the surface soil samples from the four locations (Aribail, Kodlamogaru, Miyapadavu and Seethangoli) is essentially controlled and contributed by the pedogenic component (χ_{fd}).

The magnetic susceptibility (χ_{lf}) values of Aribail samples vary from 209.7 to 849.55x 10^{-8} m^3/kg (average =433.21 x 10^{-8} m^3/kg) and the χ_{fd} values from 2.63 to 28.59 x 10^{-8} m^3/kg (average =18.16 x 10^{-8} m^3/kg). It is evident from the χ_{lf} *vs.* χ_{fd} biplot (Fig. 5) that surface soil samples from Aribail exhibit low values for both the parameters when compared with those from other locations. Besides, there is no significant correlation between χ_{lf} and χ_{fd} (Table 2).However, χ_{lf} exhibits a good correlation with several IRM parameters. The biplot of $\div_{lf}$ *vs.* SIRM (Fig.6) indicates that Aribail samples again exhibit low values for both the parameters. Values for SIRM range from 1640.4 to 11874.4 x 10^{-5} Am^2/kg (average =5951.3x 10^{-5} Am^2/kg).

The low values for these magnetic parameters may be due to either lower pedogenesis and/or top-soil erosion. There is not much difference in parent rock lithology and climate between the four locations. Hence, similar rock magnetic properties may be expected in all the four locations. For the same reason, a lower degree of pedogenesis at Aribail compared to the other locations is not plausible. However, the geomorphology and the gently sloping topography of Aribail region favour erosion of top-soil because the sampling site is on a slightly elevated lateritic hill (Fig. 2).

The χ_{fd}% *vs.* χ_{ARM}/SIRM biplot (Fig. 4) shows that the samples are mainly in the range of coarse SSD except one, which exhibits a MD + PSD grain size. Values of χ_{fd}% range from 0.31 to 9.84 %, indicating a wide variation in the concentration of SP grains. The

Table 1. 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 magnetic susceptibility χ_{lf} and χ_{hf} (10^{-8} m^3 kg^{-1})	Proportional to the concentration of magnetic minerals	Bartington susceptibility meter
Frequency-dependent magnetic susceptibility χ_{fd} (10^{-8} m^3 kg^{-1}) and χ_{fd}%	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 RemanentMagnetisation and Saturation Isothermal RemanentMagnetisation IRM and SIRM (10^{-5} A m^2 kg^{-1})	Proportional to the concentration of remanence-carrying magnetic minerals	Pulse magnetizer and fluxgate magnetometer
Hard Isothermal RemanentMagnetisation 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 and *vice versa.*	
χ_{ARM} /SIRM	----------------”-------------------	
SIRM/χ_{lf}	Indicative of magnetic grain size. A high ratio suggests a coarse grain size.	
S-ratio (IRM_{300mT} /SIRM)	Relative proportions of ferrimagnetic and anti-ferromagnetic minerals (higher ratio = A relatively higher proportion of ferrimagnetic minerals).	

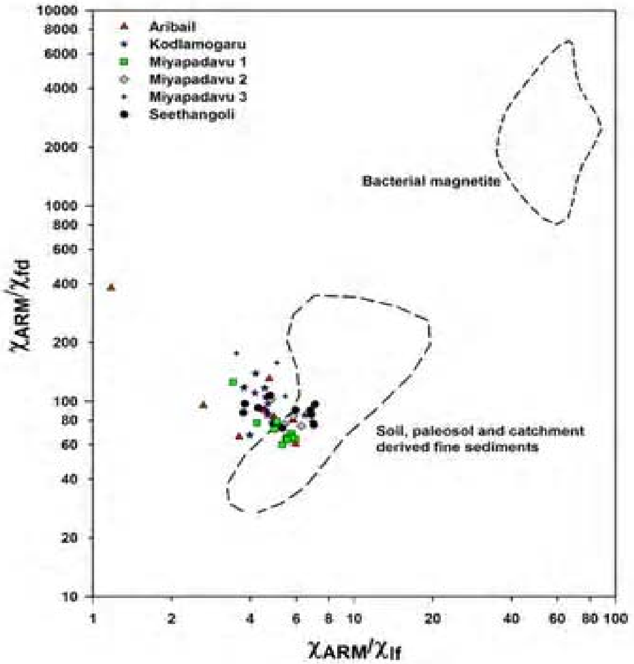

Fig. 3. Biplot of χ_{ARM}/χ_{lf} *vs.* χ_{ARM}/χ_{fd} for soil samples from Aribail, Kodlamogaru, Miyapadavu and Seethangoli. χ_{ARM}/χ_{lf} values of < 40and χ_{ARM}/χ_{fd} values of < 1000 indicate the absence of bacterial magnetite

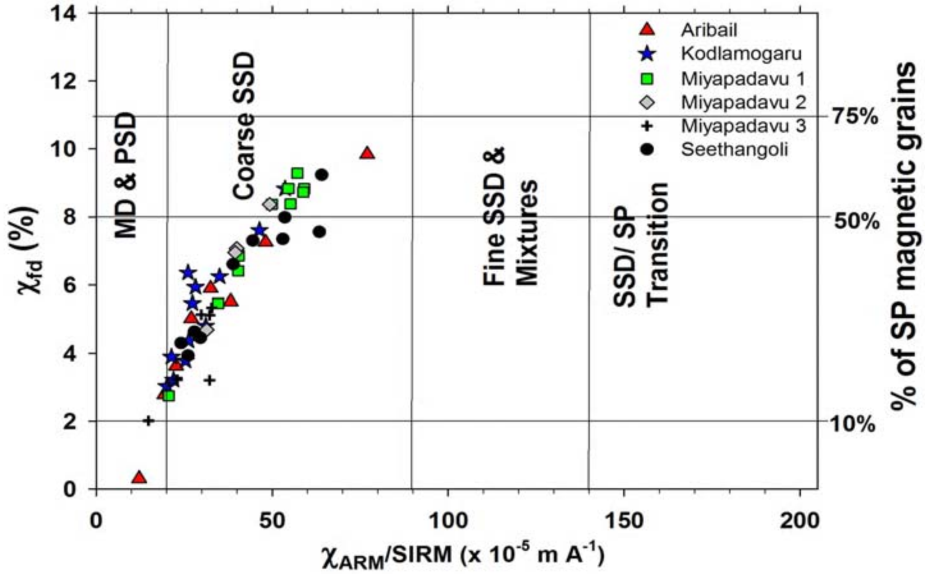

Fig. 4. Biplot of ÷$_{ARM}$/SIRM *vs.* ÷$_{fd}$ % for soil samples from the four locations. Most of the samples fall in the coarse SSD field, with only a few in the MD+PSD field, indicating the absence of anthropogenic and coarse grained lithogenic grains

magnetic grain size of Aribail samples also displays wide variations. The S-ratio values range from 0.82 to 0.90 (average = 0.86) and HIRM values from 236.33 to 213.11x10^{-5} Am^2/kg (average = 881.8 x10^{-5} Am^2/kg). From the biplot of S-ratio *vs.* HIRM (Fig. 7), it is evident that S-ratio exhibits relatively low values and HIRM values display a wide variation. The low S-ratio values may be due to the high contribution from magnetically "hard" minerals like hematite in Aribail samples. The presence of hematite, together with the slope pattern in Aribail area, corroborates the earlier interpretation that erosion plays a vital role in the spatial distribution of pedogenic magnetite in the region. During soil erosion, fine grained superparamagnetic magnetite is

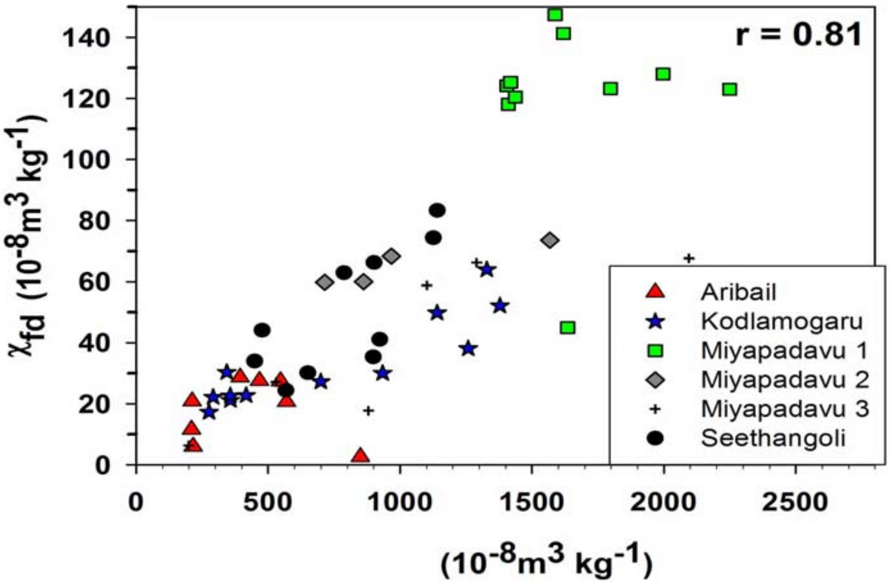

Fig. 5. Biplot of χ_{lf} *vs.* χ_{fd} for surface soil samples from all the four locations. The high correlation between the two parameters indicates that the magnetic signal is essentially controlled by fine grained pedogenic component

transported, leaving the coarse grained, magnetically "hard" hematite behind (Wang *et al.,* 2010). Factors like wind, vegetation and surface run-off play an important role in determining the erosivity of top-soil.

Kodlamogaru soil samples show wide variations in χ_{lf} and χ_{fd} values. The χ_{lf} values range from 276.30 to 1378.6 x 10^{-8} m^3/kg (average=731.84x 10^{-8} m^3/kg) and χ_{fd} values from 17.3 to 63.9 x 10^{-8} m^3/kg (average = 33.1x 10^{-8} m^3/kg). There is a significant correlation between the two parameters (r=0.89, p<0.01, n=12), indicating that the magnetic signature is mainly controlled by SP grains. Values of SIRM also exhibit wide variations (from 3805.3 to 26240.1x 10^{-5} Am^2/kg; average=12575.4x 10^{-5} Am^2/kg).

This region has a gentler slope compared to Aribail area and hence may not have experienced considerable soil erosion and the resultant loss of fine-grained pedogenic grains. The dominant grain size is coarse SSD (Fig. 4), with χ_{fd} % ranging from 3.02 to 8.8.This indicates that the percentage of SP grains in the samples is less than 50.Values of S-ratio exhibit wide variations(from 0.73 to 0.96; average=0.86). A similar trend is also exhibited by HIRM values, which range from 738.49 to 2621.4x 10^{-5} Am^2/kg (average=1436.2x 10^{-5} Am^2/kg). These data are indicative of variation in the magnetic mineralogy of soils: from a high relative proportion of hematite (samples with low values of S-ratio, < 0.9) to a high relative proportion of magnetite (samples with high values of S-ratio,>0.9; Fig. 7). But the magnetic signal is controlled by pedogenic magnetite as indicated by the significant correlation between χ_{lf} and $\chi_{fd.}$ (r = 0.82, p<0.01, n=12).

Surface soil samples were collected from three discrete locations in and around Miyapadavu. Values of χ_{lf} vary from 198.7 to 2248.8 x 10^{-8} m^3/kg (average =1338.2x 10^{-8} m^3/kg) and χ_{fd} values from 6.4 to 147.3 x 10^{-8} m^3/kg (average = 85x 10^{-8} m^3/kg). It is evident from the χ_{lf} *vs.* χ_{fd} biplot (Fig. 5) that Miyapadavu-1 samples cluster together, with relatively high values for both the parameters. This is also evident from the biplot of χ_{lf} *vs.*SIRM (Fig. 6) which shows that Miyapadavu-1 samples exhibit relatively high SIRM values compared to Miyapadavu-2 and Miyapadavu-3 samples. Values of χ_{fd} % vary from 1 to 10.1 %. The grain size is predominantly in the coarse SSD range, with > 50 % SP grains in most of the Miyapadavu-1 samples (Fig. 4). Miyapadavu-1 and -2 samples are characterized by magnetically "soft" minerals as indicated by the S-ratio *vs.* HIRM biplot (Fig. 7). S-ratio values vary from 0.80 to 0.98 and HIRM values from 273.8 to 2416.6x 10^{-5} Am^2/kg. This further corroborates the fact that Miyapadavu-1 samples are characterized by a high relative proportion of magnetically "soft" pedogenic SP grains. This is substantiated by the fact that the sampling site has a flat topography and hence a low probability of soil erosion and the subsequent loss of fine-grained SP grains of pedogenic magnetite.

The magnetic susceptibility values of surface samples from Seethangoli vary from 449.4 to 1141.4x 10^{-8} m^3/kg (average= 792.35 x 10^{-8} m^3/kg) and χ_{fd} values from 24.4 to 83.3 x 10^{-8} m^3/kg (average= 49.6x 10^{-8} m^3/

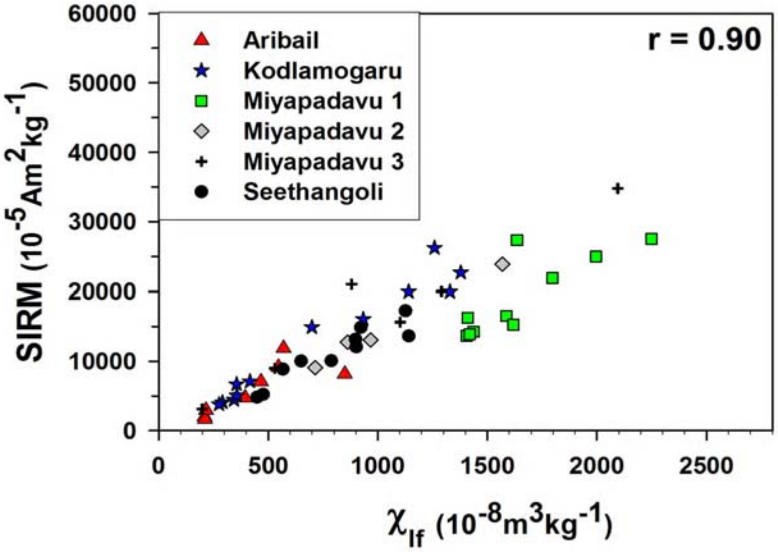

Fig. 6. Biplot of SIRM *vs.* χ_{lf} for surface soil samples from the four locations. The samples exhibit wide variations in values for both the parameters with good correlation between the two. It is evident that Miyapadavu 1 samples cluster together with distinctly high values

Table 2. Correlation of χ_{lf} with other magnetic parameters for the surface soil samples from four locations Aribail, Kodlamogaru, Miyapadavu and Seethangoli. Those in bold italics are significant at 0.01 level, those marked with * are significant at 0.02 and those with ^ are at 0.04 level. Note that χ_{lf} is well correlated with χ_{fd}, IRMs, SIRM and S-ratio except the Aribail samples which exhibit a lower correlation

	Aribail(n = 8)	Kodlamogaru(n = 12)	Miyapadavu(n = 20)	Seethangoli(n = 10)
	χ_{lf}	χ_{lf}	χ_{lf}	χ_{lf}
χ_{fd}	-0.10	**0.89**	**0.69**	**0.75**
χ_{fd}%	-0.64	-0.77^	0.12	-0.15
χ_{ARM}	0.36	**0.98**	**0.90**	**0.81**
IRM_{20mT}	0.57	**0.99**	**0.88**	**0.98**
IRM_{40mT}	0.60	**0.98**	**0.86**	**0.94**
IRM_{60mT}	0.69	**0.98**	**0.86**	**0.94**
IRM_{100mT}	0.78*	**0.98**	**0.86**	**0.95**
IRM_{300mT}	**0.83**	**0.98**	**0.85**	**0.95**
IRM_{500mT}	**0.83**	**0.98**	**0.84**	**0.94**
IRM_{600mT}	**0.82**	**0.98**	**0.83**	**0.94**
SIRM	0.80*	**0.97**	**0.83**	**0.93**
HIRM	0.61	0.60^	-0.08	**0.76**
S-ratio	0.20	**0.82**	**0.76**	**0.84**
SIRM/χ_{lf}	0.29	0.40	-0.35	0.34
χ_{ARM} /χ_{lf}	-0.44	-0.50	-0.31	-0.12
χ_{ARM} /χ_{fd}	**0.82**	**0.77**	-0.39	0.11
χ_{ARM} /SIRM	-0.60	-0.52	0.10	-0.31

Significance level: Bold italics=0.01, * = 0.02, ^ = 0.04

kg). Values of χ_{lf} and χ_{fd} exhibit a good correlation (r = 0.75), indicating the control of pedogenic magnetic minerals on the magnetic signal of soil samples. The SIRM *vs.* χ_{lf} biplot (Fig. 6) indicates the significant variation in SIRM values (4814.4 to 17240.6x 10^{-5} Am^2/kg; average= 10989.22x 10^{-5} Am^2/kg). The magnetic grain size is in the coarse SSD range, with < 50 %of SP grains. The samples are characterized by a high relative proportion of magnetically "hard" minerals as indicated by the low S-ratio values (0.81-0.87; average= 0.84). All these data indicate a relatively low content of pedogenic magnetite. This may be due to the gently sloping surface that must have facilitated soil erosion. The contour plots of χ_{lf}, χ_{fd}, S-ratio and χ_{ARM}/SIRM (Fig. 8) display identical trends: High values in the northwestern part (Aribail, Morathane, Kodlamogaru) that decrease to low ones in the southeastern/eastern part (Miyapadavu-1, -2 and -3; Fig. 8a). Values of χ_{fd}

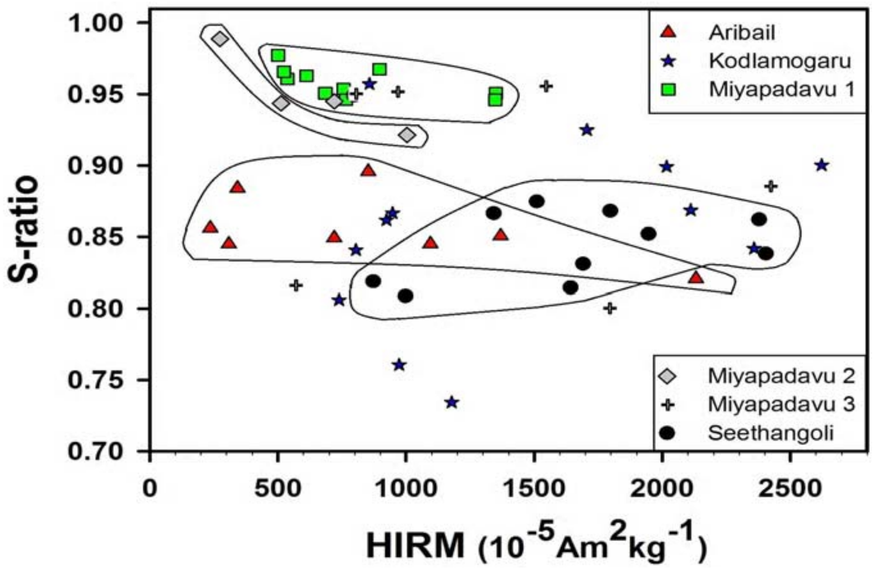

Fig. 7. Biplot of S-ratio *vs.* HIRM for surface soil samples from all the four locations indicating the variation in magnetic mineralogy. Miyapadavu samples exhibit relatively high S-ratio and low HIRM which indicates the predominance of magnetically soft minerals in those samples. Whereas, samples from Aribail, Kodlamogaru and Seethangoli samples exhibit higher proportion of magnetically hard minerals

also display a similar trend, but the high values are centred around Miyapadavu-1 samples. The concentration of pedogenic SP magnetite increases from NW to SE and east (Fig. 8a and b). Magnetic mineralogy also displays spatial variations, with high contributions from magnetically "hard" minerals in the NW part but from magnetically "soft" minerals in the SE (Fig. 8c). Magnetic grain size does not exhibit much spatial variation; it is relatively fine in Miyapadavu samples (Fig. 8d).This is probably related to slope and erosion, as other pedogenic factors are similar. The large spatial variability of magnetic properties within a small area may be due to the geographical location of the sampling sites. As all the four sampling sites are located in slightly elevated areas (Fig. 2), they are vulnerable to soil erosion. As the parent rock, climate, soil type, vegetation are almost identical in all the four locations, the variations in soil magnetic properties in the region may be attributed to soil erosion.

Table 3 gives the average values of magnetic parameters for the pre-monsoon and post-monsoon samples collected from the same geographic location in Aribail region. There is a significant increase in the magnetic parameter values (Table 3) in the post-monsoon samples. Values of c_{lf} exhibit a notable increase from 433 x 10^{-8} m^3/kg to 633.29 x 10^{-8} m^3/kg. Similarly, c_{fd} values also increase from 18.16 to 23.27 x 10^{-8} m^3/kg and so do SIRM values to 7224.05 x 10^{-5} Am^2/kg from an initial value of 5951.28 x 10^{-8} Am^2/kg. This indicates that the concentration of magnetic minerals increased significantly during the monsoon. There is a change in the magnetic mineralogy as well. Values of S-ratio increase to 0.94 from 0.86 in the pre-monsoon samples but HIRM values decrease from 881.82 to 355.47 x 10^{-5} Am^2/kg. The latter may be because hematite that formed under oxic conditions during the pre-monsoon season was reduced and converted to magnetite under the reducing conditions created by water-logging conditions during the monsoon season (Maher and Thompson, 1995). Pedogenesis is enhanced during monsoon season, resulting in an increased production of pedogenic magnetite. However, erosion is also prevalent during rainy season. But the production of pedogenic magnetite has kept pace with, or perhaps exceeded, the rate of erosion. This shows that a short time is enough for the production of pedogenic magnetite; this inference is in agreement with the observation that pedogenic susceptibility is a rapidly formed soil property (Maher and Thompson, 1995). There is not much time lag between the formation of 'new' pedogenic magnetite in top-soil and its erosion. Taylor et al. (1987) have reported that the time taken for the synthesis of magnetite in laboratory conditions varies from 36 to 2720 minutes, depending upon pH, temperature, airflow and initial Fe^{2+} and Fe^{3+} concentrations. Our soil magnetic studies of the tropical southern Indian soil samples confirm that the formation of pedogenic magnetite and the resulting magnetic enhancement are rapid. The short time required for the production of pedogenic magnetite has also been reported for soils of Kerala (Sandeep *et al.*, 2012). This observation is significant and lends credence to Shankar et al.'s (2006) proposition that c_{lf} of lake sediments may

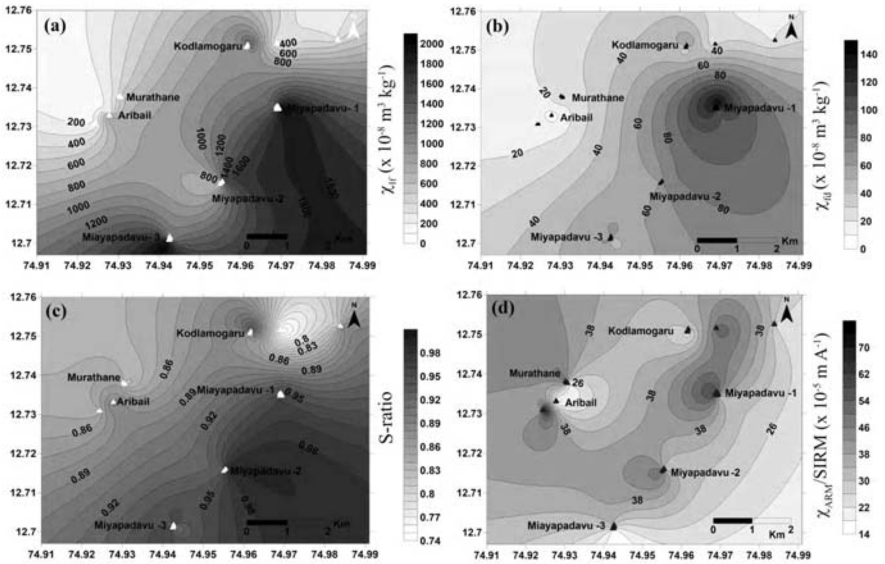

Fig. 8. The spatial variability of $\chi_{lf,}$ χ_{fd}, S-ratio and χ_{ARM}/SIRM (Figures 8a, b, c and d respectively) in the study area. As Seethangoli samples are situated at a distance from other sampling sites, they were not included for the contouring. The parameters exhibit increased values from NW (Aribail, Murathane and Kodlamogaru) to SE (Miyapadavu 1, 2 and 3) direction

be used as a proxy for past rainfall in tropical regions; if, on the other hand, pedogenic magnetite formation involved long periods, the climatic information contained in pedogenic magnetite would lag.

Fig. 9 is a schematic diagram that incorporates the findings of this study in terms of the production and erosion of pedogenic magnetite during monsoon and summer. During summer, with no/insignificant rainfall, there is only negligible production, if any, of pedogenic magnetite. The oxidising conditions prevalent favour the formation of hematite. As a consequence, concentration-dependent magnetic parameters (c_{lf}, $c_{fd,}$ $c_{ARM,}$ IRM's) and S-ratio values are subdued. Besides, there is no/insignificant erosion of top-soil and the consequent loss of fine-grained magnetic minerals. By contrast, the high rainfall (annual average = 3500 mm) induces water-logged conditions and a reducing environment in soils during monsoon. This aids the production of pedogenic magnetite, which is imprinted in increased values of concentration-dependent magnetic parameters (c_{lf}, $c_{fd,}$ $c_{ARM,}$ IRM's) and S-ratio. In addition, hematite is transformed to magnetite as can be seen in the enhanced values of S-ratio. This is also substantiated by the low HIRM values in the post-monsoon samples (Table 3). However, the values of inter-parametric ratios like c_{ARM}/c_{lf}, c_{ARM}/c_{fd} and c_{ARM}/SIRM display only a slight decrease from pre-monsoon to post-monsoon season. These magnetic characteristics are sustained in spite of the loss of some pedogenic magnetite due to erosion of top-soil in areas of sloping topography.

CONCLUSION

The following conclusions may be drawn based on the rock magnetic investigations of tropical surface soil samples from four locations in southern India, i.e., Aribail, Kodlamogaru, Miyapadavu and Seethangoli in Kasaragod District, Kerala State:

- There is no contribution from bacterial magnetite, greigite or anthropogenic sources to the magnetic signal contained in the surface soil samples studied. Therefore, the magnetic signal must have originated from pedogenic processes.
- The magnetic mineralogy is mainly magnetite/ maghemite although magnetically "hard" minerals like hematite make a contribution to some samples. For example, samples from Aribail.
- The magnetic grain size is principally coarse SSD although a couple of samples plot in the MD+PSD region.
- From northwest (Aribail and Kodlamogaru) to southwest (Miyapadavu), the concentration of pedogenic SP magnetite increases, the magnetic mineralogy becomes "softer" and the magnetic grain size finer.
- The large variability of magnetic parameters within a small area may be due to the geographical location of the samples. Parent rock lithology, soil type and vegetation being the same, the variability across the region may be attributed to soil erosional processes.
- Compared to pre-monsoon season, there is a significant production of pedogenic magnetite during monsoon and in a short time at that. This is important

Table 3. Variations in the magnetic properties of the samples during monsoon and pre-monsoon seasons

Magnetic parameters	Pre-monsoon	Post-monsoon	% change (Pre-monsoon to post- monsoon)
χ_{lf}	433.21	633.29	46.19
χ_{fd}	18.16	23.87	31.44
$\chi_{fd}\%$	5.03	4.11	-18.29
χ_{ARM}	1.67	2.26	35.33
IRM_{20mT}	1568.60	1874.09	19.48
IRM_{40mT}	3703.90	4386.20	18.42
IRM_{60mT}	4383.06	5296.68	20.84
IRM_{100mT}	4766.68	5915.59	24.10
IRM_{300mT}	5069.46	6868.57	35.49
IRM_{500mT}	5365.64	7070.13	31.77
IRM_{600mT}	5518.22	7101.22	28.69
SIRM	5951.28	7224.05	21.39
HIRM	881.82	355.47	-59.69
S-ratio	0.86	0.94	9.30
$SIRM/\chi_{lf}$	13.16	11.27	-14.36
χ_{ARM}/χ_{lf}	4.18	3.80	-9.09
χ_{ARM}/χ_{fd}	123.25	110.88	-10.04
$\chi_{ARM}/SIRM$	34.65	33.44	-3.49

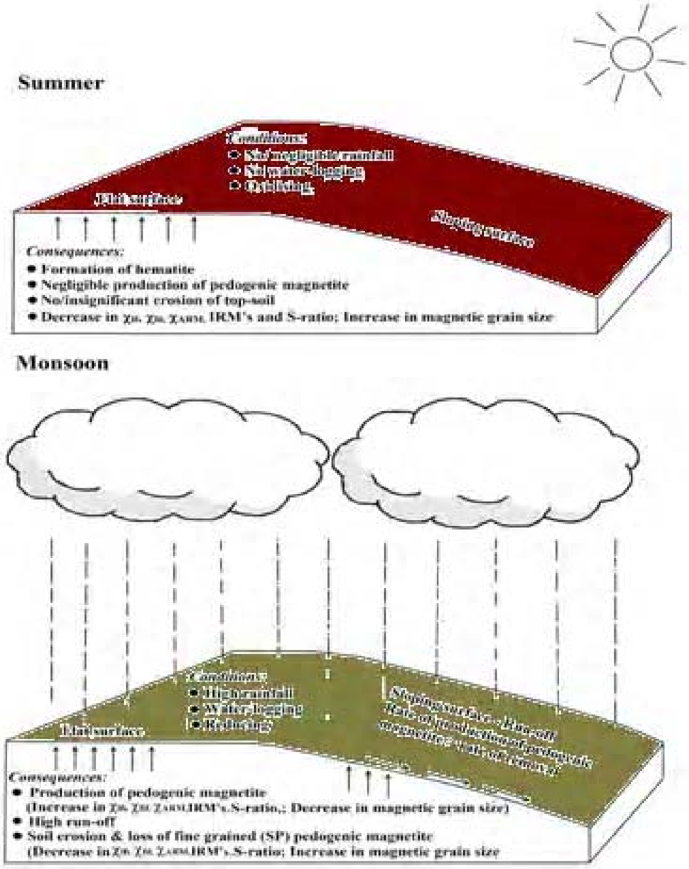

Fig. 9. A schematic diagram that incorporates the findings of this study in terms of variation in production of pedogenic magnetite during monsoon and summer seasons

in the context of paleo-precipitation studies from the c_{lf}signal in lake sediments from tropical regions.

- Although the high rainfall in the area results in soil erosion and the consequent loss of fine grained pedogenic magnetite, the rate of production of pedogenic magnetite has kept pace with the rate at which it is lost because of soil erosion.
- The rock magnetic data collected in this study would serve as baseline for future pollution studies as well as for palaeoclimatic studies.

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