Magnetic properties of black cotton soils and lateritic soils developed on the Late Cretaceous Deccan flood basalts of northern Karnataka, India

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Abstract. The magnetic properties of black cotton and lateritic soils developed on Deccan basalts in northern Karnataka, India, have been studied to determine magnetic mineral sources and decipher their relative age. These soils are highly magnetic, indicating lithogenic contribution. The results show that black cotton soils are characterized by coarse-grained stable single-domain (SSD) lithogenic magnetic minerals, and in lateritic soils, it is superparamagnetic (SP) pedogenic magnetic minerals. The main magnetic minerals in black cotton soils are titanomagnetite/maghemite, while in lateritic soils, it is magnetite/maghemite and/or hematite/goethite. The variability of these soils' magnetic properties is due to changes in the concentration of magnetic minerals, the size of their magnetic grains, or magnetic mineralogy. Black cotton soils are younger and are at the initial stage of soil development, while laterite soils are older and are at the latter stage of soil development.

Keywords: Deccan basalt; black cotton soil; laterite; lithogenic; pedogenic; titano-magnetite; magnetic enhancement

1. Introduction
The Late Cretaceous Deccan flood basalts of the Indian peninsula are the most extensive continental lava flow accumulations, spreading over 500,000 km² with an average thickness of about 2000m [1, 2]. The soils developed on the basaltic lava flows of Deccan are mainly black cotton soils (regur) and lateritic soils in some pockets. The extensively developed black cotton soils are good for cotton cultivation and have been widely studied since the last century and are observed on the plains of Deccan traps, with the exception near the coast [3, 4, 5]. The morphology, genesis, classification, and coloration of these soils have been widely discussed by various researchers [6, 7, 8, 9, 10]. Agricultural scientists have carefully studied these soils to understand their importance for sustainable crop production [11]. The mineralogical and engineering aspects of these soils have also been studied by many researchers [12, 13, 14]. The laterite, which is the residual product of extreme chemical weathering of iron and aluminium-rich rocks, is observed in the Deccan basaltic region along the western lowlands of the Konkan Plain (between the Sahyadri [Western Ghats] and the Arabian Sea), on isolated basaltic plateaus rising from the Plain and on some basaltic peaks east of the Sahyadri ranges [15, 2, 16].

Recently, environmental magnetic studies have attracted more attention due to the simple, rapid, and non-destructive way of analysis. Soils’ magnetic properties are a combined effect of in situ pedogenic
and lithogenic magnetic minerals [17, 18]. In the earth and environmental sciences, the magnetic properties of soils are used in different ways; as a climatic indicator in loess-palaeosol sequences; as a tool for archaeological mapping and exploration; as an indicator of sediment sources; as records of pollution, etc. [19, 20, 21, 22, 23, 24, 25]. Several magnetic studies were carried out on basaltic soils developed in various climatic and geographical conditions [26, 27, 28, 29, 30]. In the Indian context, some magnetic studies were conducted on Deccan basalts and soils developed on them. In some pioneering studies, Annette [3] discussed the development of black cotton soils and their black coloration. India’s black cotton soils were compared with the soils of other countries by Roy and Barde [31]. Deutsch et al. [32] conducted a comparative magnetic study of the Indian Rajmahal Traps (130 m. a. old) and Deccan basalts (65 m. a. old) with the younger Columbia River Basalt of Miocene to Early Pliocene age (16 m. a. old). They recorded the presence of a multi-domain (MD) magnetic phase in the younger Deccan Traps and Columbia River Basalts, but its absence in the older Rajmahal Traps. In addition, a large proportion of titanomagnetite was recorded in the younger Columbia River Basalts compared to the older Deccan Traps and Rajmahal Traps. Sangode et al. [33] studied the magnetic mineralogical variation of Deccan basalt and observed the titanomagnetite rich magnetic mineralogy and the predominance of the pseudo-single domain (PSD) and single domain (SD) ferrimagnets with a certain concentration of MD grains. In this present study, an attempt is made to establish the magnetic properties of black cotton and lateritic soils developed on Deccan basalts and to determine the sources of magnetic minerals (lithogenic or pedogenic) in these soils. An effort is also made to know the relative age of these soil profiles.

2. Materials and methods

2.1. Soil sampling

Three black cotton soil profiles (P33, P36, P40) and two laterite soil profiles (P37, P39) developed on Deccan basalts in northern Karnataka, India, were selected for this study. The study area is between 15° 26' 42.18” and 18° 36' 8.24”N latitude and between 74° 1' 25.32” and 78° 2' 52.04”E longitude (figure 1).

![Figure 1](image_url)

**Figure 1.** Map showing the study area and location of soil sampling stations. Undisturbed soil profiles were carefully selected and closely sampled using a wooden knife and plastic sampler to avoid contamination. The samples were oven-dried (36° - 38°C) to prevent possible storage...
diagenesis. The dried samples were carefully disaggregated and sieved through an ASTM sieve (American Standard for Testing Materials - No. 20) to separate the finer fractions (< 2 mm), in which magnetic minerals are abundant. These samples were tightly packed in polyethylene bags and placed in 8-cc plastic containers for further magnetic measurements.

2.2. Magnetic measurements
The low ($\chi_{\text{ld}}$) and high frequency ($\chi_{\text{hf}}$) magnetic susceptibilities (0.47 kHz and 4.7 kHz) were determined on a Bartington susceptibility meter (model MS2 B) with dual-frequency sensors (0.46 and 4.6 kHz). The frequency-dependent magnetic susceptibility ($\chi_{\text{fd}}$) and its percentage ($\chi_{\text{fd}}\%$) were calculated as $\chi_{\text{ld}} - \chi_{\text{hf}}$ and $[(\chi_{\text{ld}} - \chi_{\text{hf}})/\chi_{\text{ld}}] \times 100$, respectively. AnhystereticRemanent Magnetization (ARM) was grown by simultaneously exposing the sample to a slowly decreasing alternating magnetic field of 100 milli Tesla (mT) in the presence of a constant field of 0.04mT. ARM was induced by the Molspin alternating frequency (AF) demagnetizer with the ARM attachment. ARM, thus grown was measured using a MolspinFluxgate spinner magnetometer. ARM is expressed as the susceptibility of AnhystereticRemanent Magnetization ($\chi_{\text{ARM}}$), which is the quotient of volume-based ARM (A/m) and the applied DC field (31.84 A/m) [34].

Isothermal Remanent Magnetization (IRM) was induced at magnetic fields of 20, 40, 60, 100, 300, 600, and 1000 mT using a Molspin pulse magnetizer. The IRM thus grown was determined using a Molspin fluxgate spinner magnetometer. IRM grown at a field of 1000mT (the maximum possible field in the environmental magnetism laboratory of Mangalore University) is considered as Saturation Isothermal Remanent Magnetization (SIRM). Inter-parametric ratios were calculated by these parameters. Hysteresis loops and related parameters, such as saturation remanence ($M_r$), saturation magnetization ($M_s$), coercivity of remanence ($H_c$), and coercive force ($H_c$) were determined using a MolspinVuvo vibrating sample magnetometer with a maximum magnetic field of 1T at the Institute of Geophysics, Polish Academy of Sciences, Poland, and a Vibrating Sample Magnetometer (Advanced Digital Equipment make, model EV-9) with a maximum magnetic field of 2T at the Defence Research and Metallurgical Laboratory (DRML), Hyderabad, India. Treatment with citrate-bicarbonate-dithionite (CBD) [35] was carried out on selected soil samples to distinguish between pedogenic and lithogenic magnetic minerals.

2.3. Chemical and mineralogical studies
Electrical conductivity (EC) and pH were measured using an ELICO PE-136 water quality analyzer. Organic matter was determined by the method of hydrogen peroxide digestion ($H_2O_2$) on < 0.177 mm soil fractions (ASTM mesh no. 80) [36]. Scanning electron microscopic and energy dispersive X-ray spectroscopic analysis (SEM and EDS) were performed on magnetic extracts using a JEOL JSM-6360 LV scanning electron microscope and an OXFORD INCA 200 energy dispersive X-ray Spectrometer (National Centre for Polar and Ocean Research-NCPOR, Goa, India).

3. Results and Discussion
Three black cotton soil profiles and two lateritic soil profiles developed on Deccan basalt are discussed. Black cotton soil profiles were selected from Sindgi (P33), Gulbarga (P36), and Belgaum (P40), and lateritic soil profiles were sampled from Humnabad (P37) and Halbarga (P39) of the Deccan area (figure 1, 2). The results are discussed in two separate sections, depending on the type of soil.

3.1 Black cotton soil profiles
Black cotton soils usually have a dark grey to black color. They are rich in plant nutrients such as magnesia, iron, lime, and alkaline earth [12]. They are also characterized by specific clay mineralogy, a high organic matter content, and high moisture retention capacity [37, 11]. Three black cotton soil profiles were developed at altitudes of 738m (P40), 488m (P36), and 509 m (P33) above mean sea level (MSL). These areas receive an average annual rainfall of 132cm, 73cm, and 58cm, respectively.
The organic matter content in these soil profiles ranges from 3.7% to 12.4% (figure 3) and is near neutral to slightly basic (pH - from 7.05 to 8.6). Electrical conductivity (EC), which is a measure of salinity, ranges between 20 and 90μS/cm. The near-surface samples show an increase in EC, which might be due to the capillary transfer of dissolved components to the surface and its precipitation during evaporation [38]. The increasing trend of EC towards the bottom might be due to the presence of more dissolved salts [39].
Figure 3. Organic matter (OM), pH, electrical conductivity (EC), and rock magnetic parameters and inter-parametric relationships for P33 (a), P36 (b), and P40 (c) black cotton soil profiles developed on basaltic parent material.

The $\chi_{lf}$ values of these soil profiles range from 200 to 1000 x $10^{-8}$ m$^3$/kg (figure 3), which indicates a higher concentration of magnetic minerals. Although basalt was the parent material for these three soil profiles, the P33 soil profile shows the highest $\chi_{lf}$ values compared to the P36 and P40 soil profiles. This difference in $\chi_{lf}$ might be due to the variations in the $\chi_{lf}$ of the parent materials. The $\chi_{lf}$ of the parent material for P33, P36, and P40 is 1414, 527, and 399 x $10^{-8}$ m$^3$/kg, respectively, which indicates an almost threefold increase in $\chi_{lf}$ for P33 compared to the other two. This is reflected in figure 4 where $\chi_{lf}$ and other parameters of all the three soil profiles are compared. Although these soil profiles were developed on basaltic rocks, the concentration of magnetic minerals varies among them. It emphasizes the importance of the parent material in determining soils' magnetic properties [40, 41, 42, 30]. A slight magnetic enhancement is observed in the soil profiles P33 and P40, which may be associated with pedogenesis (figure 4). $\chi_{ARM}$ and SIRM also show a similar picture. P36 exhibits an almost constant magnetic behavior throughout the profile.

Figure 4. Variations of $\chi_{lf}$, $\chi_{ARM}$ and SIRM, $\chi_{fd}$% and $\chi_{fd}$ for black cotton soils developed on basaltic parent material (Note: the lowest sample of $\chi_{lf}$, $\chi_{ARM}$, and SIRM refers to the bedrock).
Inter-parametric ratios indicating the size of the magnetic grain (SIRM/χ₀, χ_ARM/χ₀, and χ_ARM/SIRM) show the presence of stable single-domain (SSD) magnetic grains in these samples (figure 3). The double plot of χ_ARM/SIRM vs. χ₀% (figure 5a) also shows the predominance of coarse SSD grains and few fine SSD magnetic grains. Magnetically stronger parent material might be the source of these coarse SSD magnetic grains than pedogenesis, which leads to fine SSD to SP magnetic grains with high χ₀% [40, 43, 44].

**Figure 5.** Scatter plots of χ₀% vs. χ_ARM/SIRM (after Maher, 1988 [45]) for black cotton soil profiles P33, P36, P40 (a) and lateritic soil profiles P37, P39 (b), developed on Deccan basalts.

The relatively finer magnetic grains in the soil profile P40 (figure 5a) may result from greater weathering and pedogenesis as a result of relatively high rainfall (132 cm/year). All three soil profiles have an insignificant amount of finer SP grains (χ₀% < 2) [22]. Despite the low χ₀%, a positive relationship with precipitation is obvious: where the area with the highest precipitation has the highest χ₀% (P40) and the lowest precipitation (58 cm), the lowest χ₀% (P33).

**Figure 6.** IRM acquisition curves for black cotton (a) and lateritic (b) soil profiles developed on basalt.
The IRM acquisition curves saturate at about 300 mT (figure 6a), suggesting a magnetically soft mineralogy (magnetite or maghemite) [20, 34]. This magnetic mineralogy is again confirmed by the S-ratio, which is close to 1 [34; figure 3]. The SEM and EDS spectra (figure 7) also confirm the presence of soft magnetic minerals. SEM images of P33-6cm (a) and P40 – 0cm(b) show broken and corroded octahedral magnetite grains. Peaks of Fe and Ti in EDS spectra indicate the content of titanomagnetite/maghemite in these samples. These titanomagnetites/maghemites might be of lithogenic origin. Similar magnetic mineralogy of Deccan basalts was previously reported by Deutsch and Sangode [32, 46]. Singer and Fine [42] and Lu et al. [30] also reported such association in basalt soils of Eastern China. Fabris et al. [26] also reported residual lithogenic magnetite association in some young Brazilian soils developed on mafic parent materials.

Figure 7. Energy dispersive spectroscopic image (EDS) and elemental concentration data from soil profiles of P33-6cm (a) and P40-surface sample (b).

To test the presence of lithogenic titanomagnetite/maghemite in the sample, the samples were treated with citrate-bicarbonate-dithionite (CBD), which typically dissolves finer pedogenic magnetic minerals and other poorly crystalline iron oxides [47]. Upon dissolution, unoxidized coarse-grained lithogenic titanomagnetite/maghemite remains unaffected [47]. The P33 surface sample shows a slight decrease of χlf (~ 2.82 %) after CBD treatment (figure 8a), which may be due to the existence of coarse lithogenic magnetic minerals in the sample and the absence of ultra-fine pedogenic magnetite/maghemite [47, 48]. Magnetic and non-magnetic analyses suggest the predominance of lithogenic titanomagnetite/maghemite throughout the black cotton soil profiles. The vertical variations in the magnetic properties of these soil profiles are mainly associated with changes in the magnetic mineral concentration and the magnetic grain size.
3.2 Lateritic soil profiles

During the laterization process, silica, alkalis, and alkaline earth materials are leached from the iron and aluminum rich parent material, leaving alumina, iron and titanium oxides in the matrix [49], which leads to the accumulation of secondary iron or aluminum oxides, or both [50]. In this study, lateritic soils are observed in some isolated areas along the study area’s northeastern direction. Two deep and well-drained lateritic soil profiles were selected from Humnabad (P37) and Halbarga (P39), which are located at altitudes of 638m and 613m above MSL. The area receives an average annual precipitation of 77cm and 88cm.

The organic matter content of soil profiles P37 and P39 (figure 9) ranges between 2 to 8 %, and most of the samples show about 6% organic matter. Soil samples P37 and P39 are slightly acidic to basic. EC ranges between 10 and 160 µS/cm with most of the samples ~ 20 µS/cm and shows an enhancement towards the top (except for a few lower samples of P39).
Figure 9. Organic matter, pH, electrical conductivity (EC), rock magnetic, and interparametric ratios for P37 (a) and P39 (b) lateritic soil profiles developed on basaltic parent material.

Magnetic susceptibility ($\chi_b$) values of these soil profiles range from 150 - 1000 x $10^{-8}$ m$^3$/kg, SIRM between 2000 - 12000 x $10^5$Am$^3$/kg, and, $\chi_{ARM}$ from 1.4 - 5.7 x $10^{-5}$m$^3$/kg. Magnetic enhancement as well as an increase in the $\chi_{ARM}$ and SIRM is also noticed towards the profile-top. The variations of $\chi_{ARM}$, $\chi_{ARM}/\chi_b$, $\chi_{ARM}/SIRM$, and $\chi_b$% in the soil profile indicate the abundance of SSD and SP grains in various proportions. The dominance of SSD and SP grains is also very clearly seen from the biplot of $\chi_{ARM}/SIRM$ vs. $\chi_b$% (figure 5b). Despite the fact that there is little rainfall in the region, the removal of finer SP grains from the top of the soil profile is noticeable by decreasing $\chi_b$% and $\chi_b$.

A surface sample of P37 was subjected to CBD treatment, and a loss of 49% $\chi_b$ during the dissolution was observed (figure 8c). This more significant loss of $\chi_b$ with respect to the black cotton soil P33 (loss of only ~ 2.82%) is explained by the dissolution of finer pedogenic magnetic minerals [47, 51, 52], which are formed during the intense chemical weathering [53].

Most of the samples in these soil profiles show an $S$-ratio between 0.80 and 0.90 (figure 9), and they do not attain saturation even at 1T magnetic field (figure 6b), which indicate the presence of antiferromagnetic minerals such as hematite and/or goethite [20, 34]. Hematite is usually saturated at a magnetic field below 3T, and goethite is not even saturated at a magnetic field > 7T [34]. Hysteresis loops of P37 (0cm) and P39 (52cm) (figure 10) show narrow loops with slightly high coercivity. The hysteresis loop and the parameters indicate the collective influence of ferri-and antiferromagnetic minerals in these samples.

Figure 10. Magnetic hysteresis loop for the P37 (surface sample) (a) and P39 (52cm) (b) lateritic soils developed on Deccan basalt.
The SEM (figure 1) images of the P37 (0cm) and P39 (2cm) magnetic extracts show the octahedral magnetite or maghemite, which are similar to those observed in Quaternary loess/paleosol sequences of north-central China [54]. EDS spectra shows a Fe peak indicating the presence of pedogenic magnetite/maghemite.

Figure 11. Energy dispersive spectroscopic image (EDS) and elemental concentration data for sample P37-0cm (a) and P39-2cm (b) showing the presence of magnetite or maghemite.

3.3 Comparison of black cotton and lateritic soil profiles

Although black cotton and lateritic soils develop on the basaltic parent material, they exhibit significantly different magnetic characteristics. The black cotton soils are enriched in lithogenic coarse SSD titano-magnetite/maghemite grains, while the lateritic soils have fine-grained pedogenic ferrimagnetic minerals (figure 12a). Comparative plots (figure 12b) of all the five soil profiles also show markedly higher χfd% and χfd for lateritic soils. This may be due to a change in the degree of pedogenesis.

Figure 12. Scatter plots of χARM/SIRM vs. χfd% (a*) (after Maher, 1988 [45]) and down-profile variations of χfd, χ Arm and χfd % (b**) for the five soil profiles developed on Deccan basaltic parent material. Note: * The two lateritic soils (P37, P39) show χfd values between 3 and 14 %, suggesting > 10 % pedogenic SP magnetic grains and coarse and fine SSD mixtures. Black cotton soils (P33, P36, P40) are characterized by coarse SSD with < 10 % SP grains, indicating lithogenic contribution. ** The lowest sample of all soil profiles represents the bedrock sample. Since SP grains are absent in the parent material, χfd % and χfd show almost zero values.

According to Lu et al. [30], χfd variations in basalt soils can be used to measure the degree of pedogenesis. They proposed a possible model for magnetic minerals' magnetic development and transformation in soils formed on basaltic parent material. According to this model, firstly, when the parent material undergoes weathering, less stable minerals, such as feldspars and pyroxenes, are
removed, while fresh, primary lithogenic multi-domain magnetite and/or titano-magnetite decrease in their size due to physical weathering. This leads to their enrichment, and the resulting soil will be characterized by high $\chi_f$ and low $\chi_d$ values. Secondly, as weathering and pedogenesis take place, detrital lithogenic magnetic grains hydrolyze and turn into new pedogenic SP ferrimagnetic and antiferromagnetic minerals. The result is soil with low $\chi_f$ and high $\chi_d$ compared to the basaltic parent material. Thirdly, as pedogenesis develops, secondary pedogenic ferrimagnetic minerals gradually form, which leads to a constant increase in $\chi_f$ and $\chi_d$ in the soil profile.

In the context of this study, all-black cotton soil profiles with high $\chi_d$ and with negligible $\chi_d$ (< 2%) can be at the I$^{\text{st}}$ stage of soil development (figure 2a). The lateritic soil profile P39 with a low $\chi_d$ and high $\chi_d$ compared to the initial basaltic parent material might be at the II$^{\text{nd}}$ stage of soil development, and soil profile P37 with magnetic enhancement (an increase in $\chi_f$ and $\chi_d$) might be at the III$^{\text{rd}}$ stage of soil development (figure 2b). Consequently, P37, which underwent more pedogenesis, could be deduced as the oldest and most well-developed soil profile developed on Deccan basalt. The variation in these soil profiles' magnetic properties strongly depends on the degree of pedogenesis and the concentration of magnetic minerals [55].

4. Conclusion
The study revealed that soil profiles developed on Deccan flood basalts are highly magnetic. Black cotton soils developed on basalts are enriched with lithogenic coarse SSD titano-magnetite/maghemite grains, while lateritic soils developed on the same parent material are rich in fine-grained pedogenic magnetite/maghemite. A certain concentration of antiferromagnetic minerals, such as hematite/goethite, is also noticed in lateritic soils, indicating the soil’s maturity. The vertical variation in these soil profiles' magnetic properties is associated with differences in the magnetic mineral concentration, the size of magnetic grains, and magnetic mineralogy. Lateritic soils are characterized by a higher degree of pedogenesis compared to black cotton soils. Black cotton soils are younger and are at the beginning of soil development compared to the matured lateritic soils at the latter stages of soil development.

References
[1] Radhakrishna B P and Vaidyanadhan R 1997 Geology of Karnataka (Geological Society of India, Bangalore, India) p 353
[2] Gunnell Y and Radhakrishna B P 2001 Sahyadri: The great escarpment of the Indian subcontinent (Geol. Soc. India Memoir, Bangalore) vol 47(1-2) p 1054
[3] Annette H E 1910 InMemoirs of the Department of Agriculture in India (Published for The Imperial Department of Agriculture in India, Chemical series) vol 9 pp 185-203
[4] Bal D V 1935 Trans. 3 rd Int. Congr. Soil Sci. vol 3 pp 154-158
[5] Pascoe E H 1964 A manual of Geology of India and Burma, vol. III, (GSI. Govt. of India press, Calcutta) p 483
[6] Basu J K and Sirur S S 1938 Indian J. Agric. Sci. vol 8 pp 637-697
[7] Wadia D N 1945 J. Intl. Indust. Res. vol 3 pp 359-367
[8] Singh S A 1954 J. of Soil Sci. vol 5 pp 289-299
[9] Landey R J, Hirekerur L R and Krishnamurthy P 1982 12th Intl. Cong. Soil sci., (New Delhi, India) pp 484-497
[10] Pal D K, Wani S P and Sahrawat K L. 2013Curr. Sci. vol 105 No. 3 pp 309-318
[11] NBSS-LUP 1998 Soils of Karnataka for optimizing land use (NBSS Publication) vol 47 pp 88
[12] Kolay A K 2007 Soil Genesis, Classification Survey and Evaluation - set of 2 vols (Atlantic Publishers and Distributors) p 744
[13] Manoj Krishna and Ramesh 2012 J. of Mechanical and Civil Engineering vol 2 Issue 6 pp 21-25
[14] Mishra B 2015 Int. J. Sci. Res. vol 4 issue 11 pp 290-294
[15] Ollier C D and Powar K B 1985 Geomorph. N.F. 54 pp 57-69
[16] Ollier C D and Sheth H C 2008 J. Earth Syst. Sci. vol 117 pp 537-551
[17] Mullins C E 1977 J. Soil Sci. vol 28 pp 223-246
[18] Singer M J, Vero sub K L, Fine P and TenPas J 1996 Quat. Int. 34 - 36 pp 243-248
[19] Thompson R, Bloemendal J, Dearing J A, Oldfield F, Rummery T A and Stoher J C 1980 Science vol 207 pp 481-486
[20] Thompson R and Oldfield F 1986 Environmental Magnetism (Allen and Unwin, London) p 227
[21] Maher B A and Thompson R 1995 Quaternary Research vol 44 pp 383-391
[22] Dearing J A 1999 Magnetic susceptibility. In: Walden, J., Oldfield, F., Smith, J. (Eds.), Environmental magnetism, a practical guide. Quaternary Research Association, Technical Guide No. 6 (London) pp 35-62
[23] Retallack G J, Sheldon N D, Cogoini M and Elmore R D 2003 Palaeogeogr. Palaeoclimatol. Palaeoecol. vol 198 pp 373-380
[24] Roberts A P 2015 Earth Sci. Rev. vol 151 pp 1-47
[25] Gonet Tomasz and Wojas Anna 2016 Geol. Geophy. and Envi. vol 42 (1) pp 7-18
[26] Fabris D, Coey J M D and Mussel W D N 1998 Hyperfine Interact. vol 113, pp 249-258
[27] Goulart A T, Fabris J D, De Jesus Filho M E, coey J M D, Da Costa G M and De Grave E 1998 Clay Clay Miner. vol 46 No 4 pp 369-378
[28] Fontes M P F, de Oliveira T S, da Costa L M and Campos AA G 2000 Geoderma vol 96 (1-2) pp 81-99
[29] Van Dam R L, Harrison J B, Hirschfeld D A, Meglich T M, Li Y and North R E 2006 Soil Sci. Soc. Am. J. vol 72 pp 244-257
[30] Lu S G, Xue Q F, Zhu L and Yu J Y 2008 Catena vol 73 pp 23-33
[31] Roy B B and Barde N K 1962 Soil Sci. vol 93 - Issue 2 pp 142-147
[32] Deutsch E R, Murthy G S and Radhakrishnamurthy C 1981 Proc. of the group discussion held at Bombay-Khandala-1979, pp 117-127
[33] Sangode S J, Venkateshwarulu M, Rasika Mahajan and Vinay Randive 2017b Jour. Geol. Soc. India vol 90 pp 769-775
[34] Walden J F, Oldfield F and Smith J 1999 Environmental Magnetism: A Practical Guide No.6 (Quaternary Research Association, London) p 243
[35] Metha O P and Jackson M L1960 Clay Clay Miner. vol 7 pp 317-327
[36] Schumacher B A 2002 Methods for the determination of total organic carbon (TOC) in soils and sediments (United States Environmental Protection Agency) p 23
[37] Sehgal J L and Bhattacharjee JC 1988 Pedologie pp 67-95
[38] Aswathanarayana U 1999 Soil Resources and the Environment (Science publishers) p 248
[39] Hanlon E A 2012 Soil pH and Electrical Conductivity: A County ExtensionSoil Laboratory Manual, Series of the Soil and Water Science Department (Institute of Food and Agricultural Sciences (IFAS), University of Florida) p 10
[40] Maher B A and Taylor R M 1988 Nature vol 336 pp 368-370
[41] Fine P and Singer M J 1989b Soil Sci. Soc. Am. J vol 53 pp1119-1127
[42] Singer M J and Fine P 1989 Soil Sci. Soc. Am. J. vol 531 pp 1119-1127
[43] Zhou LP, Oldfield F, WinkleAG, RobinsonSG and Wang JT 1990 Nature vol 346 pp 737-739
[44] Maher B A and Thompson R 1991 Geology vol 19 pp 3-6
[45] Maher B A 1988 J. Geophys Res. vol 94 pp 83-96
[46] Sangode S J, Sharma R, Mahajan R, Basavaiah N, Srivastava P, Gudadhe S S, Meshram D C and Venkateshwarulu M 2017a Jour. Geol. Soc. India vol 89 pp 631-642
[47] Fine P and Singer M J 1989a Soil Sci. Soc. Am. J. vol 53 pp 191-196
[48] Hunt C P, Singer M J, Kletetschka G, TenPas J and Verosub K L 1995 Earth Planet. Sc. Lett. vol 130 pp 87-94
[49] Schellmann W 1983 A New Definition of Laterites (Natural resources and development) vol 18 pp 7-21
[50] Alexander L T and Cady J G 1962 Techni. Bull. no 1282 (Soil Conservation Service, US Dept. of Agriculture) p 90
[51] Fine P, Singer M J, LaVen R, Verosub K and Southard R J 1989 Geoderma vol 44 pp 287-306
[52] Fine P, Singer M J, Verosub K L and TenPas J 1993 Soil. Sci. Soc. Am. J. vol 57 pp 1537-1542
[53] Schwertmann U 1985 The Adv. in Soil Sci. vol 1 pp 171-200
[54] Maher B A and Thompson R 1999 Quaternary Climates, Environments and Magnetism (Cambridge University Press) pp 81-125
[55] Van Dam RL, Hendrickx J M H, Harrison B, Borchers B, Norman D I, Ndur S A, Jasper C, Niemeyer P, Narrey R, Vega D, Calvo L and Simms J E 2004 Soc. for Optical Eng. pp 665-676

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