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Rock Magnetic and Mineralogical Properties of Lateritic Soil Profiles Developed on Two Different Parent Rocks in Northern Kerala, South-Western India

M. Reethu[1], V. Jyothi[1], K. Sandeep[1*], A.K. Rafaz[1],G.H. Aravind[1] and J. Jithin[2]

[1]Department of Geology, Central University of Kerala, Tejaswini Hills, Periye (P.O.), Kasaragod-671320 (KL), India.
[2]Department of Marine Geology, Mangalore University, Mangalagangotri-574199 (KN), India
*(*Corresponding author Email: sandeepk@cukerala.ac.in)*

Abstract

The rock magnetic and mineralogical properties of two lateritic soil profiles developed on two different parent rocks (khondalite and granite) in northern Kerala, south-western India were investigated to better understand pedogenic processes under tropical climate. Field investigations reveal the presence of various horizons in the lateritic profiles, such as saprolite, mottled zone, pebble horizon and top soil. The particle size, rock magnetic, Vibrating Sample Magnetometer (VSM), Scanning Electron Microscopy (SEM)-Energy-Dispersive X-ray Spectrometer (EDS) and X-Ray Diffraction (XRD) analyses were performed on samples collected from different horizons of the two profiles. Magnetic susceptibility (χ_{lf}) values of the lateritic profiles vary from 9.97 to 1717.04 x 10^{-8} m^3 kg^{-1}, with the granitic profile exhibiting overall higher values. The percentage frequency-dependent susceptibility (χ_{fd}%) ranges between 0 % and 13.9 %. The XRD data reveal the presence of kaolinite, gibbsite (except for top soil layer) and quartz along with magnetic minerals like magnetite, hematite and goethite. The upper horizons (top-soil and pebble horizon) exhibit high values for concentration dependent magnetic parameters like χ_{lf} and χ_{fd}%, whereas, the lower horizons (saprock, saprolite, pallid zone horizons) exhibit low values. The tropical soils in the region have undergone a higher degree of pedogenesis with increased magnetic mineral concentration compared to temperate soils. The magnetic enhancement in the topsoil may be due to the neoformation of ultra fine-grained SP magnetite/maghemite (with minor anti-ferro magnetic component), aided by sufficient Fe supply, alternate wetting and drying cycles, dehydration, oxidation and redox conditions.

Keywords: Lateritic Soils; Soil Magnetism; XRD; SEM; Magnetic Enhancement; Pedogenesis; Southern India.

Introduction

Iron is a vital component of the soil system and a necessary nutrient for the development of plants. Iron minerals are found in the soils as oxides (such as magnetite, titanomagnetite, hematite, and maghemite), sulphides (such as greigite and pyrrhotite), and hydroxides (such as goethite and limonite) (Roberts, 2015). Iron oxides are produced in soils as a result of chemical weathering and pedogenesis, which in turn depends significantly on the local climate. Consequently, variations in the climate can affect the magnetic concentration, mineralogy, and magnetic grain size of soils.The rock magnetic, mineralogical and geochemical properties of temperate soils and their relation to parent rocks are well-documented (Sardoo *et al.*, 2023; Chaparro *et al.*, 2020). In addition, there are a few studies on soils from tropical regions (Barbosa *et al.*, 2021).In the Indian context, soil magnetic studies are limited to loess-paleosols of the Himalayan region (Ali and Achyuthan, 2020), pollution studies in urban and agricultural soils (Patil *et al.*, 2020; Banerjee *et al.,* 2021), and weathering characteristics of Deccan basalts (Shaikh *et al.*, 2022). Although, the lateritic soils cover one-fourth of the total geographic area of India (Pal *et al.*, 2014), only a few investigations focused on tropical lateritic soils of southern India in terms of their pedogenic development and the role of parent rocks in soil formation (Ananthapadmanabha *et al.*, 2014; Amrutha *et al.*, 2021).

In order to address this lacunae, the present study focusses on assessing mineral magnetic, textural and mineralogical changes (iron, Al oxides and hydroxides) during lateritisation and pedogenic processes under tropical climatic conditions.The magnetic mineral concentration, grain size and mineralogy of soils may provide essential clues on the nature of chemical weathering of different rocks under tropical climates. An integrated approach involving environmental magnetic, particle size, Scanning Electron Microscopy (SEM)-Energy-Dispersive X-ray Spectrometer (EDS) analysis and X-Ray Diffraction (XRD) analysis is adopted in this study to characterize lateritic soil profiles developed on two different lithologies. As southern India is a part of a tropical climatic zone where the lateritization process is predominant, the present study can reveal new information on the dynamics involved in the formation and development of soil profiles.The rock magnetic techniques and mineralogical studies can provide valuable insights into the pedogenesis of lateritic soils, as they contain a significant concentration of iron oxides (goethite and hematite), kaolinite and

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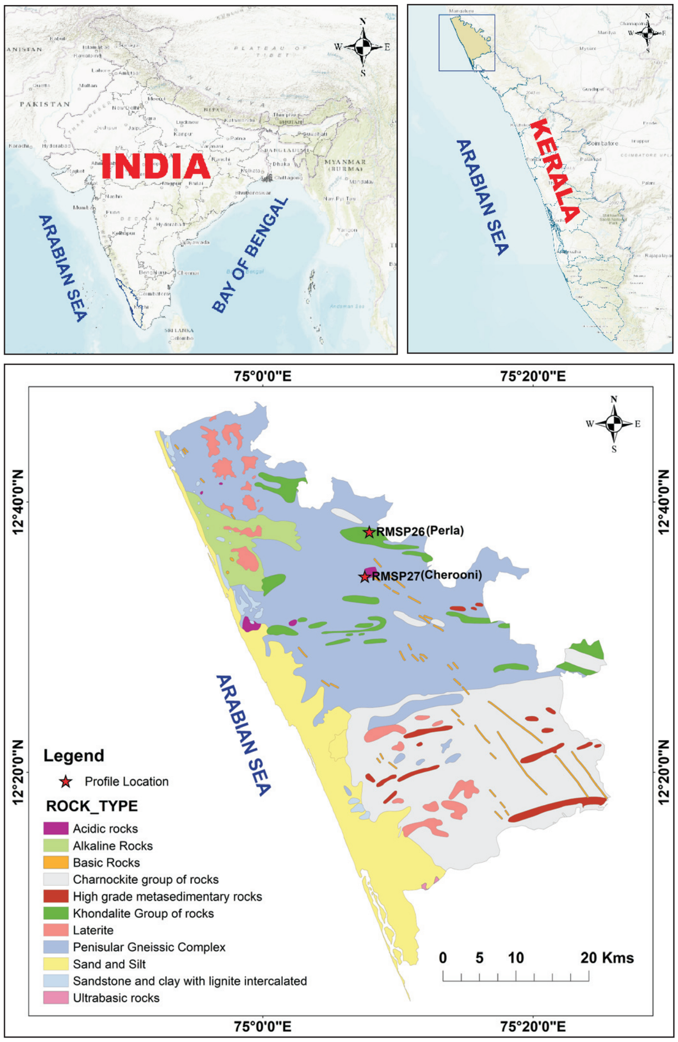

Fig.1. Geological map of the study area displaying the locations of two lateritic profiles, RMSP26 (khondalite) and RMSP27 (granite).

gibbsite (Mareddy, 2017). Rock magnetic techniques are a good tool for soil studies because they are sensitive to iron oxide concentration, magnetic grain size and mineralogy (Amrutha *et al.*, 2021). Rock magnetic techniques are rapid, less expensive and very sensitive to even low concentrations of magnetic minerals.

Study Area

The soil samples were collected from exposed vertical sections/lateritic profiles from two different locations of the Kasaragod district, Perla (RMSP26; 12°37'48.648”N, 75°07'52.536”E) and Cherooni (RMSP27; 12°34'30.72”N, 75°07'32.664”E) during the pre-monsoon season of March 2019 (Fig. 1). The two lateritic profiles belong to the same climate regime (Am) as per Koppen's Climatic classification with similar rainfall (average rainfall = 3300-3600 mm/year) and temperature conditions (minimum = 20.1° C and maximum = 29.9° C) (Pai *et al.*, 2014). The southwest monsoon, which occurs from June to September, is the main contributor to precipitation, accounting for ~ 85% of the total.

The important rocks in the Kasaragod district include the Charnockite Group, Khondalite Group and Peninsular Gneissic Complex of the Archaeozoic Era (Department of Mining and Geology, 2016). The acid intrusives (granites and syenites) of the Proterozoic Era occur as isolated patches in the District. The coastal plain and valley floors are covered with unconsolidated Quaternary sediments, primarily sand or a mixture of sand, silt, and clay (Department of Mining and Geology, 2016). They are a collection of various units, including palaeo-marine deposits, river deposits, fluvio-marine deposits, beach and barrier beach deposits, which occur as a narrow strips (with elevation < 5 m). The crystalline rocks are overlain by Neogene sedimentary strata, known as the Warkalli Formation (Department of Mining and Geology, 2016). Grit, sandstone, clay, and carbonaceous clay with or without lignite are interspersed and alternated in this Formation. Due to the tropical environment and subsequent chemical weathering, the Archaean and Tertiary rocks have undergone severe lateritization.The parent rocks of the two soil profiles selected for this study are khondalite (RMSP26-Perla) and granite (RMSP27-Cherooni).The khondalites are light-coloured, fine to medium-grained, garnet-sillimanite gneiss/schist with varying amounts of graphite. These rocks occur as isolated patches within hornblende biotite gneiss and quartzo-feldspathic gneiss of Peninsular gneissic complex.The granites of Late Proterozoic Era occur as intrusives within the gneissic rocks of the Archaean. They are pink and gray coloured, coarse grained and exhibit sharp contact with the country rock. Laterites developed over both the khondalite and granite are primary and formed in-situ by lateritisation of the crystalline rocks during pre-Oligocene before the deposition of Tertiary Formations (Narayanaswamy, 1992).

Methodology

Sampling

The exposed vertical sections were gently scrapped before the collection of samples to expose a fresh surface. Samples were collected at an interval of 2 cm (0 to 10 cm depth) to 10 cm (10 to 230 cm depth). Plastic and wooden tools were used instead of metallic ones to avoid contamination. The soils were gently loosened using a wooden spatula and transferred to polythene envelopes. Four replicate soil samples from each depth were collected at an interval of 10 cm which were mixed subsequently for homogenisation of samples. Around 100 grams of sub-surface soil samples were collected from each lateritic horizon.The samples were labelled and transferred to the laboratory, which were then air-dried and further disaggregated with a pestle and mortar.The samples were then passed through a sieve with mesh size of 2 mm (ASTM sieve No.10). The < 2 mm size fraction was used for further analytical studies.

Particle Size Analysis

Around 30% hydrogen peroxide (for removal of organic matter) and 10 % acetic acid (to remove carbonates) were added to ten grams of samples. The wet sieving procedure using a sieve of 63 µm mesh size was used to separate sand content. The liquid with silt and clay content were transferred to a measuring cylinder of 1000 ml, to which 1 gm of sodium hexametaphosphate was added. It was made up to 1000 ml volume by adding double distilled water. The pipette analysis procedure was employed to calculate the silt and clay proportion in soil samples (Carver, 1971). This method requires that the silt and clay liquid be thoroughly mixed, and afterwards 20 ml of the sample (at 20 cm depth) was taken out using a pipette. After one hour and 34 minutes, the 20 ml of the liquid containing only the clay content was pipetted out from 5 cm depth. The pipetted-out liquids were transferred to 50 ml beakers and dried in a hot air oven. The proportion of clay was calculated by multiplying the weight of the clay by 50. The proportion of silt was calculated using these values.

Loss on ignition (LOI) analysis

The loss on ignition (LOI) procedure was employed to ascertain organic carbon (C_{org}) and $CaCO_3$ content in soils by continuous heating in a muffle furnace (Heiri *et al.*, 2001). The soil was first dried at 105 °C in a hot air oven for one day. After this, the sample was weighed, placed in a muffle furnace, and kept at 550°C, which combusts the organic matter to ash. The LOI is determined using the following equation:

$$LOI_{550} = ((DW_{105} – DW_{550})/DW_{105}) \times 100$$

Where, $LOI_{550}$is LOI at 550 °C, DW_{105}signifies the dry weight of the sample before combustion and DW_{550}denotes the weight after heating to 550 °C.The loss of weight gives the amount of organic matter contained in the sample (Heiri *et al.*, 2001). A conversion factor of 1.724 has been used to convert organic matter to organic carbon in grams (organic matter/1.724 = organic C) (Nelson and Sommers, 1996). In the second step, the sample was again combusted at 950 °C. The LOI at 950 °C (LOI_{950}) is computed as per the following equation,where DW_{950}denotes the dry weight of the sample after heating to 950°C.

$$LOI_{950} = ((DW_{550} – DW_{950})/DW_{105}) \times 100$$

The weight loss by LOI at 950°C multiplied by 1.36 gives the weight of the carbonate in the original soil sample (Heiri *et al.*, 2001).

Rock Magnetic Analyses

Standard rock magnetic techniques were applied to investigate the magnetic properties of soil (Walden *et al.*, 1999). The samples were placed in non-magnetic cylindrical pots of 10 cm^3 in size. The sample holders were labelled, and a series of magnetic properties were determined (Dearing, 1999; Walden *et al.*, 1999). The volume magnetic susceptibility (κ) was determined at 0.47 kHz and 4.7 kHz with the help of a MS2B Bartington sensor. The mass-specific magnetic susceptibility (χ) was computed by dividing κ by sample density. The device's calibration was done with the 1% Fe_3O_4 standard supplied by the manufacturer. Low-frequency magnetic susceptibility (χ_{lf}) is the concentration dependent parameter (Gawali *et al.*, 2022), which indicates the total amount of ferromagnetic, diamagnetic, paramagnetic, and canted antiferromagnetic minerals in samples. The difference between χ_{lf} and $\chi_{hf}$is used to define the frequency-dependent susceptibility (χ_{fd}), and percentage-frequency dependent susceptibility (χ_{fd}%) according to the equations, $\chi_{fd} = \chi_{lf} - \chi_{hf}$and $\chi_{fd}\% = ((\chi_{lf} - \chi_{hf}) / \chi_{lf}) \times 100$, respectively (Dearing, 1999). This parameter represents the proportion of superparamagnetic (SP) grains in the sample (Dearing, 1999). Around 10mg of the sample was analysed using the Vibrating Sample Magnetometer (Make: Quantum Design's Versa Lab physical property measurement system). It has a Quantum Design Linear motor servo controller with a VSM detection and a VSM oven modules.The VSM provides continuous data of magnetization of the sample (M) against the applied magnetic field (H). This data was used to plot the hysteresis loop using Origin Pro version 9.9 software. The shape of the hysteresis loop indicates the magnetic mineralogy of the sample. The amount of magnetic minerals present in the sample determines the height of the loop, while the 'magnetic hardness' of the sample affects the width.

Scanning Electron Microscope (SEM) - Energy-Dispersive X-ray Spectrometer (EDS) Analysis

The sample was dispersed in a 1000-ml glass beaker containing deionized water and suspended using a magnetic stirrer. A strong neodymium magnet sealed in a zip-lock polythene cover was gently suspended in the beaker. The iron oxide minerals that stuck to the polythene cover were collected in a small beaker and dried (Warrier *et al.*, 2021).These magnetic extracts were analysed using Field Emission Scanning Electron Microscopy (FESEM) with an energy dispersive spectrometer (EDS) to determine the elemental composition and morphology of magnetic minerals. The images were taken at magnifications of 800x, and 2000x using ZEISS Ultra-55 Scanning Electron Microscope. The chosen magnifications allow the analysis of the chemical and morphological characteristics of particles. To determine the specific elemental composition of the particle, individual particle spectra were obtained by scanning an electron beam with an accelerating voltage.

X-Ray Diffraction (XRD) Analysis

To have bulk mineralogical representation for XRD, 50 grams of samples from each unit were pulverised and properly mixed (Singh *et al.*, 2020). The bulk soil samples (230 mesh) from topsoil and other lateritic horizons (~10 mg) were analysed using the Rigaku Mini Flex 600 diffractometer. The scans were run using Cu-Kα anode with a wavelength of 1.5406 A°, the voltage of 30kV and an intensity of 15 mA. The scan performance was recorded in 2θ in a range between 5 to 90° with a speed of 4 degree/minute. MiniFlex Guidance and PDXL 2 software was used for recording and plotting the data.

Results and Discussion

Field Investigations

The field description of the different horizons (Fig. 2) observed in the two lateritic profiles is given below.

Topsoil

This horizon is characterised by loose, unconsolidated reddish-coloured soil which supports vegetation. This layer consists of abundant humous and plant rootlets. The thickness of the topsoil layer varies from 5 to 70 cm. The colour ranges from 5YR 6/3 - 5YR6/4 as per Munsell's colour code.

Pebble Horizon

This horizon is characterised by rounded pebbles of different sizes (0.5 – 2.5 cm) inter-mixed in a medium of compact, kaolinitic soil. The pebble horizon is 10-50 cm thick which lies below the topsoil. The colour varies from 7.5YR 6/4-5YR 7/6.

Mottled Zone

This zone is characterised by hard laterite with mottles of brownish red colour formed by the precipitation of goethite and haematite in a kaolinite matrix (Ghosh and Guchhait, 2015). This zone also consists of macro-voids (tubules and alveoles). It has a thickness of 50-220 cm with colour ranging from 5 YR 7/6–7.5 YR 6/8.

Saprolite

The saprolite zone is characterized by weathered parent materials with the structures of the parent rock mostly preserved. It occurs at a depth of 250-300 cm. Its colour varies from 7.5 YR 4/6-7.5YR 6/4.

The khondalitic profile displays all the four horizons (Fig. 2a), whereas, the granitic profile displays only two (top soil and mottled zone; Fig. 2b).

Particle Size, Organic Carbon and Calcium Carbonate Data

The increased clay content with depth provides evidence of pedogenic development (Bhaskar *et al.*, 2009).The clay content is nearly similar in both profiles, varying from 24 to 61 % (average = 41.6 %).The highest clay content (~ 60 %) is seen in the pebble horizon and top part of the mottled zone (50-140 cm) of the khondalitic profile (Fig. 2a), and in the top soil (0-20 cm) of granitic profile (Fig. 2b). The process of illuviation might have led to the leaching of clay particles down-profile in khondalite profile. The high clay percentage at the top portion of the profiles indicate the deeply weathered nature of soil profiles under tropical climate. The silt (15-30 %) and sand (40-60 %) fraction are relatively high at the bottom parts of both the profiles (80-230 cm). The higher sand content in this depth may be due to the influence of the parent rock.The higher concentration of organic carbon (4-6 %) is documented in the topsoil horizon (0-40 cm) in both profiles, as compared to the bottom (1-3 %), because of the presence of abundant humous and plant rootlets. The calcium carbonate ($CaCO_3$) content is very low (average =0.65 %) in both the profiles, except for one sample in granite profile which shows a very high value (8.5 %). The precipitation of pedogenic $CaCO_3$ in the soils of Kerala (under tropical monsoon climate) is rather low, compared to other regions of India that experience arid and semi-arid climate (Pal et al., 2000).

Rock Magnetic Characteristics

In the lateritic profile developed over Khondalite (RMSP26; Fig. 2a), the χ_{lf} values range from 9.0 to 161.14 x $10^{-8}m^3kg^{-1}$ with an average(± S.D) of 76.1(±48.27) x $10^{-8}m^3kg^{-1}$.The χ_{fd}values range from 0 to 17.5 x $10^{-8}m^3kg^{-1}$with an average (± S.D) of 7.71(±6.02) x $10^{-8}m^3kg^{-1}$. χ_{fd}% range from 0 to 13.9% (average ± S.D = 8.9% ± 4.63%). The top soil exhibits low values and decreasing trend for

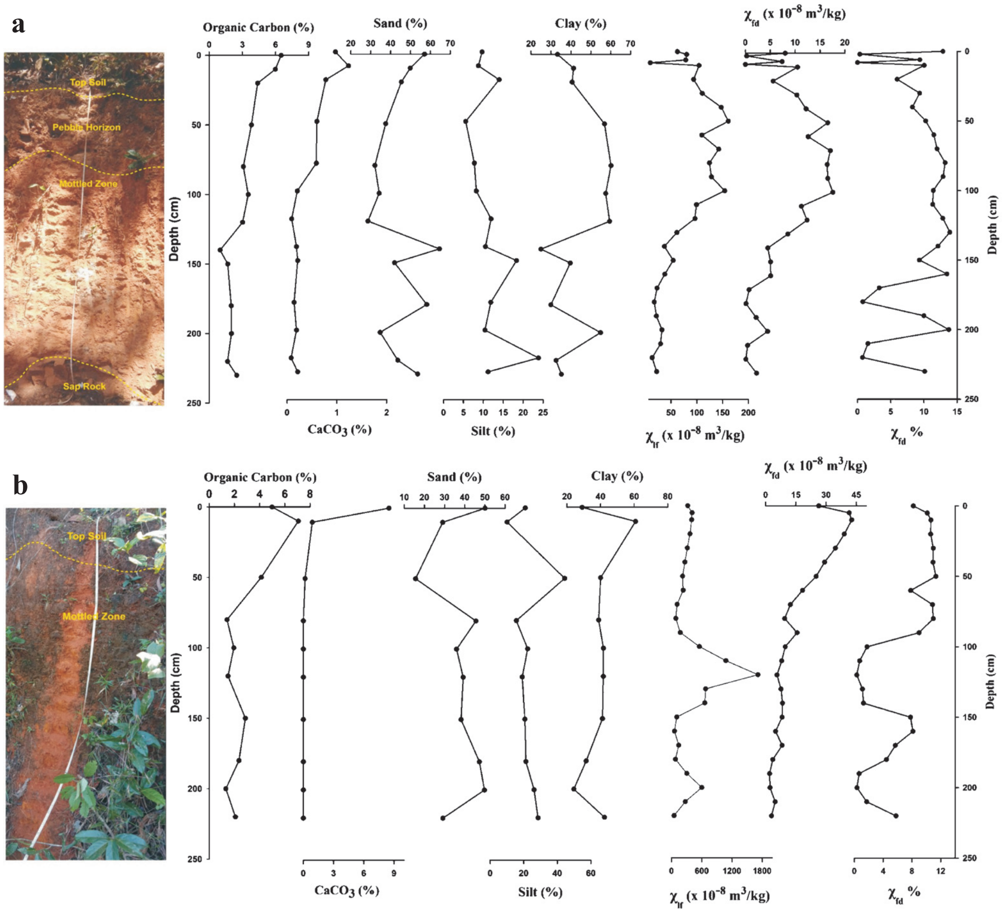

Fig. 2. The soil profile, its organic carbon (%), $CaCO_3$ (%), particle size (percentages of sand, silt and clay), rock magnetic parameters (χ_{lf},χ_{fd},χ_{fd}%)of lateritic profile developed over (a) khondalite (RMSP26) at Perla,(b) granite (RMSP27) at Cherooni in northern Kerala.

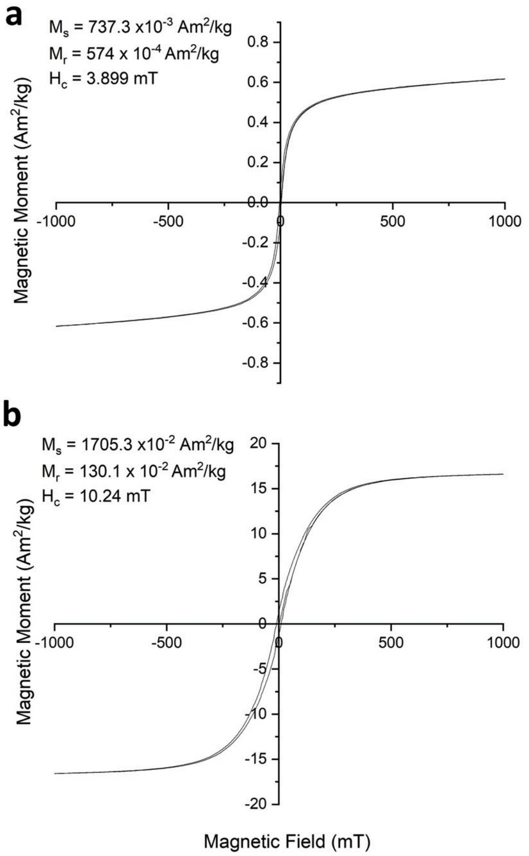

Fig. 3. Magnetic hysteresis loop for the magnetic extracts from top soil samples of (a) khondalitic and (b) granitic profiles.

these parameters. Higher values for these parameters are documented in the pebble horizon and top part of the mottled zone.

In the soil profile developed over granite (RMSP27; Fig. 2b), the χ_{lf} and χ_{fd} values exhibit an increasing trend towards the top. The χ_{lf} values range from 51 to 1717x10^{-8}m^{3}kg^{-1} (average ± S.D = 384.8 ± 375.4 x 10^{-8}m^{3}kg^{-1}). The χ_{fd}values range from 2 to 42.7 x 10^{-8}m^{3}kg^{-1} (average ± S.D = 15.4 ± 13.3m^{3}kg^{-1}). χ_{fd}% range from 0.36 to 11.3% (average ± S.D = 6.3 ± 4.23%). The top soil exhibits high values and increasing trend for the three parameters. Whereas the mottled zone exhibits steady and low values, except for a peak in χ_{lf}values at a depth of 120 cm.

The hysteresis loop of topsoil samples of khondalitic and granitic profiles are displayed in Fig. 3. The hysteresis parameters of khondalitic profile include M_s= 737.3 x 10^{-3}Am^2/kg, M_r = 574 x 10^{-4} Am^2/kg and H_c = 3.899 mT. The hysteresis parameters of granitic profile sample are M_s = 1705.3 x 10^{-2} Am^2/kg, M_r = 130.1 x 10^{-2} Am^2/kg and H_c = 10.24 mT. The samples exhibit narrow hysteresis loops with low coercivity and low saturation magnetization, indicating soft ferrimagnetic minerals (mainly Single Domain (SD) grain size) such as magnetite. However, the shape of the hysteresis loop also indicates the presence of a minor canted anti-ferromagnetic component.

Scanning Electron Microscope (SEM) Energy Dispersive X-Ray Spectrometer (EDS) Data

The Scanning electron microscope (SEM) images along with Energy Dispersive X-Ray Spectrometer (EDS) data of magnetic extracts of the top soil layer (0 cm depth) and mottled zone (100 and 200 cm depth) of khondalitic and granitic profiles is displayed in Fig. 4. The grains are well-developed with angular to sub-angular in shape. The magnetite crystal is identified based on its octahedral shape, whereas, hematite is ascertained based on its tabular form. The grains are also highly weathered with dissolution and etch pits. The highest Fe percentage is observed in top soil layer of khondalitic (1.53 %) and granitic (5.86 %) layers, in comparison to the bottom layers (0.62 % and 2.92 % respectively). Titanium is also high in top soil layers of khondalitic and granitic (0.11 % and 0.60 % respectively) profiles compared to the bottom layer (0.09 % and 0.29 %, respectively).The occurrence of high Ti and Fe in the sample indicates the presence of titano-magnetite. The occurrence of Al (1.06 – 2.14 %) and Si (0.56 - 1.76 %) in magnetic extracts of both the profiles indicates that some amount of clay particles has also adhered to the magnetic minerals during extraction.

Mineralogy of Lateritic Layers

The XRD spectra of samples from topsoil and bottom horizons of khondalitic and granitic profiles are displayed in Fig. 5. The characteristic peaks in XRD spectra are identified by comparing it with those documented in literature (Ali *et al.*, 2022). The samples show the peaks of minerals like quartz (4.34 A°, 4.34 A° and 3.34 A°), kaolinite (7.21 A°,7.14 A°and 3.58 A°), gibbsite (4.85 A°, 4.37 A°, 4.37 A°), hematite (2.69 A°, 2.51 A°, 1.69 A°, 1.50 A°),

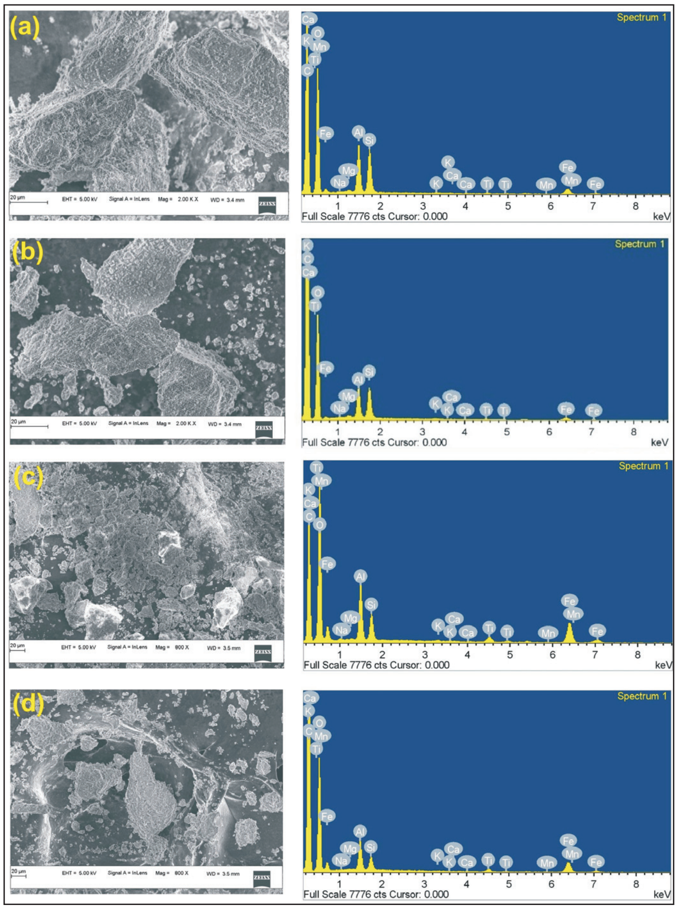

Fig.4. Scanning electron micrographs and Energy dispersive Spectra (SEM-EDS) of grains from the magnetic extracts of khondalitic (a: top soil, 0 cm; b: mottled zone, 100 cm) and granitic profiles (c: top soil, 0 cm; d: mottled zone, 200 cm).

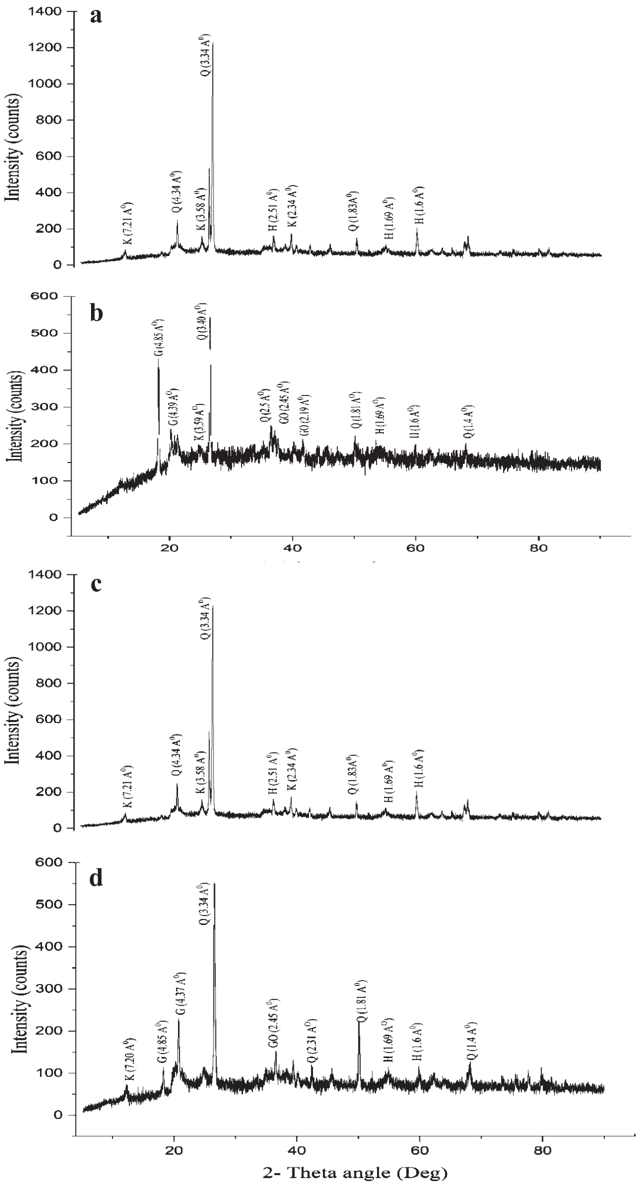

Fig.5. X-ray diffractogram of lateritic profilesdeveloped on khondalite at depths (a) 0cm (b) 230 cm and granite at depths (c) 0 cm(d) 220 cm (Q, quartz; G, gibbsite; GO, goethite; K, kaolinite and H, hematite).

and goethite (2.45 A°, 2.69 A°). The quartz, hematite and kaolinite are present in all the lateritic horizons of khondalitic and granitic profiles. Whereas, goethite and gibbsite are present only in the bottom layers (pebble horizon and mottled zone), and are absent in top soil.The degree of Al-substitution in goethite reflects the pedogenesis of tropical soils. Both Al-hematite substitution and Al-goethite are quite common under tropical conditions (Cornell and Schwertmann, 2003). Kaolinite is a significant indicator of weathering under tropical temperatures if found in soil profiles (Deepthy and Balakrishnan, 2005). Silica in migrating solutions inhibits crystal development and causes minerals like goethite to have a low degree of crystallinity (Jones *et al.*, 2009).

Pedogenesis of Tropical Lateritic Soils

As per an earlier study, the tropical soil profiles in southern India display a thick magnetically enhanced zone (0-50 cm) at the top, instead of a sharp increase in magnetic parameters observed in the upper few centimeters of temperate soil profiles (Ananthapadmanabha *et al.*, 2014). This magnetically enhanced zone may be due to the neo-formation of fine-grained SP magnetite, aided by sufficient Fe supply, alternate wetting and drying cycles, dehydration, oxidation and redox conditions (Dearing *et al.*, 1996). However, the topmost portion (0-30 cm) of the khondalitic profile displays a decreasing trend for χ_{lf},χ_{fd} and χ_{fd}%. However, these values are still higher compared to the bottom layers in the profile. This decreasing trend may be due to the reduction of iron and dissolution of finer grains in the topsoil due to water logging conditions under high rainfall (Ananthapadmanabha *et al.*, 2014).

The higher super paramagnetic grains at the 50-100 cm zone are probably due to the illuviation of finer particles and accumulation at lower horizons (Thiffault, 2019).This magnetically enhanced zone is also characterised by high proportion of clay (average = 58.5 %). The illuviation in khondalitic profile is confirmed by a good correlation between clay % and χ_{fd}% ($r = 0.51$; $p < 0.05$; $n = 12$). This fine-grained magnetite might have leached downwards from the top soil along with the clay minerals during the illuviation process. However, such a trend is absent in granitic layers with no significant correlation between clay percentage and χ_{fd} %. In the granitic profile, this magnetically enhanced zone is documented in the top part of the profile (0-80 cm), with no evidence of illuviation as seen in the steady values of clay percentage along the profile. The χ_{fd}% values tend to increase with pedogenesis (Dearing *et al.*, 1996).

The parent rocks (khondalite and granite) exhibit lower values for χ_{lf}, χ_{fd} and χ_{fd}% in comparison to the lateritic layers and top soil developed over them. In addition, both the parent rocks exhibit χ_{fd}%< 1 % and $\chi_{fd} < 2\times 10^{-8} m^3 kg^{-1}$. This designates that the magnetic minerals in the parent rocks are predominantly primary/lithogenic, which may be of coarser magnetic grain size with the absence of SP grains.The granite exhibits much higher χ_{lf} values than khondalite, which indicates that the former contains higher concentration of primary magnetic minerals. The median values of χ_{lf}, χ_{fd} and χ_{fd} % of different horizons along with the accumulation factor (A.F.), which is the ratio between the median values of the top soil samples andthat of the parent rocks (Preetz *et al.*, 2017) are provided in Table 1. There is a significant enhancement in the SP-sized soft magnetic minerals as indicated by a high accumulation factor in percentage frequency-dependent susceptibility for both Khondalite (12.1) and granite (13.0) (Table 1). The enhancement in magnetic susceptibility and concentration of SP sized magnetite/maghemite in top soils is higher in granites as compared to khondalite. The rock magnetic, VSM and SEM-EDS data confirm the presence of secondary, fine-grained magnetite/titanomagnetite in topsoil and the minor amount of canted antiferromagnetic minerals like hematite. The higher amount of Fe in topsoil is documented in the granitic profile. Hence, the granitic profile exhibits a slightly higher degree of magnetic enhancement than the khondalitic profile. This may be due to higher lithogenic Fe contributed by granitic rocks compared to khondalite during the weathering process. This high initial Fe concentration might have contributed to increased topsoil enhancement with a higher proportion of fine-grained secondary iron minerals (SP magnetite).

The overall proportion of clay in both khondalitic (average = 43.6 %) and granitic profiles is very similar (39.1 %), except for one sample in topsoil of the latter with very high clay percentage (60.1 %). The geochemical and mineralogical findings point to extensive weathering, which implies a warm, humid climate with a long

Table 1: Median values of χ_{lf}, χ_{fd}, χ_{fd}% and their accumulation factor (A.F.) of the two soil profiles developed on different parent rocks.

Sl. No.	Parent rock	Soil horizon	χ_{lf}	A.F.	χ_{fd}	A.F	χ_{fd}%	A.F
1.	Khondalite	All	78.64	5.6	7.38	67.1	10.11	12.1
		Top soil	80.40		7.38		9.36	
		Pebble horizon	142.46		16.45		11.49	
		Mottled Zone	37.88		5.06		11.40	
		Saprolite	17.83		1.17		5.43	
		Unweathered rock	14.35		0.11		0.77	
2.	Granite	All	290.91	6.7	8.94	86.7	7.81	13.0
		Top soil	322.52		34.68		10.65	
		Mottled Zone	233.88		8.01		4.47	
		Unweathered rock	48.3		0.40		0.82	

history of heavy rainfall where the study area is located. The source rock had undergone extreme chemical and physical weathering as indicated by the higher values for the magnetic parameters in the samples and the abundance of kaolinite, quartz, and magnetic minerals. The X-Ray diffraction (XRD) pattern of samples collected from different horizons of both profiles indicates dominance of kaolinite, quartz and hematite, gibbsite, and goethite in the bottom layers. The presence of the gibbsite usually suggests intense leaching conditions under tropical climates and the further removal of silica from kaolinite (Bijilal and Santhil, 2016). However, as per Chandran *et al.* (2005), the presence of gibbsite in soils may not point towards an enhanced stage of weathering.The gibbsite might have been produced in an initial alkaline environment. The presence of kaolinite and gibbsite in bottom layers (pebble horizon and mottled zone) also indicate that steady-state conditions may occur in soils over long periods.This is corroborated by the sharpness and intensity of the peak of gibbsite which suggest a high degree of crystallization. The absence of gibbsite in the topsoil may be due to an acidic environment due to high rainfall.

Conclusions

The present study highlights the differences in the rock magnetic and mineralogical properties of the different horizons of the lateritic profiles developed over two different parent rocks. The top soil and lateritic pebbly layer exhibit high concentration of ferrimagnetic SP phases (magnetite/maghemite) compared to bottom layers like mottled zone, saprock and the parent rocks. The higher concentrations of magnetic minerals, high Fe % and maximum enhancement of the fine-grained ferrimagnetic grains in top soil are documented for the granitic profile compared to the khondalitic profile.The granitic profile has undergone higher degree of magnetic enhancement than khondalite, probably because of higher initial Fe (lithogenic) contributed by the parent rock in the former.The higher SP grains in the topsoils may be due to the neoformation of fine-grained SP magnetite as per the standard model because the pre-conditions like sufficient Fe supply, cyclic changes in alternate wetting and drying, dehydration, oxidation and redox conditions prevailing in the laterites. Both the profiles have undergone extreme chemical and physical weathering as indicated by the abundance of kaolinite, gibbsite and quartz along with magnetic minerals like magnetite, hematite and goethite. The presence of both kaolinite and gibbsite together may indicate an earlier alkaline environment and steady-state conditions for long periods.

Authors' Contributions

RM:Sampling, Methodology, Formal Analysis, Writing-Original Draft. **VJ**: Methodology, Formal Analysis. **SK**: Conceptualization, Supervision, Editing, Reviewing. **AKR**: Data Curation and Software. **GHA**: Investigation, Formal Analysis. **JJ**: Methodology, Formal Analysis.

Conflict of Interest

The authors declare no conflict of interest.

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