CHAPTER 3

Down-Profile variations of Magnetic and Non-Magnetic Parameters
3.1 Influence of topography on the mineral magnetic properties of lateritic soils

The study area has thick lateritic soils, which in most of the places, have developed on low-altitude mounds or dissected plateaus/mesas of tropical laterites. The laterites usually cover the basement rocks, which are mostly crystalline rocks like charnockites and gneisses or in a few places sedimentary rocks like sandstones. The topography of the localities in the study area maybe identified as valleys, hill sides with either gentle or moderate slopes or laterite mesas with gentle slope.

In the following section, ten soil profiles developed on similar lithology (charnockitic rocks) and climate are discussed.

3.1.1 Aribail (APP1)

The Aribail soil profile is developed on charnockitic rocks and is situated in a lateritic valley with a moderate slope. The pH, electrical conductivity (EC), environmental magnetic parameters and inter-parametric ratios for the Aribail soil profile (n=25) are displayed in Fig. 3.1. The soils are slightly acidic as evident from the pH values which range from 4.7 to 5.7 (average = 5.1). Electrical conductivity values also exhibit significant fluctuations in the profile (9 to 23 µS/cm). The $\chi_{lf}$, IRM$_{20mT}$ and SIRM values exhibit a general increase towards the profile-top. The $\gamma_\mu$ values range from 34 to $778.3 \times 10^{-8}$ m$^3$ kg$^{-1}$ and IRM$_{20mT}$ values from 49.5 to $1049.2 \times 10^{-5}$ Am$^2$ kg$^{-1}$. Thus, there is a significant variation in the magnetic parameters from the bottom to the top of the profile.

Based on the variations in rock magnetic parameters, the profile may be divided into three zones.
Fig. 3.1 The Aribail soil profile and its rock magnetic parameters and inter-parametric ratios. Note: The profile may be divided into three zones based on the variations in magnetic parameters. The values of $\chi_{ld}$, IRM$_{20mT}$ and SIRM exhibit a steady increase towards the profile-top with a slight enhancement in Zone 1. However, $\chi_{lf}$% exhibits the highest values in Zone 3.
Zone 1 (0 to 10.5 cm depth) is characterised by a slight enhancement in the values of $\chi_{lf}(\text{average}=581.5 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1})$ and SIRM (average=$4679 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$). However, $\chi_{fd}$ and $\chi_{fd} \%$ values are relatively low (average = $12.6 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ and 2.2 % respectively). Values of $\chi_{ARM}$ also are not high in this zone. Hence, the relatively high magnetic susceptibility values in this zone may not be due to the presence of superparamagnetic grains but coarse magnetic grains, probably of multi-domain (MD) size. This is substantiated by the semi-quantitative granulometry plot (Fig. 3.2) of Dearing et al. (1997) where Zone 1 samples are concentrated in the MD + PSD field. This is unlike most temperate soil profiles which show magnetic enhancement of surface soil due to the presence of ultra-fine superparamagnetic magnetite produced during pedogenesis (Maher and Taylor, 1988). The IRM acquisition curves (Fig. 3.3) reveal that samples from this zone do not get saturated even at 1T field but continue to acquire magnetisation, indicating the presence of magnetically “hard” minerals. The higher HIRM values documented in this zone testify to the presence of magnetically “hard” minerals.

The citrate-bicarbonate-dithionite (CBD) procedure (Mehra and Jackson, 1960) was used to estimate the relative contributions of lithogenic and pedogenic magnetic components to the magnetic signal of the Aribail samples. It is particularly effective in dissolving and extracting maghemite and antiferromagnetic components (haematite and goethite) as well as fine grained magnetite, but leaving the coarse lithogenic grains unaffected (Vidic et al., 2000). The three samples in this zone (at depths of 0-1, 4-5 and 8-9 cm) exhibit only a small decrease (average of 16 %) in the values after the first step of CBD treatment (Fig. 3.4). This is followed by little reduction in the subsequent steps. The data indicate that the lithogenic component is significant in the profile-top. Frequency-dependent susceptibility values exhibit a significant reduction after the first
step itself; after the third step the values decrease to zero. The down-profile variations of pre-CBD $\chi_{lt}$, post-CBD $\chi_{lt}$ and pedogenic $\chi_{lt}$ are displayed in Fig. 3.5. The down-profile variations of percent sand, silt and clay in the Aribail profile are shown in Fig. 3.6. The lone sample from this zone exhibits high percentage sand (50.4%) and a relatively low clay content (40.2%).

**Fig. 3.2** Biplot of $\chi_{ARM}/SIRM$ vs. $\chi_{fd}$ % (Dearing et al., 1997) for soil samples from the Aribail and Miyapadavu profiles. Most of the samples plot in the coarse SSD field, with only a few in the MD+PSD field. Note that magnetic grain size decreases toward profile-bottom.
Fig. 3. IIRM (Isothermal remanent magnetization) acquisition curves for soil profile samples (APP1, APP2, APP3, APP6, APP9 and APP10). Note: Most of the samples get saturated at a field of ~ 300 mT, indicating a magnetically "soft" mineralogy. However, IIRM values continue to increase even at 1T field for a few samples, indicating the presence of hematite/goethite in them.

Zone 2, which extends from 10.5 to 74.5 cm, exhibits the highest values for $\chi_{lf}$ and SIRM (average = $391.2 \times 10^{-8}$ m$^3$ kg$^{-1}$ and $2900 \times 10^{-5}$ m$^3$ kg$^{-1}$ respectively). $\chi_{fd}$ % (average = 5.71 %) also exhibits high values compared to Zone 1. The magnetic grain size is coarse as suggested by low $\chi_{ARM}$/SIRM ratio (Fig. 3.1). S-ratio values do not
exhibit significant variations in this zone. The average value of 0.90 suggests the presence of magnetically "soft" minerals like magnetite and maghemite. However, HIRM values are low (291.25 x 10^{-8} m^3 kg^{-1}) compared to Zone 1. Three samples in this zone (which have relatively low $\chi_{lf}$ values) at depths of 18-19, 42-43, 58-59 cm are characterized by a relatively high reduction in $\chi_{lf}$ after the first step of CBD treatment. The percentage decrease in these samples after the third step is 44, 54 and 59% respectively. These data indicate that the relative proportion of pedogenic magnetite content is high although its absolute concentration is low in comparison with the lithogenic component. Frequency-dependent susceptibility values exhibit a significant reduction after the first step itself; after the third step the values decrease by 100%. Sand content decreases significantly (average = 35 %) and clay content increases (average = 52.5 %)(Fig. 3.6). The magnetic grain size becomes relatively finer compared to zone 2 associated with an increase in SP grains (Fig. 3.2).

Zone 3 (74.5 to 142.5 cm) is characterized by the lowest values for $\chi_{lf}$, $\chi_{fd}$, $\chi_{ARM}$ and SIRM. However, $\chi_{fd}$% value is the highest in this zone (average = 9.3 %). S-ratio values (average = 0.85) are the lowest, indicating a relatively high proportion of magnetically “hard” minerals in this zone compared to the other two. One sample from this zone (at 122-123 cm) is characterized by a relatively high reduction in $\chi_{lf}$ after the first step itself of CBD treatment. The percentage decrease in $\chi_{lf}$ after the third step is 74%. The CBD data show that the relative proportion of the pedogenic magnetite content is high although its absolute concentration is low in comparison with the lithogenic component.
Fig. 3.4CBD extraction data for Aribail soil samples. (a) Magnetic susceptibility ($\chi_{lf}$); and (b) Frequency-dependent susceptibility ($\chi_{fd}$). Data for each sample are represented as four bars corresponding to the $\chi_{lf}$ or $\chi_{fd}$ measured before and after the 1st, 2nd and 3rd steps of CBD treatment. The percentage reductions in values are expressed as numbers above each bar.
Fig. 3.5 CBD extraction data for selected soil samples from the Aribail profile. (a) Magnetic susceptibility and (b) Frequency-dependent susceptibility. The grey area indicates pedogenic $\chi_{lf}$ and pedogenic $\chi_{fd}$ respectively.
Fig. 3.6 Magnetic susceptibility and particle size data for selected pre-monsoon samples from the Aribail soil profile.

Pedogenic $\chi_{lf}$ exhibits a low correlation coefficient of 0.12 with $\chi_{lf}$ and a high correlation coefficient of 0.92 with pedogenic $\chi_{fd}$ (Fig. 3.7). Pedogenic $\chi_{fd}$ and $\chi_{fd}$ are exceedingly well correlated between themselves ($r=1.00$). These data suggest that the magnetic susceptibility signal of the Aribail soil profile is not contributed by the pedogenic component. Laterites developed on charnockite have a higher content of ilmenite and magnetite when compared to those developed on other parent rock types (Soman, 1997). Hence, the coarse grained magnetite as well as hematite in the Aribail
profile may have been derived from the underlying laterite. IRM acquisition curves (Fig. 3.3) show that most samples get saturated at a field of ~ 300 mT, indicating the "soft" magnetic mineralogy of the samples. However, a few, especially from Zone 1, display an increasing trend even at 1T field, confirming the presence of magnetically "hard" minerals.

Fig. 3.7 Binary plots of magnetic parameters for Aribail soil profile samples. (a) $\chi_{lf}^*$ vs. $\chi_{fd}^*$; (b) pedogenic $\chi_{lf}$ vs. $\chi_{fd}$; (c) pedogenic $\chi_{lf}$ vs. pedogenic $\chi_{lf}$; and (d) pedogenic $\chi_{fd}$ vs. pedogenic $\chi_{fd}$ (* = $x \times 10^{-8}$ m$^3$ kg$^{-1}$).

Considering the entire profile, the content of SP grains is high in the bottom of the profile (Zone 3; Fig. 3.2); as the profile-top is approached, however, magnetic grain size turns coarse (Fig. 3.2). The proportion of magnetically "hard" to magnetically "soft" minerals does not vary as such (as indicated by the constant S-ratio values), but the absolute concentration of magnetically "hard" minerals increases. One possible reason for the high content of SP grains at the profile-bottom is eluviation, i.e. transport of fine
Particles of soil from upper to lower levels by percolating water, and accumulation of this material at lower levels (illuviation) (Jackson and Bates, 1980). This is substantiated by the higher clay content in this zone (Fig. 3.6). The other possible reasons are transformation and/or reduction/dissolution of SP magnetite. Magnetite of SP grain size in the top-soil may get transformed to other minerals like ferrihydrites due to intense chemical weathering. Under very high rainfall conditions, iron reduction and dissolution of fine grains predominate (Maher and Thompson, 1995; Maher et al., 2003) due to changes in soil Eh and pH conditions. This may have resulted in the low susceptibility values documented for the top-soil. The latter interpretation is substantiated by the fact that $\chi_{il}$, $IRM_{20mT}$ and SIRM display higher values in Zone 2 when compared to Zone 3. If eluviation were the cause, these magnetic parameters would have shown an increase in Zone 3 too. However, it also depends upon the local hydrology and where in the soil profile redox changes occur. Further, EC values do not exhibit a marked increase in Zone 3. High EC values in soils usually indicate a high proportion of clay. Top-soil erosion may be another factor which contributes to the loss of SP grains. As the Aribail profile is situated in a lateritic valley, the probability of erosion is high.

Further data on the magnetic mineralogy of the Aribail profile were obtained through SEM and EDS studies of the magnetic extract from a soil sample (102-103 cm depth). The SEM images and Fe peak in the EDS spectra illustrate the presence of both haematite and titano-magnetite/maghemite. The distinct hexagonal shape with thin tabular habit in the SEM image with peaks of Fe in EDS spectra indicates the presence of haematite (Fig. 3.8a). The SEM images of the grains of octahedral magnetite (Fig. 3.8b) and Fe and Ti peaks in the EDS spectra illustrate the presence of titano-magnetite/maghemite in the samples. The haematite and titano-magnetite/maghemite may be lithogenic.
Fig. 3.8 Scanning electron micrographs and Energy dispersive Spectra (EDS) of two grains from the magnetic extract at a depth of 102-103 cm from the Aribailprofile (APP1). The first grain (a) is identified as haematite based on its hexagonal shape, platy habit and peaks of Fe, whereas the second grain (b) is identified as titanomagnetite/maghemite based on its octahedral shape and peaks in Fe and Ti.

3.1.2 Miyapadavu (APP2)

The Miyapadavu profile samples are slightly acidic (pH = 5 to 6.5). The soil profile (n=25) may be divided into two zones based on their magnetic properties (Fig. 3.9): Zone 1 (0-46.5 cm) is characterised by enhanced values for concentration-dependent parameters like $\chi_{lf}$, $\chi_{fd}$, IRM$_{20mT}$ and SIRM. Values of $\chi_{lf}$ exhibit an increasing trend, with remarkably high values in the depth range of 30.5-16.5 cm, followed by a decrease in the top 16 cm of the profile. The values of $\chi_{fd}$, IRM$_{20mT}$ and SIRM also
display a similar trend. The average values for the zone are: $\chi_{lf} = 677.6 \times 10^{-8}$ m$^3$ kg$^{-1}$, $\chi_{fd} = 60.6 \times 10^{-8}$ m$^3$ kg$^{-1}$, $\chi_{fd}\% = 9\%$, $\text{IRM}_{20\text{mT}} = 2210.2 \times 10^5$ Am$^2$ kg$^{-1}$ and SIRM = 5526.7 x $10^5$ Am$^2$ kg$^{-1}$. The relatively low $\chi_{ARM}$ /SIRM values indicate a coarse (probably coarse SSD) magnetic grain size (Dearing et al., 1997; Fig. 3.2). The high $\chi_{ARM}$ values in this zone indicate a high concentration of stable single domain (SSD) grains. The S-ratio also displays high values (average = 0.93); there is not much variation in the relatively high HIRM values. These data suggest a high concentration of magnetically “soft” minerals. The sand content in this zone is 43.8 % and the clay content 45.7 %. The silt content is comparatively low (10.4 %) (Fig. 3.10).

Zone 2 (46.5-142.5 cm) is characterised by low values for $\chi_{lf}$, $\chi_{fd}$, $\chi_{ARM}$, $\text{IRM}_{20\text{mT}}$ and SIRM. The average values in the zone are: $\chi_{lf} = 265.8 \times 10^{-8}$ m$^3$ kg$^{-1}$, $\chi_{fd} = 32.8 \times 10^{-8}$ m$^3$ kg$^{-1}$, $\chi_{ARM} = 1.9 \times 10^{-5}$ m$^3$ kg$^{-1}$, $\text{IRM}_{20\text{mT}} = 627 \times 10^5$ Am$^2$ kg$^{-1}$ and SIRM = 1791.2 x $10^5$ Am$^2$ kg$^{-1}$. These are markedly low when compared to those of Zone 1. The magnetic grain size is fine (probably fine SSD) when compared to Zone 1 (Fig. 3.2). This is also indicated by an increase in $\chi_{ARM}$ /$\chi_{lf}$ ratio values (Fig. 3.9). The concentration of SP grains also displays a marked increase as can be inferred from the increased $\chi_{fd}\%$ values. This may be due to illuviation as indicated by the very high clay content (Fig. 3.10) in this zone (average = 72.9 %). The sand content is considerably low (average = 16.2 %).
Fig. 3.9 The Miyapadavu soil profile and its rock magnetic parameters and inter-parametric ratios. *Note:* The profile is divisible into two zones based on variations in magnetic parameters. Zone 1 is characterised by enhanced values and Zone 2 by decreased values for concentration-dependent parameters like $\chi_{lf}$, $\chi_{fd}$, IRM$_{20mT}$ and SIRM. However, values of $\chi_{fd}$% and $\chi_{ARM}/$SIRM display a marked increase in Zone 2, indicating the predominance of SP grains.
The S-ratio values are low (average=0.78), suggesting an increased contribution from magnetically “hard” minerals. IRM acquisition curves (Fig. 3.3) show that most samples get saturated at a field of ~ 300 mT, suggesting a magnetically "soft" mineralogy. However, a few samples belonging to Zone 2 display an increasing trend, confirming the presence of magnetically "hard" minerals.

As the Miyapadavu profile is located in an elevated region with a very gentle slope (stable upland), the same characteristic as seen in the Aribail profile is seen here, i.e., the absence of magnetic enhancement. The high $\chi_{lf}$ value in Zone 1 may be due to the presence of SSD, and not SP, grains. Eluviation is another possibility as suggested by the increased clay % in this zone. Unlike Aribail (situated in a lateritic valley), Miyapadavu is a stable, flat upland region. Hence, the probability of soil erosion is low. The most probable interpretation, then, would be that coarse grained magnetite and
hematite are derived from the underlying laterite. Iron derived from chemical weathering is transformed to SP magnetite during pedogenesis. However, due to high monsoonal rainfall and the resulting water-logged conditions, the SP magnetite in the upper zone may be transformed to other magnetic minerals like ferrihydrites. Alternatively, reduction and dissolution of iron is also possible (Maher and Thompson, 1995; Maher et al., 2003).

### 3.1.3 Uliyathadka (APP3)

This profile may be divided into three zones based on magnetic properties (Fig. 3.11). Zone 1 extends from 0 to 22.5 cm depth. There is no magnetic enhancement of the top-soil. In fact, the values of $\chi_{df}$, $\chi_{fd}$ %, $\chi_{fd}$, SIRM and $\chi_{ARM}$ exhibit a decreasing trend towards the profile-top. The average values in the zone are: $\chi_{df}$ = 910.6 x $10^{-8}$ m$^3$ kg$^{-1}$, $\chi_{fd}$ % = 10 % and SIRM = 7254.6 x $10^{-5}$ Am$^2$ kg$^{-1}$. Values of the inter-parametric ratio $\chi_{ARM}/\chi_{df}$ do not exhibit much variation though $\chi_{ARM}$/SIRM values are low, indicating a relatively coarse magnetic grain size (Figs. 3.11 and 3.12). The S-ratio value does not exhibit much variation; the average S-ratio of 0.91 indicates the predominance of magnetically “soft” minerals. The sand content is relatively low in this zone (35.5 %) and low silt content (50.3 %) (Fig. 3.13).

Zone 2 extends from 22.5 to 74.5 cm depth with relatively high values for $\chi_{df}$ (average = 1026 x $10^{-8}$ m$^3$ kg$^{-1}$), $\chi_{fd}$% (average = 12.7 %) and $\chi_{fd}$ (average = 129.8 x $10^{-8}$ m$^3$ kg$^{-1}$) but low values for IRM$_{20mA}$ (average = 2474.1x $10^{-5}$ Am$^2$ kg$^{-1}$) and SIRM (average = 5751.8x $10^{-5}$ Am$^2$ kg$^{-1}$). The magnetic grain size is relatively fine compared to Zone 1 (Fig. 3.12) as indicated by the higher values of $\chi_{ARM}$/SIRM. The average $\chi_{fd}$% of 12.7 indicates a relatively high contribution from SP grains to the magnetic make-up of the profile.
Fig. 3.11 The Uliyathadka soil profile and its rock magnetic parameters and inter-parametric ratios. Note: The profile may be divided into three zones based on the variations in magnetic parameters. Zones 1 and 3 are characterised by relatively low values and Zone 2 by relatively high values of $\chi_{mf}$ and $SIRM$. The $\chi_{mf}$% and $\chi_{ARM}/SIRM$ values are the highest in Zone 3, indicating the highest concentration of SP grains; the values steadily decrease towards the profile-top.
Fig. 3.12 Biplot of $\chi_{\text{ARM}}/\text{SIRM}$ vs. $\chi_{\text{id}}$ % (Dearing et al., 1997) for soil samples from the Uliyathadkaprofile. Most of the samples plot in the field of Coarse SSD to Fine SSD and mixtures. Note that magnetic grain size decreases towards the profile-bottom with an increase in the proportion of SP grains.
There is not much difference in the S-ratio and HIRM values between Zones 1 and 2. However, HIRM values exhibit a slight decrease, which indicates an increase in the proportion of magnetically "soft" minerals. In Zone 2, relatively high values of $\chi_{lf}$ are the result of contributions from fine magnetic grains. The increase in $\chi_{lf}$ values in Zone 2 may be due to an increase in the proportion of fine magnetic minerals (Fig. 3.11). A very high content of SP grains in this zone may be responsible for the high $\chi_{fd}$% values. The sand content decreases (average = 25.7 %) and clay content increases (average = 62.8 %) in this zone (Fig. 3.13).

In Zone 3 (74.5-142.5 cm), the values of concentration-dependent parameters ($\chi_{lf}$, $\chi_{fd}$, $\text{IRM}_{20\text{mT}}$ and SIRM) exhibit a decrease towards the profile-bottom. The average values of these parameters are $\chi_{lf} = 411.1 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, $\chi_{fd} = 57.7 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$,
IRM$_{20\text{mT}} = 760.5 \times 10^{-5} \text{Am}^2 \text{kg}^{-1}$ and SIRM = $1813.7 \times 10^{-5} \text{Am}^2 \text{kg}^{-1}$. In fact, these values are the lowest for the entire profile. Zone 3 is characterised by a relatively high contribution from SP grains to the magnetic signal of this zone as suggested by the high $\chi_{fd}\%$ values (14.2 %) and high $\chi_{\text{ARM}}/\text{SIRM}$ ratio value (Fig. 3.12). In fact, the bottom three samples in this zone exhibit $\chi_{fd}\%$ values of 14.4 to 14.6 %. But a $\chi_{fd}\%$ of 14 is considered the upper limit and any value higher than this is considered erroneous (Dearing, 1999). However, measurements on a large number of samples indicate a higher upper limit of $\approx 15 \%$ for $\chi_{fd}\%$ (Thompson and Oldfield, 1986; Forster et al., 1994; Dearing et al., 1996a, 1997). Worm (1998) also proposed that a $\chi_{fd}\%$ value of 17 % is theoretically possible. Hence, the very high content of SP grains in this zone compared to the other two may be responsible for the exceptionally high $\chi_{fd}\%$ values. Values of HIRM exhibit a slight decrease, which indicates an increase in the proportion of magnetically “soft” minerals. IRM acquisition curves (Fig. 3.3) show that most samples get saturated at a field of $\approx 300 \text{ mT}$, indicating the magnetically "soft” mineralogy. However, a few samples do display an increasing trend confirming the presence of magnetically" hard"minerals. The sand content further decreases (average = 18 %) and clay content (average = 70.4 %) increases in this zone.

The SEM image and Fe and Ti peaks in the EDS spectra demonstrate the presence of titano-magnetite/maghemite in the samples (Fig. 3.14)
Fig. 3.14 Scanning electron micrograph and energy dispersive spectrum (EDS) of a grain from the magnetic extract from the Uliyathadka soil profile (APP3; 102-103 cm depth).

The sample of laterite that underlies the Uliyathadka soil profile displays very low values for concentration-dependent parameters like $\chi_{lf}$, $\chi_{fd}$, IRM$_{20mT}$, and SIRM. However, S-ratio exhibits an average value of 0.44 and HIRM a peak. These data indicate that the laterite consists of magnetically “hard” minerals like haematite and/or goethite with a coarse magnetic grain size as indicated by the remarkably low $\chi_{ARM}$/SIRM values (Fig. 3.12). The charnockitic parent rock occurring below the laterite displays high values for concentration-dependent parameters like $\chi_{lf}$, $\chi_{fd}$, IRM$_{20mT}$, and SIRM with zero $\chi_{fd}$ and $\chi_{fd}$. S-ratio is close to 1.0 with notably low HIRM values. These data suggest that the charnockite consists essentially of magnetically “soft” minerals with no SP grains. Only lithogenic magnetite is present in the parent rock.

The Uliyathadka profile is situated in a flat, low-lying area just below a lateritic hill. Hence, one would expect high magnetic values and a high content of SP grains because of top-soil erosion in the nearby hill and slope. However, the rock magnetic characteristics are very similar to the other two profiles irrespective of the topography. The high $\chi_0$ value in Zone 1 is due to the presence of coarse SSD grains and not SP grains.
3.1.4 Panjikallu (APP6)

This profile may be divided into two zones based on magnetic properties (Fig. 3.15). Zone 1 extends from 0 to 26.5 cm depth. The values of $\chi_{lf}$, $\chi_{fd}$ %, $\chi_{fd}$ and $\chi_{ARM}$ exhibit a slight decreasing trend towards the profile top. The average values in the zone are: $\chi_{lf} = 993.4 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, $\chi_{fd} = 8\%$ and SIRM = $7867.1 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$. Values of the inter-parametric ratio $\chi_{ARM}/\chi_{lf}$ do not exhibit much variation though $\chi_{ARM}$/SIRM values do register an upward decrease, indicating a relative coarsening of magnetic grain size (Fig. 3.16). The S-ratio exhibits high values; the average value of 0.97 indicates the predominance of magnetically “soft” minerals.

Zone 2 extends from 26.5 to 142.5 cm depth. The $\chi_{lf}$ values, although relatively low, do show an upward increasing trend. $\chi_{fd}$ % values are constant and comparable to those of zone 1. However, $\chi_{ARM}$, $\chi_{fd}$, IRM$_{20mT}$ and SIRM show an increasing trend towards the profile-top. The average values of these parameters are $\chi_{lf}=881.2 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, $\chi_{fd} = 79.6 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, IRM$_{20mT} = 1684.7 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$ and SIRM = $6328.1 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$. There is a decrease in S-ratio and increase in HIRM values at the bottom of this zone, indicating a slightly higher concentration of magnetically" hard" minerals. IRM acquisition curves (Fig. 3.3) demonstrate that most samples are saturated at a field of ~ 300 mT, indicating a magnetically “soft" mineralogy. However, a few display an increasing trend even at a field of 1T, suggesting the presence of magnetically "hard" minerals. However there is no significant variation in $\chi_{fd}$ % between the two zones and only a slight decrease is noted in $\chi_{ARM}$/SIRM values in Zone 2 (Fig. 3.16).
Fig. 3.15 The Panjikallu soil profile and its rock magnetic parameters and inter-parametric ratios. Note: The profile may be divided into two zones based on the variations in magnetic parameters. Zone 1 is characterised by relatively low values of $\chi_{\text{ff}}$ compared to Zone 2.
Fig. 3.16 Biplot of $\chi_{\text{ARM}}$/SIRM vs. $\chi_{\text{fd}}$% (Dearing et al., 1997) for samples from Panjikallu and Thekkilparamba soil profiles. Most of the samples plot in the field of Coarse SSD to Fine SSD and Mixtures. Note that magnetic grain size decreases towards profile-bottom with an increase in the proportion of SP grains. Samples of the parent rock are devoid of SP grains and contain only coarse grained lithogenic magnetite.

The charnockitic parent rock occurring below the laterite displays high values for concentration-dependent parameters like $\chi_{\text{ff}}$, $\chi_{\text{fd}}$, IRM$_{20\text{mT}}$, and SIRM with zero $\chi_{\text{fd}}$ and $\chi_{\text{fd}}$%. An S-ratio value of close to 1.0 and the substantially low HIRM values indicate the presence of coarse grained lithogenic grains and the absence of pedogenic SP grains.

As the profile is situated near the base of low lateritic mound with a moderate slope, top-soil erosion, rather than down-profile transportation (illuviation), of fine grains would be dominant.
3.1.5 Thekkilparamba (APP9)

This profile may be divided into two zones based on magnetic properties (Fig. 3.17). Zone 1 extends from 0 to 14.5 cm depth. The average values of magnetic parameters in the zone are: $\chi_{lf} = 633.63 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, $\chi_{fd} \% = 10.74 \%$ and SIRM = $5039.2 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$. Values of the inter-parametric ratios $\chi_{ARM}/\chi_{lf}$ and $\chi_{ARM}/\text{SIRM}$, exhibit an upward decrease, indicating a relatively coarse magnetic grain size (Fig. 3.16). The S-ratio values initially exhibit a decrease and subsequently an increase towards the profile-top; values of HIRM exhibit an opposite trend.

Zone 2 extends from 14.5 to 142.5 cm depth with relatively low values for $\chi_{lf}$ (average = $494.4 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$). Values of $\chi_{fd} \%$, $\chi_{ARM}$, $\chi_{fd}$, IRM$_{20\text{mT}}$ and SIRM increase towards the top of the zone. The magnetic grain size is slightly coarser as indicated by relatively higher $\chi_{ARM}$/SIRM values. There is a decrease in S-ratio values at the bottom of this zone, indicating a slightly higher concentration of magnetically "hard" minerals. IRM acquisition curves (Fig. 3.3) show that many samples do get saturated at ~ 300 mT field, suggesting a magnetically "soft" mineralogy.

The charnockite underlying the laterite shows high values for concentration-dependent parameters like $\chi_{lf}$, $\chi_{fd}$, IRM$_{20\text{mT}}$, and SIRM with zero $\chi_{fd}$ and $\chi_{fd} \%$ values. S-ratio value (close to 1.0) and the remarkably low HIRM values indicate the presence of coarse grained lithogenic grains and the absence of pedogenic SP grains.

As the profile is located on the top of lateritic stable upland with little slope, top-soil erosion may be insignificant and illuviation more dominant. An increase in the $\chi_{fd} \%$ values at the profile bottom is associated with a decrease in $\chi_{lf}$ and $\chi_{ARM}$ values. Hence, there is no increase in the absolute concentration of SP grains as $\chi_{fd}$ values do not
Fig. 3.1 The Thekkilparamba soil profile and its rock magnetic parameters and inter-parametric ratios. *Note:* The profile may be divided into two zones based on the variations in magnetic parameters.
increase at the bottom. Also there is a relative decrease in SSD grains as indicated by decrease in $\chi_{\text{ARM}}$ values.

The production of pedogenic magnetite (SP grains) is the highest at the profile-top where there is unhindered interaction with the atmosphere. This leads to higher values for concentration-dependent parameters at the profile-top and lower values at the bottom of the profile. However, high $\chi_{\text{fd}}\%$ values towards the profile-bottom indicate the presence of SP grains, which may have been transported from the surface layers as a result of illuviation. As illuviation does not affect SSD grains, $\chi_{\text{ARM}}$ values do not exhibit an increase at the profile-bottom. The absolute concentration of SP grains does not vary much and the overall magnetic signal is weak in the profile-bottom samples.

3.1.6 Devalokam (APP10)

This profile may be divided into two zones based on magnetic properties (Fig. 3.18). Zone 1 extends from 0 to 34.5 cm depth. The magnetic parameters and ratios have the following average values in the zone: $\chi_{\text{lf}} = 1368.42 \times 10^{-8}$ m$^3$ kg$^{-1}$, $\chi_{\text{fd}}\% = 12.6\%$, $\text{IRM}_{20\text{mT}} = 3150.1 \times 10^{-5}$ Am$^2$kg$^{-1}$ and $\text{SIRM} = 6172.76 \times 10^{-5}$ Am$^2$kg$^{-1}$. Concentration-dependent parameter values are relatively high compared to Zone 2. Values of the inter-parametric ratio $\chi_{\text{ARM}}/\text{SIRM}$ exhibit a slight decrease (Fig. 3.19). The S-ratio values exhibit an increasing trend. The average S-ratio value in this zone is 0.97, indicating the predominance of magnetically "soft" minerals.

Zone 2 extends from 34.5 to 182.5 cm depth. Values of $\chi_{\text{lf}}$ (average = 1075.3 x $10^{-8}$ m$^3$ kg$^{-1}$), $\chi_{\text{ARM}}, \chi_{\text{fd}}, \text{IRM}_{20\text{mT}}$ and $\text{SIRM}$ are low with respect to Zone 1 and register an increasing trend towards the top of the zone. However, $\chi_{\text{fd}}\%$ shows an increase with finer magnetic grain size (Fig. 3.19) and the values decrease towards the top.
Fig. 3.18 The Devalokam soil profile and its rock magnetic parameters and inter-parametric ratios. Note: The profile may be divided into two zones based on the variations in magnetic parameters.
Fig. 3.19 Biplot of $\chi_{\text{ARM}}/\text{SIRM}$ vs. $\chi_{\text{fd}}$ % (Dearing et al., 1997) for samples from Devalokam, Cherupanathady and Mundott soil profiles. Most of the samples plot in the field of Coarse SSD and SSD/SP Mixtures. Note that the magnetic grain size decreases towards the profile-bottom with an increase in the proportion of SP grains.

S-ratio values are low at the bottom of this zone indicating a slightly higher concentration of magnetically "hard" minerals. The pattern of IRM acquisition (Fig. 3.3) indicates that most samples get saturated at a field of ~ 300 mT, suggesting a magnetically" soft" mineralogy.

The Devalokam profile exhibits relatively higher values for concentration-dependent parameters compared to the other profiles developed on a similar lithology, i.e., charnockite. There is only a slight difference in the magnetic parameters between Zones 1 and 2. The magnetic grain size is notably fine (plotting in the SSD/SP transition
These data indicate strong pedogenesis in this profile. As the profile is located along the slope of a lateritic hill, illuviation is less pronounced and there is no significant increase in SP grains at the bottom of the profile.

### 3.1.7 Cherupanathady (APP13)

This profile may be divided into two zones based on magnetic properties (Fig. 3.20). Zone 1 extends from 0 to 66.5 cm depth. The rock magnetic parameters exhibit relatively high values with an increasing trend towards the profile-top. The average values of the magnetic parameters are: \( \chi_{lf} = 528.3 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \), \( \chi_{fd} \% = 8.8 \% \), \( \text{IRM}_{20\text{mT}} = 1107.3 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1} \) and \( \text{SIRM} = 3412.9 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1} \). Values of the inter-parametric ratios \( \chi_{\text{ARM}/\text{SIRM}} \) and \( \chi_{\text{ARM}/\chi_{lf}} \) exhibit a decrease upwards. The S-ratio values exhibit an upward increasing trend with a relatively high average value (0.96), indicating the predominance of magnetically "soft" minerals.

Zone 2 extends from 66.5 to 182.5 cm depth. All the concentration-dependent parameter values are low compared to Zone 1 and are nearly constant; the average values in Zone 2 are \( \chi_{lf} = 204.1 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \), \( \chi_{fd} \% = 9.6 \% \), \( \text{IRM}_{20\text{mT}} = 336.7 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1} \) and \( \text{SIRM} = 1376.7 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1} \). However, \( \chi_{fd} \% \) is relatively high. There is a downward decrease in the S-ratio value (average = 0.93), indicating a higher concentration of magnetically "hard" minerals. A magnetically "soft" mineralogy may be inferred from IRM acquisition curves (Fig. 3.21): Most of the samples get saturated by \( \sim 300 \text{ mT} \) field.

The data suggest that there is some magnetic enhancement in Zone 1 of this profile because all the concentration-dependent parameter values increase towards the profile-top, magnetic mineralogy becomes "soft" but the magnetic grain size coarsens as suggested by magnetic grain size ratio (\( \chi_{\text{ARM}/\text{SIRM}} \) and \( \chi_{\text{ARM}/\chi_{lf}} \) values.
Fig. 3.20 The Cherupanathady soil profile and its rock magnetic parameters and inter-parametric ratios. *Note:* The profile may be divided into two zones based on the variations in magnetic parameters. Concentration–dependent parametervalues are low but constant in Zone 2 whereas in Zone 1 they are much high and display an upward increasing trend.
Fig. 3.21 Isothermal remanent magnetization (IRM) acquisition curves for soil profile samples (APP13, APP14, APP15 and APP17). Note: Most of the samples get saturated at a field of ~ 300 mT, indicating a magnetically "soft" mineralogy. However, IRM values continue to increase even at 1T field for a few samples, indicating the presence of hematite/goethite in them.

Samples from both the zones plot in the coarse SSD range of $\chi_{ARM}/SIRM$ vs. $\chi_{fd}$ % biplot (Dearing et al., 1997) with not much variation in the magnetic grain size between them. The profile is situated on a flat mid-upland region with little slope. Hence, surface soil erosion might be less. As concentration-dependent magnetic parameters exhibit a steady increase towards profile top, it appears that iron reduction is insignificant at the profile top.
3.1.8 Mundott (APP14)

Based on the magnetic properties, this profile may be divided into two zones (Fig. 3.22). Zone 1 extends from 0 to 66.5 cm depth. The rock magnetic parameters exhibit relatively high values with an increasing trend towards the profile-top suggesting an upward increase in the magnetic mineral concentration. The average values of the magnetic parameters are: $\chi_{fl}=548 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, $\chi_{fd} \%= 8.9 \%$ and SIRM = $3162.1 \times 10^{-5}$ Am$^2$ kg$^{-1}$. The $\chi_{ARM}/\chi_{fl}$ and $\chi_{ARM}/\text{SIRM}$ values generally decrease towards the profile-top, indicating a coarsening of the magnetic grain size. The S-ratio values increase towards the profile-top; a high average S-ratio value (0.95) shows a progressively magnetically "soft" mineralogy towards the surface. The particle size data reveals a decrease in the clay percentage and increase in the sand percentage towards profile top in Zone 1 (Fig. 3.23). The average sand content is 29.5 % and clay content 56.5 %.

Zone 2 extends from 66.5 to 142.5 cm depth. The average values of concentration-dependent parameters in this zone $\chi_{fl}=191.5 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, $\chi_{fd} \%= 9.9 \%$, $\text{IRM}_{20\text{mT}} = 611 \times 10^{-5}$ Am$^2$ kg$^{-1}$, $\chi_{ARM}= 1.7 \times 10^{-5}$ m$^3$ kg$^{-1}$ and SIRM = $1683.6 \times 10^{-5}$ Am$^2$ kg$^{-1}$, are low compared to Zone 1. Besides, they show a gradual increase upwards. The S-ratio values are low (average=0.89), indicating a relatively less "soft" mineralogy.

IRM acquisition curves (Fig. 3.21) suggest a magnetically "soft" mineralogy as most samples get saturated at a field of ~ 300 mT. However, a few samples belonging to Zone 2 have magnetically hard minerals as these samples are not yet saturated even at 1T field.

Particle size analysis results show that there is an increase in clay percentage and decrease in sand percentage towards the bottom of the profile (Fig. 3.23).
Fig. 3.22 The Mundotto soil profile and its rock magnetic parameters and inter-parametric ratios. Note: The profile may be divided into two zones based on the variations in magnetic parameters. In Zone 2, concentration-dependent parameters exhibit slow but steady values, whereas in Zone 1, they exhibit much higher values with an upward increasing trend.
Fig. 3.23 Magnetic susceptibility and sand silt and clay percentages for a few selected samples from the Mundott soil profile.

The magnetic grain size does not vary much between Zone 1 and Zone 2 of the Mundott soil profile (Fig. 3.19). The general trend of magnetic parameters of the Mundott profile is very similar to those of the Cherupanathady profile, in spite of the fact that the former is situated on the slope of a lateritic upland whereas the latter is in a flat upland with little slope. In both the profiles there is no decrease in the values of magnetic parameters at the top of the profile, indicating the absence of iron reduction. Illuviation is active in the profile as indicated by an increase in SP grains at the profile-bottom.

The SEM image and Fe peak in the EDS spectra illustrate the presence of magnetite/maghemite in the samples (Fig. 3.24).
3.1.9 Karichery (APP15)

This profile may be divided into three zones based on magnetic properties (Fig. 3.25). Zone 1 extends from 0 to 46.5 cm depth. The concentration-dependent magnetic
parameters exhibit nearly constant and relatively high values although they tend to decrease in the top ~20 cm. These characteristics suggest a relatively high magnetic mineral concentration in Zone 1, with a decrease in the top ~ 20 cm. The average values in the zone are: \( \chi_{\text{lf}} = 756.6 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \), \( \chi_{\text{fd}} \% = 7.9 \% \), \( \chi_{\text{fd}} = 59.5 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \), \( \text{IRM}_{20\text{mT}} = 2016.3 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1} \), and \( \text{SIRM} = 5725.3x \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1} \). Inter-parametric ratio values for \( \chi_{\text{ARM}}/\chi_{\text{lf}} \) and \( \chi_{\text{ARM}}/\text{SIRM} \) decrease towards the surface, suggesting a coarsening of magnetic grain size, probably due to loss of fine magnetic minerals. The S-ratio values are uniform with an average of 0.95. Such a high S-ratio value is suggestive of a high relative proportion of ferrimagnets like magnetite and maghemite. Values of HIRM increase towards the profile-top.

Zone 2 extends from 46.5 to 82.5 cm depth. The concentration-dependent magnetic parameter values are relatively low compared to Zone 1.

Zone 3 extends from 82.5 to 142.5 cm depth with relatively low values for \( \chi_{\text{lf}} \). The concentration-dependent magnetic parameter values are the lowest for the entire profile. The average values in the zone are: \( \chi_{\text{lf}} = 183 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \), \( \chi_{\text{fd}} \% = 7.8 \% \), \( \text{IRM}_{20\text{mT}} = 430 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1} \), \( \chi_{\text{ARM}} = 0.96 \times 10^{-5} \text{ m}^3 \text{ kg}^{-1} \) and \( \text{SIRM} = 1307.1x \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1} \). The S-ratio values are low (average = 0.85) in this zone indicating a lower relative proportion of magnetically "soft" minerals. IRM acquisition curves (Fig. 3.21) nevertheless testify to the magnetically "soft" mineralogy as most samples get saturated at a field of ~ 300 mT. However, a few samples do display an increasing trend of IRM acquisition at 1T field too confirming the presence of magnetically "hard" minerals.
Fig. 3.25 The Karichery soil profile and its rock magnetic parameters and inter-parametric ratios. Note: The profile may be divided into three zones based on the variations in magnetic parameters. In Zone 1, concentration-dependent parameters exhibit high but steady values, whereas in Zone 2, they exhibit an upward increasing trend. In Zone 3, the values are low and steady.
Fig. 3.26Biplot of $\chi_{\text{ARM}}/\text{SIRM}$ vs. $\chi_{\text{fd}}$ % (Dearing et al., 1997) for soil profile, laterite and parent rock samples from Karichery. Most of the samples fall in the field of coarse SSD and SSD/SP mixtures. Note that the magnetic grain size decreases towards profile-bottom with an increase in the proportion of SP grains. The parent rock samples are devoid of SP grains and contain only coarse grained lithogenic magnetite.

The laterite that underlies the soil profile displays very low values for concentration-dependent parameters like $\chi_{\text{lf}}$, $\chi_{\text{fd}}$, IRM$_{20\text{mT}}$ and SIRM. S-ratio exhibits low value (Fig. 3.25) for this sample which indicates that laterite consists of hard magnetic minerals like haematite and/or goethite with a coarse magnetic grain size as brought out by the very low $\chi_{\text{ARM}}/\text{SIRM}$ values (Fig. 3.26). The parent rock (charnockite) occurring below the laterite displays high values for concentration-dependent parameters like $\chi_{\text{lf}}$, IRM$_{20\text{mT}}$, and SIRM with zero $\chi_{\text{fd}}$ and $\chi_{\text{fd}}$%. S-ratio is close to 1.0 and
HIRM values are very low. This indicates that the charnockite consists essentially of soft magnetic minerals with no SP grains. Only lithogenic magnetite is present in the parent rock.

3.1.10 Kundamkuzhy (APP17)

This profile may be divided into two zones based on magnetic properties (Fig. 3.27). Zone 1 extends from 0 to 66.5 cm depth. The rock magnetic parameter values are high; in fact some are the highest for the entire profile. They exhibit an increasing trend towards the profile-top. These data suggest magnetic enhancement in Zone 1 although the top ~ 5 cm document a loss of magnetic minerals as indicated by a decrease in concentration-dependent parameter values. The average values in the zone are: $\chi_{lf} = 2174 \times 10^{-8}$ m$^3$ kg$^{-1}$, $\chi_{fd} = 72.3 \times 10^{-8}$ m$^3$ kg$^{-1}$, $\chi_{ARM} = 4.6 \times 10^{-5}$ m$^3$ kg$^{-1}$, $\text{IRM}_{20\text{mT}} = 3263.4 \times 10^{-5}$ Am$^2$ kg$^{-1}$ and $\text{SIRM} = 16806.3 \times 10^{-5}$ Am$^2$ kg$^{-1}$. Values of the inter-parametric ratios $\chi_{ARM}/\chi_{lf}$ and $\chi_{ARM}/\text{SIRM}$ are low compared to Zone 2. They show an upward decrease, suggesting a coarsening of magnetic grain size. This coarsening may be an indication of the loss of fine magnetic minerals from this zone (Fig. 3.28). The S-ratio values exhibit an upward increasing trend with a relatively high average of 0.96, indicating the predominance of magnetically "soft" minerals.

Zone 2 extends from 66.5 to 122.5 cm depth with relatively low values for concentration-dependent parameters in comparison with Zone 1 values. The average values in the zone are: $\chi_{lf} = 1021.7 \times 10^{-8}$ m$^3$ kg$^{-1}$, $\chi_{fd} = 57.2 \times 10^{-8}$ m$^3$ kg$^{-1}$, $\chi_{ARM} = 3.1 \times 10^{-5}$ m$^3$ kg$^{-1}$, $\text{IRM}_{20\text{mT}} = 1568.4 \times 10^{-5}$ Am$^2$ kg$^{-1}$ and $\text{SIRM} = 7709.5 \times 10^{-5}$ Am$^2$ kg$^{-1}$. The values remain nearly constant throughout the zone.
Fig. 3.27 The Kundamkuzhy soil profile and its rock magnetic parameters and inter-parametric ratios. Note: The profile may be divided into two zones based on the variations in magnetic parameters. In Zone 1, concentration-dependent parameter values are high and exhibit an upward increasing trend, whereas in Zone 2, they are low and constant.
Fig. 3.28 Biplot of $\chi_{ARM}/SIRM$ vs. $\chi_{fd}$ % (Dearing et al., 1997) for soil profile and parent rock samples from Kundamkuzhy. Most of the samples fall in the field of coarse SSD grain size range indicating a coarse magnetic grain size. Note that magnetic grain size decreases towards profile bottom with an increase in the proportion of SP grains. SP grains are absent in the parent rock sample; only coarse grained lithogenic magnetite is present.

Although the average S-ratio value is high (0.96), it is slightly low compared to Zone 1 values, indicating a relatively lower proportion of magnetically "soft" minerals. $\chi_{ARM}/SIRM$ ratio exhibits low values (Fig. 3.28). The very high values for concentration-dependent parameters like $\chi_{lf}$, IRM$_{20mT}$, $\chi_{ARM}$ and SIRM, low values for $\chi_{fd}$% and very low values for $\chi_{ARM}/SIRM$ point towards magnetite of anthropogenic /lithogenic origin. However, such a high concentration of coarse lithogenic grains at the top and low concentration at the bottom of the profile may be ruled out.

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). The low proportion of SP grains in Zone 1 and 2 samples also substantiates this interpretation.

A comparison of \( \chi_L, \chi_{fd}, S\)-ratio and \( \chi_{ARM}/SIRM \) for all the charnockite-hosted soil profiles is displayed in Figure 3.29. The Kundamkuzhy profile (APP17) exhibits relatively high values for \( \chi_L \) (especially in Zone 1). This may be attributed to the profile being situated near a road. The magnetite from vehicular emission may have contributed to the very high values of \( \chi_L \) and low values of \( \chi_{fd} \). The \( \chi_L \) values in the upper part of this profile are high and are over and above the high background \( \chi_L \) values in comparison with other profiles studied. The high background values themselves may be due to lithogenic magnetite derived from the underlying charnockite. As the magnetic mineralogy is "soft" (Fig. 3.27), the high values for concentration-dependent parameters in this profile may not reflect any topographic effect. IRM acquisition curves (Fig. 3.21) show that most samples get saturated at a field of \(~300\) mT, indicating magnetically "soft" mineralogy.

3.2 Variation of magnetic parameters in relation to topography

The \( \chi_L, \chi_{fd}, \chi_{ARM}/SIRM \) and S-ratio data for the ten charnockite-hosted lateritic soil profiles are displayed in Fig. 3.29. The general trends of all the parameters in the profiles are similar. A summary of topographic effect on magnetic parameters (Table 3.1) also does not show a significant topographic control. Although the profiles may be divided in to two or three zones based on variations in magnetic parameters, there are variations in the absolute values of magnetic parameters (Fig. 3.29) indicating between-profile differences in magnetic mineral concentration, grain size and mineralogy. These may be attributed to variations in the magnetic mineral content in the charnockite itself.
Concentration of lithogenic magnetic minerals may vary among the charnockites from different locations. The primary magnetic mineral in the charnockites is MD magnetite as indicated by the values of S-ratio close to one and the very low $\chi_{\text{ARM}}$/SIRM ratio. Pedogenic magnetite is absent in the parent rocks. During lateritisation these lithogenic magnetite grains may get released into the laterite and convert to haematite/goethite as indicated by the low values of S-ratio. Some amount of Fe present in these magnetically "hard" minerals may provide the initial Fe concentration necessary for pedogenic processes. During the weathering of laterite, lithogenic Fe may be transformed to fine grained superparamagnetic magnetite, which may then migrate into the lateritic soils developed over them.

If the initial Fe concentration in similar parent rocks (charnockites or laterites) is high/low it is reflected in the high/low Fe concentration in soils developed above them. However, topography or slope may also be playing a role in determining the absolute concentration of magnetic minerals especially near the surface. The two profiles situated near the base of lateritic hill (APP3 and APP6) exhibit relatively high values compared to profiles situated in the slopes or lateritic upland. This is consistent with the findings of Thompson and Oldfield (1986) where they documented a progressive down slope increase in magnetic values with the enrichment of fine grained magnetic minerals. The magnetic values display higher range between different profiles in top soils compared to sub-soils. This may be because magnetic properties of sub-soils are usually independent of slope (Thompson and Oldfield, 1986).
Fig. 3.29 A comparison of (a) $\chi_{lf}$, (b) $\chi_{fd}$%, (c) $\chi_{fd}$ (d) S-ratio and (e) $\chi_{ARM}/SIRM$ values for soil profile samples developed on similar parent rocks (charnockite) and under different topographic conditions.
Table 3.1 Details of topography and general behaviour of magnetic parameters in the profiles investigated. Note: There is not much influence of topography on the magnetic characteristics of lateritic soil profiles developed on charnockites.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Topography</th>
<th>Profile No.</th>
<th>General behaviour of magnetic properties in the profile</th>
<th>Magnetic concentration</th>
<th>Magnetic grain size</th>
<th>Magnetic mineralogy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Gently sloping lateritic plateau/upland</td>
<td>APP2, APP9, APP13</td>
<td>High and increasing upwards; Low and steady at the bottom.</td>
<td>Top: Coarse, low SP content Bottom: Fine, high SP content</td>
<td>Top: Magnetically &quot;softer&quot;. Bottom: Slight increase in magnetically &quot;hard&quot; minerals.</td>
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<tr>
<td>2.</td>
<td>Gently sloping lateritic hillside</td>
<td>APP10, APP15</td>
<td>High and increasing upwards; Low and steady at the bottom.</td>
<td>Minimum variation; however, Top: Coarse, low SP content Bottom: Fine, high SP content</td>
<td>Variation is minimum; Top: Magnetically &quot;softer&quot;. Bottom: Slight increase in magnetically &quot;hard&quot; minerals.</td>
<td></td>
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<tr>
<td>3.</td>
<td>Moderately sloping lateritic hillside</td>
<td>APP14</td>
<td>High and increasing upwards; Low and steady at the bottom.</td>
<td>Top: Coarse, low SP content Bottom: Fine, high SP content</td>
<td>Top: Magnetically &quot;softer&quot;. Bottom: Slight increase in magnetically &quot;hard&quot; minerals.</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Base of lateritic hill with gentle slope</td>
<td>APP3</td>
<td>High and increasing upwards; Low and steady at the bottom.</td>
<td>Top: Coarse, low SP content Bottom: Fine, high SP content</td>
<td>Variation is minimum; Top: Magnetically &quot;softer&quot;. Bottom: Slight increase in magnetically &quot;hard&quot; minerals.</td>
<td></td>
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<tr>
<td>5.</td>
<td>Base of lateritic hill with moderate slope</td>
<td>APP6</td>
<td>High at the top with a decreasing trend.</td>
<td>Top: Coarse, low SP content Bottom: Fine, high SP content</td>
<td>Variation is minimum; Top: Magnetically &quot;softer&quot;. Bottom: Slight increase in magnetically &quot;hard&quot; minerals.</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Lateritic valley with moderate slope</td>
<td>APP1</td>
<td>High at the top with a decreasing trend.</td>
<td>Top: Coarse, low SP content Bottom: Fine, high SP content</td>
<td>Variation is minimum; Top: Magnetically &quot;softer&quot;. Bottom: Slight increase in magnetically &quot;hard&quot; minerals.</td>
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3.3 Influence of parent rock on mineral magnetic properties of lateritic soils

In order to detect the influence of parent rock lithology on the magnetic parameters of lateritic soils, four soil profiles developed on different parent rock types namely quartzo-feldspathic gneiss, hornblende-biotite gneiss ferruginous sandstone and charnockite were investigated.

3.3.1 Soil profile developed on quartzo-feldspathic gneiss (Shanthinagar- APP7)

This profile may be divided into two zones based on magnetic properties (Fig. 3.30). Zone 1 extends from 0 to 26.5 cm depth. The concentration-dependent magnetic parameters exhibit relatively low or similar values compared to Zone 2. The values decrease towards the profile-top. The average values in the zone are: $\chi_{df}=947.7 \times 10^{-8}$ m$^3$ kg$^{-1}$, $\chi_{fd}=108.4x 10^{-8}$ m$^3$ kg$^{-1}$, $\chi_{ARM}=5.4x 10^{-5}$ m$^3$ kg$^{-1}$, $IRM_{20mT}=2775.2x 10^{-5}$ Am$^2$ kg$^{-1}$ and SIRM = 6777.4 $10^{-5}$Am$^2$ kg$^{-1}$. Values of the inter-parametric ratio, $\chi_{ARM}/\chi_{lf}$ do not exhibit much fluctuation; however, $\chi_{ARM}$/SIRM values decrease towards the surface (Figs. 3.30 and 3.31). The average S-ratio is reasonably high (average = 0.90). The average HIRM is $669.7x 10^{-5}$Am$^2$ kg$^{-1}$.

Zone 2 extends from 26.5 to 142.5 cm depth. The concentration-dependent parameter values are low at the bottom but increase upwards. Generally, the values are high or similar to those of Zone 1. The average values in the zone are $\chi_{df}=1044.9 \times 10^{-8}$ m$^3$ kg$^{-1}$, $\chi_{fd}=130.8x 10^{-8}$ m$^3$ kg$^{-1}$, $\chi_{ARM}=5.9x 10^{-5}$ m$^3$ kg$^{-1}$, $IRM_{20mT}=2582.7x 10^{-5}$ Am$^2$ kg$^{-1}$ and SIRM = 5823x $10^{-5}$Am$^2$ kg$^{-1}$. The average S-ratio value is 0.90 indicating a magnetically "soft" mineralogy. However, IRM acquisition curves (Fig. 3.32) show that most samples do not get saturated at 1T field too; IRM values continue their march to high values. These data suggest the presence of magnetically hard minerals like haematite and/or goethite. The average HIRM value is $564.3x 10^{-5}$ A m$^2$ kg$^{-1}$.
Fig. 3.30 The Shanthinagarsoil profile (developed on quatzo-feldspathic gneiss) and its rock magnetic parameters and inter-parametric ratios. Note: The profile may be divided into two zones based on the variations in magnetic parameters. In the upper Zone 1, the concentration-dependent parameter values are low and exhibit a decreasing trend, whereas in Zone 2, they are higher and increase upwards.
Fig. 3.31 Biplot of $\chi_{ARM}/SIRM$ vs. $\chi_{fd}$ % (Dearing et al., 1997) for samples from soil profile and parent rock of Shantinagar and Narampady profiles and Ramanchira profile soil samples. Most of the samples fall in the field of coarse SSD and Fine SSD and mixtures.
Fig. 3.32 Isothermal remanent magnetization (IRM) acquisition curves for soil profile samples (APP7, APP8 and APP12). Note: Profile APP8, developed on ferruginous sandstone, exhibits relatively high IRM values, where as profile APP12 developed on hornblende-biotite gneiss exhibits the lowest values. Most of the samples get saturated at a field of ~ 300 mT, indicating a magnetically "soft" mineralogy. However, IRM values continue to increase even at 1T field for a few samples in APP8 and APP12 and most of the samples in APP 7, indicating the presence of hematite/goethite in them.

3.3.2 Soil profile developed on hornblende-biotite gneiss (Narampady - APP12)

This profile may be divided into two zones based on magnetic properties (Fig. 3.33). Zone 1 extends from 0 to 34.5 cm depth. The concentration-dependent magnetic parameters exhibit relatively high values. They exhibit steady values from 34.5 to 16.5 cm and decrease thereafter towards the profile-top. The average values in the zone are: $\chi_{\text{lf}} = 411.3 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, $\chi_{\text{fd}}\% = 10.5 \%$, $\chi_{\text{fd}} = 43x 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, $\chi_{\text{ARM}} = 2.8 \times 10^{-5} \text{ m}^3 \text{ kg}^{-1}$, $\text{IRM}_{20 \text{mT}} = 1329.2 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$ and $\text{SIRM} = 3111.2 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$. Values of the inter-parametric ratios $\chi_{\text{ARM}}/\chi_{\text{lf}}$ and $\chi_{\text{ARM}}/\text{SIRM}$ do not exhibit much fluctuation (Fig. 3.31). The
average S-ratio is 0.93 and HIRM is $225.6 \times 10^{-5} \text{Am}^2 \text{kg}^{-1}$. The citrate-bicarbonate-dithionite (CBD) procedure (Mehra and Jackson, 1960) was used to estimate the relative contributions of the lithogenic and pedogenic magnetic components in Narampady samples. The three samples in zone 1 (at depths of 0-1, 10-11 and 22-23 cm) exhibit a significant decrease in magnetic susceptibility and frequency-dependent susceptibility values after the first two steps itself (Fig. 3.34). This indicates that the lithogenic component is low in this zone. The down-profile variations of pre-CBD $\chi_{lf}$, post-CBD $\chi_{lf}$ and pedogenic $\chi_{lf}$ are plotted in Fig. 3.35.

Zone 2 extends from 34.5 to 142.5 cm depth. The concentration-dependent magnetic parameters exhibit relatively low values compared to Zone1 with an increasing trend upwards. The average values for magnetic parameters in the zone are $\chi_{lf}= 217.8 \times 10^{-8} \text{m}^3 \text{kg}^{-1}, \chi_{fd} \% = 11.1 \%, \chi_{ARM}= 1.8 \times 10^{-5} \text{m}^3 \text{kg}^{-1}, \text{IRM}_{20\text{mT}}= 755.8 \times 10^{-5} \text{Am}^2 \text{kg}^{-1}$ and SIRM = $1582.8 \times 10^{-5} \text{Am}^2 \text{kg}^{-1}$. Values of $\chi_{fd} \%$ (average = 11.1 %) are relatively high and those of S-ratio marginally compared to Zone1. The magnetic grain size decreases slightly in Zone 2 (Fig. 3.31). There is slight decrease in average S-ratio values between two zones. There is a decrease in the average HIRM value ($145.4 \times 10^{-5} \text{Am}^2 \text{kg}^{-1}$) also. This may indicate that there is decrease in "soft" as well as "hard" magnetic minerals at the bottom of the profile. IRM acquisition curves (Fig. 3.32) demonstrate that most samples get saturated at a field of ~ 300 mT, indicating a magnetically "soft" mineralogy. CBD treatment data reveal that the three samples in zone 2 (at depth 42-43, 66-67 and 122-123 cm) exhibit a significant decrease in magnetic susceptibility and frequency-dependent susceptibility values after the first two steps itself (Fig. 3.34).
Fig. 3.33 The Narampady soil profile (developed on hornblende-biotite gneiss) and its rock magnetic parameters and inter-parametric ratios. Note: The profile may be divided into two zones based on the variations in magnetic parameters. In the upper Zone 1, the concentration-dependent parameter values are high and exhibit a decreasing trend upwards, whereas in Zone 2, they exhibit low values and an upward increasing trend.
Fig. 3.34 CBD extraction data for Narampady soil samples. (a) Magnetic susceptibility ($\chi_{lf}$); and (b) Frequency-dependent susceptibility ($\chi_{fd}$). Data for each sample are represented as three bars corresponding to the $\chi_{lf}$ or $\chi_{fd}$ measured before and after the 1st and 2nd steps of CBD treatment. The numbers above the bars indicate percentage reduction after 2nd step.

There is no significant down-profile variation in particle size distribution. The sand content varies from 29.4 to 48.2 %, whereas clay content ranges from 37 to 55 % (Fig. 3.36). This indicates that illuviation is not very active in the profile.
This interpretation is substantiated by the $\chi_{fd}\%$ values which do not exhibit considerable variation between the two zones. The absolute concentration of pedogenic magnetite decreases in Zone 2, its relative proportion in the sample remains high (Fig. 3.35). Pedogenic $\chi_{lf}$ exhibits a lower correlation coefficient of 0.98 with $\chi_{lf}$ and a higher correlation coefficient of 0.99 with pedogenic $\chi_{fd}$ (Fig. 3.37). Pedogenic $\chi_{fd}$ and $\chi_{fd}$ are also well correlated between themselves ($r=1.00$). This indicates that the magnetic susceptibility signal of the Narampady soil profile is contributed mainly by the pedogenic component.
Fig. 3.36 Magnetic susceptibility and particle size analysis data for selected samples from Narampady soil profile.
The SEM image and EDS spectra of magnetic extract of soil sample from the top of the profile (0 - 1 cm depth) is displayed in Fig. 3.38. The roughly octahedral shape in the SEM image suggests the presence of magnetite/maghemite.
Fig. 3.38 Scanning electron micrograph (SEM) and energy dispersive spectrum (EDS) of the magnetic extract from 0-1 cm depth in the Narampady soil profile.
3.3.3 Soil profile developed on ferruginous sandstone (Ramanchira - APP8)

This profile may be divided into two zones based on magnetic properties (Fig. 3.39). Zone 1 extends from 0 to 58.5 cm depth. The concentration-dependent magnetic parameters exhibit relatively high values. The average values in the zone are: $\chi_{lf} = 1575.2 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, $\chi_{fd\%} = 12 \%$, $\chi_{fd} = 189.2 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, $\chi_{\text{ARM}} = 9.4 \times 10^{-5} \text{ m}^3 \text{ kg}^{-1}$, $\text{IRM}_{20\text{mT}} = 4177.4 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$ and $\text{SIRM} = 8702.9 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$. Values of the inter-parametric ratios, $\chi_{\text{ARM}}/\chi_{lf}$ and $\chi_{\text{ARM}}/\text{SIRM}$, exhibit a slight decreasing trend towards the surface. The average $S$-ratio is 0.98, indicating the predominance of magnetically "soft" minerals. The average HIRM value is $161.7 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$.

Zone 2 extends from 58.5 to 142.5 cm depth. The concentration-dependent magnetic parameter values exhibit relatively low values compared to Zone 1 with an upward increasing trend. The average values for magnetic parameters in the zone are: $\chi_{lf} = 1448.44 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, $\chi_{fd\%} = 12.3 \%$, $\chi_{fd} = 177.6 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, $\chi_{\text{ARM}} = 8.5 \times 10^{-5} \text{ m}^3 \text{ kg}^{-1}$, $\text{IRM}_{20\text{mT}} = 3429.6 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$ and $\text{SIRM} = 6711.7 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$. There is not much variation in the average $S$-ratio values between the two zones; so is the pattern of variation in the magnetic grain size (Fig. 3.31). However, there is a decrease in the average HIRM value ($205.8 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$). This may indicate that there is a decrease in the concentration of magnetically “hard” minerals in Zone 2. IRM acquisition curves (Fig. 3.32) show that most samples get saturated at a field of $\sim 300 \text{ mT}$, suggesting a magnetically "soft" mineralogy.

The SEM image and EDS spectrum of the magnetic extract of the 0-1cm depth soil sample are displayed in Fig. 3.40. The roughly octahedral shape in SEM image and the Fe peak in the EDS spectrum confirm the presence of magnetite/maghemite.
Fig. 3.39 The Ramanchira soil profile (developed on ferruginous sandstone) and its rock magnetic parameters and inter-parametric ratios. Note: The profile may be divided into two zones based on the variations in magnetic parameters. In the upper Zone 1, the concentration-dependent parameter values are high and exhibit a decreasing trend, whereas in Zone 2, they exhibit low values and an upward increasing trend.
Fig. 3.40 Scanning electron micrograph and Energy dispersive spectrum (EDS) of the magnetic extract from the 0-1cm depth soil sample from Ramanchira profile.
3.3.4 Soil profiles developed on charnockite

In order to facilitate a comparative study of the rock magnetic properties of soil profiles developed on charnockite with those developed on other rock types viz. hornblende-biotite gneiss, quartzo-feldspathic gneiss and ferruginous sandstone, two representative soil profiles, one from Devalokam (APP 10) and the other from Mundott (APP 14) are selected. They show a range in the values of rock magnetic parameters. The magnetic properties of the two soil profiles are already discussed in section 3.1.6 and 3.1.8. These profiles are selected as representative ones, because they are located on topography almost similar to that of the other three profiles selected for comparison.

3.4 Variation of magnetic parameters in relation to parent rock

A comparison of the $\chi_{lf}$, $\chi_{fd}$%, $\chi_{fd}$, S-ratio and $\chi_{ARM}/SIRM$ values for the soil profiles is displayed in Fig. 3.41. The charnockite-hosted profile APP10 developed on a gentle slope was selected as representative, as APP14 is on a moderate slope, hence displaying relatively low values. From Fig. 3.41 it is evident that the magnetic mineral concentration is the lowest in the profile developed on hornblende-biotite gneiss; it increases from profiles hosted by quartzo-feldspathic gneiss to charnockite, with the highest in the ferruginous sandstone-hosted profile. The general trends of the profiles too are similar, with low values at the profile-bottom, gradually increasing up to a certain depth and either a decrease or steady values thereafter towards the profile-top. However, the profile developed on quartzo-feldspathic gneiss exhibits a sharp reduction in the values at the profile-top compared to other profiles. This may probably be attributed to the moderate slope in the area compared to the gentle slope in other profiles. Soils developed on ferruginous sandstone expectedly show the highest values because of their high iron content. Hence, parent rock is the dominant factor which determines the magnitude of the magnetic parameters in lateritic soil profiles.
Fig. 3.41 A comparison of the down-profile variations in (a) $\chi_{lf}^{(10^{-8} m^3 kg^{-1})}$, (b) $\chi_{fd}^{\%}$, (c) $\chi_{fd}$ (d) S-ratio and (e) $\chi_{ARM}/SIRM$ values for soil profiles developed on different parent rock types.

During the weathering of rocks, iron-bearing minerals are released and chemically altered, releasing Fe$^{2+}$ ions, which are subsequently converted to pedogenic magnetite (Shenggao, 2000). The magnetic grains at the top of the profile are not derived from the parent material, but produced during pedogenesis during alternate wetting/drying cycles. The ferrimagnets at the top of the profile come mainly from the formation of newly formed pedogenic SP and SSD grains, whereas those at the bottom are primary and are inherited from parent rocks (Shenggao, 2000). The difference in the
\( \chi_{lf} \) values (especially at the bottom of the profiles) between different rock types may be due to differences in the contribution of primary magnetic minerals from parent rocks. The exceptionally high \( \chi_{lf} \) values exhibited by the profile developed on ferruginous sandstone may be due to a large amount of inherited magnetite/titanomagnetite. In profiles hosted by other rock types the contribution is progressively less and minimal in the profile developed on hornblende-biotite gneiss. Charnockites display high \( \chi_{lf} \) values and soils developed on them also exhibit comparatively high susceptibility values. Gneisses, on the other hand, display relatively low \( \chi_{lf} \) values, and accordingly, soils developed on them exhibit low values. Although both hornblende-biotite gneiss and quartzo-feldspathic gneiss exhibit similar magnetic susceptibility values, soils developed on hornblende-biotite gneiss exhibit lower \( \chi_{lf} \) values compared to those developed on quartzo-feldspathic gneiss. This indicates that soils developed on quartzo-feldspathic gneiss have undergone a higher degree of pedogenesis. This may be due to variations in the local Eh-pH conditions or organic matter content.

Laterite itself is produced as a result of intense chemical weathering of parent rocks under a humid, tropical climate, resulting in the enrichment of iron and aluminium hydroxides (Banerjee, 1998; Mitchell and Soga, 2005). Thus, iron-bearing minerals in lateritic soils are originally derived from ferruginous laterite (which, in turn, is derived from the weathering of parent rocks like gneiss, charnockites, sandstones); they subsequently get transformed into superparamagnetic magnetite during pedogenesis. The relative concentrations of magnetic minerals in ferruginous laterites may be different, depending on the type of parent rocks.

The continuous pedogenic development of a soil profile in homogenous parent rock type results in enhancement of magnetic susceptibility values and a gradual shift from MD to SSD and SP grain size. Hence, one would expect at the bottom of the
profile, a higher proportion of coarser lithogenic grains. Although the absolute concentration of SP grains is low at the profile-bottom (which results in low $\chi_{fd}$ values), the proportion of SP grains is high at the bottom (indicated by high $\chi_{fd}$ % and $\chi_{ARM}/SIRM$ values) which decreases towards the profile-top. This may be due to leaching and illuviation of fine grained magnetic minerals during the rainy season. The absolute concentration of SP grains increases towards profile-top. The overall $\chi_{fd}$ % is high (> 6 %) which indicates the presence of SSD/SP grains (Fine et al., 1993) but it is > 10 % in soil profiles developed on quartzo-feldspathic gneiss, charnockite and ferruginous sandstone. This indicates the deeply weathered nature of the lateritic soil profiles. The soils developed on ferruginous sandstones, though possessing a high content of lithogenic magnetic minerals, also attain a high content of SP grains due to pedogenic processes. This is due to the fact that initial Fe concentration is one of the significant factors which determine the pedogenic magnetite content in soils (Taylor et al., 1987). It is evident from the $\chi_{fd}$ % and $\chi_{ARM}/SIRM$ values that the degree of pedogenesis follows the order charnockite > ferruginous sandstone > hornblende-biotite gneiss > quartzo-feldspathic gneiss. The initial lithogenic contribution of magnetic minerals from parent rock follows the order: ferruginous sandstone > charnockite > quartzo-feldspathic gneiss > hornblende-biotite gneiss. This indicates that the initial Fe concentration is not the sole factor which determines the degree of pedogenesis. The local hydrology may play a significant part as well in soil-forming processes.

The magnetic mineralogy (Fig. 3.41) also exhibits significant variations among the profiles. The soil profile developed on ferruginous sandstone shows a high proportion of magnetically "soft" minerals like magnetite/maghemite, whereas the profile developed on quartzo-feldspathic gneiss shows a high proportion of hematite/goethite. The
decrease of magnetically "soft" minerals is in the order: ferruginous sandstone > charnockite > hornblende-biotite gneiss > quartzo-feldspathic gneiss.

The soil profiles developed on different rock types do not display the characteristic $\chi_\ell$ enhancement at the top that is seen in temperate soils (Maher, 1986; Singer and Fine, 1989). Instead, the highest $\chi_\ell$ values are generally documented at depths of 8.5-58.5 cm. This may be due either to iron reduction and/or transformation of magnetite to other magnetic minerals like ferrihydrites due to excessively high rainfall in the region or illuviation of fine grained magnetite, reducing the surface soil magnetic susceptibility.

3.5 Comparison of soil magnetic properties of pre- and post-monsoon samples

As rainfall and temperature are nearly similar in all the soil profiles investigated, the influence of climate on soil magnetic properties cannot be investigated. However, the variation in soil magnetic properties of Aribail (APP1) and Miyapadavu (APP2) soil profiles during pre- and post-monsoon periods are studied.

3.5.1 Aribail (APP1 and APP4)

A comparison of the pre-monsoon (APP1) and post-monsoon (APP4) data is displayed in Fig. 3.42. Table 3.2 gives the average values of magnetic parameters for pre- and post-monsoon samples in Zone 1, 2 and 3. It reveals that the values of pH increase in the post-monsoon samples in all the three zones as soils tend to get neutralized. However, EC values decrease in the post-monsoon samples of all the three zones. This may be due to the leaching of dissolved ions during the high-rainfall conditions.
Fig. 3.42 A comparison of rock magnetic parameters and inter-parametric ratios of pre- and post-monsoon samples of Aribail profile. Note: The solid lines in black represent the pre-monsoon data and the broken lines in red, the post-monsoon data. The trends of the two datasets are nearly similar, although there is a slight variation in the magnitude of some rock magnetic parameters.
Table 3.2 A comparison of the average values for magnetic parameters for pre- and post-monsoon samples from different zones in the Aribai soil profile. (* = $10^{-8}$ m$^3$ kg$^{-1}$; ** = $10^{-5}$ Am$^2$ kg$^{-1}$; # = $10^{-5}$ m A$^{-1}$; + = $10^3$ Am$^{-1}$; ^ = $\mu$S/cm).

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Relative to pre-monsoon samples, the post-monsoon samples of Zone 1 and 2 exhibit high values of $\chi_{fd}\%$ and S-ratio but low values of HIRM, suggesting a high proportion of ferrimagnets. The concentration-dependent parameters $\chi_{lf}$, $\chi_{ld}$ and SIRM of Zone 1 and 2 exhibit a decrease in values. The inter-parametric ratios, $\chi_{ARM}/SIRM$ and $\chi_{ARM}/\chi_{lf}$, increase in values.

However, the post-monsoon samples of Zone 3 exhibit low values of $\chi_{fd}\%$ and S-ratio but high values of HIRM, suggesting a low concentration of soft magnetic minerals. The concentration-dependent parameters $\chi_{lf}$, $\chi_{ld}$ and SIRM of Zone 3 exhibit an increase in values. The inter-parametric ratios, $\chi_{ARM}/SIRM$ and $\chi_{ARM}/\chi_{lf}$, decrease in values. The post-monsoon samples of Zone 1 exhibit slight decrease in clay content and those of Zone 3 increase in clay content, associated with a decrease in sand content.

There is a slight decrease in magnetic mineral concentration of post-monsoon samples in Zone 1 and Zone 2. However there is an increase in SP grains. The magnetic grain size becomes finer in these two zones. The post-monsoon samples of zone 3 are characterised by an increase in magnetic mineral concentration, decrease in SP grains, and decrease in the magnetic grain size. Magnetically "hard" minerals are also relatively high in the post-monsoon samples of Zone 3. This may be due to active illuviation during the rainfall periods. There is a slightly increased production of finer, magnetically "soft" minerals in the top layers of the soil profile during monsoon season.

These interpretations are substantiated by the CBD data. Most of the samples treated with CBD display a remarkable part of the decrease in the values of magnetic parameters after the first step itself when compared to the pre-monsoon samples (Fig. 3.43); in the subsequent steps there is hardly any reduction in the $\chi_{lf}$ and $\chi_{ld}$ values. The down-profile variations of pre-CBD $\chi_{lf}$, post-CBD $\chi_{lf}$ and pedogenic $\chi_{lf}$ are displayed in Fig.
Pedogenic $\chi_{lf}$ values also exhibit an increase in the post-monsoon samples (Table 3.2; Fig. 3.44). This indicates that the pedogenic magnetic component increased during the monsoon season. This increase is the highest in Zone 1. Like $\chi_{lf}$, $\chi_{fd}$ values too exhibit a significant reduction after the first step itself; after the third step the values decrease by 100% in all the samples. These data corroborate the interpretation made regarding the pedogenic magnetite content.

**Fig. 3.43** CBD extraction data for the post-monsoon samples from the Aribail soil profile. (a) Magnetic susceptibility ($\chi_{lf}$); and (b) Frequency-dependent susceptibility ($\chi_{fd}$). Data for each sample are represented as four bars corresponding to the $\chi_{lf}$ or $\chi_{fd}$ measured before and after the 1st, 2nd, and 3rd steps of CBD treatment. The numbers above each bar indicates percentage reductions after the third step.
Fig. 3.44: CBD extraction data for selected post monsoon soil samples from the Aribail profile. (a) $\chi_{lf}$ and (b) $\chi_{fd}$. The grey area indicates pedogenic $\chi_{lf}$ and pedogenic $\chi_{fd}$ respectively.

Pedogenic $\chi_{lf}$ exhibits a low correlation coefficient of 0.25 with $\chi_{lf}$ as against a value of 0.12 in pre-monsoon samples. Thus, the correlation between the two parameters has increased in the post-monsoon samples. Pedogenic $\chi_{lf}$ exhibits a high correlation coefficient of 0.93 with pedogenic $\chi_{fd}$ (Fig. 3.45). Pedogenic $\chi_{ld}$ and $\chi_{fd}$ are well correlated between themselves ($r=1.00$). All these data vouch for the increase in pedogenic magnetite content during monsoon.
Fig. 3.45 Binary plots of magnetic parameters for the Aribail soil profile samples (post-monsoon). (a) $\chi_{fd}^* vs. \chi_{lf}^*$; (b) pedogenic $\chi_{ld}^* vs. \chi_{lf}^*$; (c) pedogenic $\chi_{fd}^* vs. \chi_{ld}^*$; and (d) pedogenic $\chi_{ld}^* vs. \chi_{fd}^*$ ($^* = x 10^{-8} \text{ m}^3 \text{ kg}^{-1}$).

Maher and Thompson (1995) from their studies of Chinese loess and palaeosols reported that pedogenic susceptibility is a rapidly formed soil property. Taylor et al. (1987) synthesized fine and ultra-fine grained magnetite (of SP and SD size) under pH and temperature conditions which are analogous to natural soil environment. They reported that the time taken for magnetite formation varied from 36 to 2720 minutes depending upon pH, temperature, airflow and initial Fe$^{2+}$ and Fe$^{3+}$ concentrations. However, due to excessively high rainfall seen in the region, the enhancement does not proceed to the degree seen in temperate regions probably due to iron reduction. Due to illuviation, the magnetically "soft" and "hard" minerals are brought down to the bottom zones. However, finer and softer magnetic minerals are continuously and rapidly
produced due to pedogenesis. The magnetically “hard” minerals and coarse grained, magnetically “soft” minerals are not produced at upper levels of soil during the same period. This is substantiated by particle size data (Table 3.2). There is a downward transport of clay sized particles as evident from the increase in clay percentage at the bottom. There is an increase in the clay content too in the bottom zone during the post-monsoon season (Table 3.2). This substantiates the interpretation that illuvial processes are active in the Aribail profile.

3.5.2 Miyapadavu (APP2 and APP5)

A comparison of the pre-monsoon(APP2) and post-monsoon (APP5) data of the Miyapadavu soil profile is displayed in Fig. 3.46. Table 3.3 gives the average values of the magnetic parameters for pre- and post-monsoon samples in Zone 1 and 2. It reveals that the values of pH increase in post-monsoon samples in all the three zones as soils tend to get neutralized. However, EC values decrease in the post-monsoon samples of all the three zones. This may be due to the leaching of dissolved ions during the high-rainfall conditions.

Relative to pre-monsoon samples, the post-monsoon samples of Zone 1 and 2 exhibit high values of concentration- dependent parameters $\chi_{hf}$, $\chi_{fd}$ and SIRM. $\chi_{fd}$% exhibits a slight decrease in both the zones. The inter-parametric ratios $\chi_{ARM}$/SIRM and $\chi_{ARM}/\chi_{hf}$ exhibit increase in their values in both the zones. Compared to the Aribail profile, the post-monsoon samples of upper zones in Miyapadavu profile do not exhibit decrease in magnetic mineral concentration. Both Zone 1 and 2 exhibit a general increase in magnetic mineral concentration and decrease in grain size. As general trend of the profile in both the pre-monsoon and the post-monsoon seasons is similar, it can be inferred that illuviation is not very active in the Miyapadavu profile.
Fig. 3.46. A comparison of rock magnetic parameters and inter-parametric ratios of pre- and post-monsoon samples of Miyapadavuprofile. 

Note: The solid lines in black represent the pre-monsoon data and the broken lines in red, the post-monsoon data. The trends of the two datasets are nearly similar, but there is a slight variation in the magnitude of some rock magnetic parameters.
Table 3.3: A comparison of the average values for magnetic parameters for pre- and post-monsoon samples from different zones of the Miyapadavu soil profile. (* = \(10^{-8}\) m\(^3\) kg\(^{-1}\); ** = \(10^{-5}\) Am\(^2\) kg\(^{-1}\); # = \(10^{-5}\) m A\(^{-1}\); + = \(10^{3}\) Am\(^{-1}\); ^ = \(\mu\)S/cm).

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<td>37.9</td>
<td>15.5</td>
</tr>
<tr>
<td>(\chi_{fd})%</td>
<td>9.0</td>
<td>8.5</td>
<td>-5.5</td>
<td>12.6</td>
<td>12.5</td>
<td>-0.3</td>
</tr>
<tr>
<td>(\chi_{ARM})*</td>
<td>3.6</td>
<td>4.3</td>
<td>16.8</td>
<td>1.9</td>
<td>2.5</td>
<td>28.2</td>
</tr>
<tr>
<td>IRM(_{200})*</td>
<td>2210.2</td>
<td>2524.2</td>
<td>14.2</td>
<td>627.0</td>
<td>793.4</td>
<td>26.5</td>
</tr>
<tr>
<td>IRM(_{600})*</td>
<td>4654.7</td>
<td>5062.4</td>
<td>8.8</td>
<td>1199.4</td>
<td>1448.3</td>
<td>20.8</td>
</tr>
<tr>
<td>IRM(_{1000})*</td>
<td>4733.1</td>
<td>5223.9</td>
<td>10.4</td>
<td>1224.2</td>
<td>1507.8</td>
<td>23.2</td>
</tr>
<tr>
<td>IRM(_{3000})*</td>
<td>5171.7</td>
<td>5489.5</td>
<td>6.1</td>
<td>1431.8</td>
<td>1600.5</td>
<td>11.8</td>
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<tr>
<td>IRM(_{5000})*</td>
<td>5206.5</td>
<td>5632.3</td>
<td>8.2</td>
<td>1540.6</td>
<td>1740.8</td>
<td>13.0</td>
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<tr>
<td>IRM(_{4000})*</td>
<td>5248.3</td>
<td>5734.2</td>
<td>9.3</td>
<td>1611.3</td>
<td>1808.9</td>
<td>12.3</td>
</tr>
<tr>
<td>SIRM**</td>
<td>5526.7</td>
<td>5999.2</td>
<td>8.5</td>
<td>1791.2</td>
<td>1949.4</td>
<td>8.8</td>
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<td>S-ratio</td>
<td>0.93</td>
<td>0.91</td>
<td>-2.0</td>
<td>0.78</td>
<td>0.81</td>
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<tr>
<td>HIRM**</td>
<td>355.0</td>
<td>509.7</td>
<td>43.6</td>
<td>359.4</td>
<td>348.9</td>
<td>-2.9</td>
</tr>
<tr>
<td>(\chi_{ARM}/\chi_{f})</td>
<td>5.4</td>
<td>6.0</td>
<td>11.0</td>
<td>7.3</td>
<td>8.0</td>
<td>10.1</td>
</tr>
<tr>
<td>(\chi_{ARM}/\chi_{fd})</td>
<td>60.9</td>
<td>71.0</td>
<td>16.6</td>
<td>58.2</td>
<td>64.5</td>
<td>10.8</td>
</tr>
<tr>
<td>(\chi_{ARM}/\text{SIRM}#)</td>
<td>67.3</td>
<td>71.2</td>
<td>5.8</td>
<td>111.6</td>
<td>132.9</td>
<td>19.0</td>
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<td>SIRM/(\chi_{f})</td>
<td>8.2</td>
<td>8.5</td>
<td>4.4</td>
<td>6.6</td>
<td>6.1</td>
<td>-7.4</td>
</tr>
<tr>
<td>pH</td>
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<tr>
<td>EC</td>
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<td>9.9</td>
<td>-28.9</td>
<td>19.1</td>
<td>7.9</td>
<td>-58.6</td>
</tr>
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</table>
There is an enhancement of magnetic values in the profile in general. There may be iron reduction at the top of the profile which results in a decreasing trend of magnetic mineral concentration towards the profile-top.

The study highlights the enhancement of magnetic parameters in certain zones or throughout the profile during the post-monsoon season. This may probably be accompanied by illuviation leading to variation in iron oxide concentration, magnetic grain size and mineralogy of the post-monsoon samples.

### 3.6 The effect of organic matter on the magnetic properties of lateritic soils

The organic carbon percentage in the lateritic soil profiles investigated varies from 0.4 to 8.4 % (average = 2.5 %). The down-profile variation of organic carbon in selected profiles is displayed in Fig. 3.47.

![Graph showing organic carbon variation](image)

**Fig. 3.47** Down-profile variation of % organic carbon in selected soil profiles. Note that the values generally exhibit an increase towards the profile-top.
The organic carbon percentage is low at the bottom of the profile (80-140 cm) above which it shows an increasing trend with the highest values near the surface (0-20 cm depth). In the five profiles (Aribail, Miyapadavu, Uliyathadka, Mundott and Narampady) on which organic carbon analysis was carried out, the concentration-dependent magnetic parameters (χlf, χfd and IRM’s and SIRM) also exhibit a general increase towards the profile-top. Hence, it may be inferred that an increased organic matter content enhances pedogenic processes at the profile-top, with a greater production of pedogenic magnetite. The Aribail profile samples have relatively low organic carbon content compared to the other profiles with only a slight increase towards the profile-top. The Aribail profile also exhibits low values for concentration-dependent rock magnetic parameters (Fig. 3.29). However, Miyapadavu, Uliyathadka, Mundott and Narampady soil profiles exhibit higher and almost similar range of values for the magnetic parameters.

3.7 Comparison with temperate soils

When compared with temperate soils, the tropical lateritic soil profiles do not exhibit significant magnetic enhancement. Temperate soils show an increase in susceptibility values at the profile-top (Fig. 3.48), which is attributed to a high proportion of SP grains resulting in magnetic enhancement. Instead of a steep increase in the values of magnetic parameters in the upper few centimetres of the soil profile, lateritic soil profiles display a magnetically enhanced zone at the profile-top. Even in this magnetically enhanced zone with a higher content of SP grains, the top few centimetres exhibit a decrease of values in most of the profiles studied. This may be attributed to the high rainfall (~ 3500 mm/year) characteristic of tropical regions. However, this zone of enhancement is not sharp as in temperate soils, but the magnitude of χlf values is much high when compared to those of temperate soils.
Fig. 3.48 Comparison of down-profile variations of $\chi_{lf}$ of tropical soil profiles from Aribail, Miyapadavu and Uliyathadka (this study) with those of soils from the Russian Steppe (Maher et al., 2003) and loessic soils from mid-western USA (Geiss and Zanner, 2006). Note: Tropical soil profiles do not exhibit significant magnetic enhancement but their $\chi_{lf}$ values are high when compared to temperate soils.

The $\chi_{lf}$ values of the Russian Steppe soils (Maher et al., 2002) and loessic soils of USA (Geiss and Zanner, 2006) range from around 10 to 100 x $10^{-8}$ m$^3$ kg$^{-1}$ (Fig. 3.48). But the soil profiles in this study exhibit $\chi_{lf}$ values ranging from 32 to 1141.2 x $10^{-8}$ m$^3$ kg$^{-1}$ (average = 542.9 x $10^{-8}$ m$^3$ kg$^{-1}$). The order of magnitude high values may be attributed to two factors: 1) The parent rock of lateritic soil is ferruginous laterite enriched in iron; and 2) The area receives a much higher rainfall (~ 3500 mm/year)
compared to 300-500 mm/year for the Russian Steppe and 500-1000 mm/year for the mid western USA.

The magnetic grain size, however, is remarkably similar to that of temperate soils (Fig. 3.49). The samples plot in the envelope for soils, paleosols and catchment-derived fine sediments in the bi-plot of $\chi_{\text{ARM}}/\chi_{\text{lf}}$ vs. $\chi_{\text{ARM}}/\chi_{\text{fd}}$ (Oldfield, 1994).

![Bi-plot of $\chi_{\text{ARM}}/\chi_{\text{lf}}$ vs. $\chi_{\text{ARM}}/\chi_{\text{fd}}$ (Oldfield, 1994) for lateritic soil samples from all the soil profiles studied. Note: Most of the soil samples plot in the envelope for soils, paleosols and catchment-derived fine sediments. Hence, the grain size of the lateritic soils from the region is similar to that of temperate soils.](image)

Fig. 3.49

The ferrimagnetic mineral assemblages produced as a result of fire have a significantly finer grain size than those resulting from weathering and soil formation (Oldfield and Crowther, 2007). Hence, burning gives rise to a distinctive envelope of values in this bi-plot. But the soil samples of this study do not show any signature of fire
activity. The grain size is much similar to the unburnt Cotswold Woodland soils (Oldfield and Crowther, 2007).

3.8 Pedogenic model for lateritic soils from tropical southern India

A pedogenic model for the lateritic soils developed under the high rain fall tropical climate is proposed here, based on the results obtained in this study (Fig. 3.50). Coarse grained lithogenic magnetite (MD) dominates the magnetic mineralogy of charnockite, the most extensive rock type in the study area. The concentration of lithogenic magnetite is variable both within and across lithology. Some amount of haematite may be present in hornblende-biotite gneiss. SP grains are absent in these crystalline parent rocks. During lateritisation, parent rocks (like gneisses, charnockites, sandstones) are converted into laterites with the enrichment of iron and aluminium hydroxides and leaching of silica and other constituents. Laterite is ferruginous and consists mainly of magnetically "hard" minerals like haematite and goethite. The lithogenic coarse (MD) grains are converted into fine grained (SP and SSD) during pedogenesis.
Fig. 3.50: A pedogenic model for lateritic soils developed under tropical high-rainfall conditions of southern India.
Pedogenic processes are initiated at the surface and proceed downwards. The concentration of pedogenic magnetite (SP and SSD) is high in the upper zones but low in deeper layers. Due to the excessively high rainfall in the region, magnetite in the upper layers may undergo reduction and get converted into ferrihydrites leading to a decrease in the magnetic mineral concentration in the top 10 or 20 cm of the profile. The initial Fe concentration in parent rocks may influence the magnetic properties of soils that eventually develop on them. Rocks with a high initial Fe concentration give rise to magnetically strong profiles with a high pedogenic magnetite content and *vice versa*. Illuviation may transport the SP grains along with clay particles to the bottom of the profile, resulting in a relative increase in the proportion of SP grains although their absolute concentration may be low. As only fine grains (SP but not SSD) undergo illuviation, the relative proportion of SP grains increases in the profile-bottom. This explains the very low values of S-ratio (= magnetically" hard" minerals) and increased $\chi_{sd}\%$ (= magnetically "soft" SP grains). A high degree of pedogenesis produces a higher concentration of SP grains in soil profiles especially in the profile-top. Slope or topography does not much influence the magnetic properties of soils. However, profiles situated at the base of lateritic hills may be magnetically enhanced compared to those developed on slopes or stable uplands. Similarly, a higher organic matter content at the profile-top may also enhance pedogenic processes giving rise to higher magnetic values at the profile-top.