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Rock magnetism and anisotropy of magnetic susceptibility studies on charnockites, southern India

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Abstract

Rock magnetism and anisotropy of magnetic susceptibility (AMS) results are reported for the first time from the southernmost (Nagercoil) charnockites of the Southern Granulite Terrane (SGT), south India. Forty-eight oriented block samples from nine sites have been collected and analysed. The integrated results of isothermal remanent magnetization (IRM), hysteresis loops, day plot, and thermomagnetic curves indicate the presence of magnetite with pseudo-single domain (PSD) and multidomain (MD) magnetite particles dominating the studied samples. Rock magnetic investigations reveal that the ratio of remanence (M_{rs}/M_s) range from 0.04 to 0.53 and the coercivity ratio (H_{cr}/H_c) between 1.19 and 5.17. The magnetization saturation was at 250–300 mT, and the coercive force ranged from 24 to 41 mT in all the samples. The results of the thermomagnetic study reveal the Curie temperatures between 560 °C and 580 °C, indicating the presence of magnetite. The observed principal AMS axes show mainly two types of magnetic fabrics. The first one shows the maximum susceptibility axes (K1) horizontal to sub-horizontal, and the minimum susceptibility axes (K3) plot near the pole. The second fabric describes that the minimum susceptibility axes (K3) show intermediate to vertical and the maximum susceptibility axes (K1) plot near the horizontal to sub-horizontal. AMS studies reveal that Nagercoil charnockites formed during the late-stage metamorphic event, magma flow (magnetic grains aligned) was sub-horizontal to horizontal, and the magnetic fabric grains are from prolate to oblate in shape.

Keywords Rock magnetism · AMS · Paleoproterozoic · Charnockites · Southern Granulite Terrane

Introduction

The South Indian shield has robust igneous and metamorphic geological features to understand the dynamics of the Earth's Precambrian tectonic history, and it is regarded as a crustal unit comprised essentially of Archaean continental nuclei and Proterozoic mobile belts, which are represented by the granite-greenstone terrain of Karnataka and the high-grade terrain further south (Naqvi and Rogers 1987). Fermor (1936) divided charnockitic (granulitic) and non-charnockitic (gneiss-schist) terrains in the shield. It is also recognized that a narrow transition zone exists along which low-grade gneiss granite-greenstone rocks transform into higher grade granulite facies rocks (Pichamuthu 1965; Radhakrishna and

Naqvi 1986; Naqvi and Rogers 1987; Radhakrishna et al. 1990; Poornachandra Rao and Mallikarjuna Rao., 2006, Plavsa et al. 2012; 2014; Plavsa et al. 2015, Vijay Kumar et al. 2017). The regional metamorphic grade changes gradually from greenschist and granulite facies in the north to charnockite terrains in the south.

The Southern Granulite Terrain (SGT) consists of Proterozoic mobile belts and faults/shear zones. The early Proterozoic mobile belts produced low-grade and high-grade metamorphic terrains in the north and south, respectively (Poornachandra Rao and Mallikarjuna Rao, 2006). Previously, many studies put constraints on the structure, tectonics, paleomagnetic, anisotropy of magnetic susceptibility (AMS), mineralogical, petrological, and geochemical signatures of the SGT (Bhimasankaram 1964; Prasad et al., 1999; Bhaskara Rao and Lakshmipathi Raju 1981; Rajesh and Santosh 2012; Plavsa et al. 2014; Piper et al. 2003; Ramesh Babu et al. 2020). Rock magnetic properties and magnetic fabrics of high-grade metamorphic rocks are important as they are often related to the metamorphic and tectonic events experienced by geological terrains (Tarling

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and Hrouda, 1993). Magnetic properties are least studied in the high-grade metamorphic rocks of several geological terrains in India (Raposo and Egydio-Silva 2001; Viegas et al. 2013). AMS analysis are excellent tool for studying deformation and tectonics related fabric development, especially in metamorphic rocks (Hrouda and Janák 1976; Parés and Pluijm 2002; Ferre et al. 2004). AMS has been used in understanding deformation and fabric patterns in high-grade metamorphic rocks (Viegas et al. 2013; Ferré et al. 2014, Ferre et al. 2004). Magnetic fabric studies are reported in some metamorphic terrain in SGT (Mondal et al. 2009).

Therefore, rock magnetism and AMS studies are very helpful in understanding tectonic-related fabric developments. Here, we carried out the rock magnetism and AMS study and presented their new results from the Nagercoil charnockites of the SGT, southern India. This study is the first attempt to report the magnetic properties and AMS results on high-grade metamorphic rocks (charnockites) from the southernmost tip of India. The objectives of the present study are the determination of detailed rock magnetism and AMS, which can help to understand the magnetic properties, principal anisotropy of magnetic susceptibility directions, and the shape of the magnetic fabric.

Regional geology and sampling

The South Indian Shield comprises intrusive mafic dykes, and extrusive plutonic and metamorphic felsic rocks, which are widespread and occur in the provinces of Kerala, Tamil Nadu, Karnataka, Telangana, and Andhra Pradesh states of India from Proterozoic to the Cretaceous period (Nagaraju et al. 2018a, b; Ramesh Babu et al. 2018; Plavsa et al. 2015; Rajesh and Santosh 2012; Srivastava 2010; Halls et al. 2007; Poornachandra Rao and Mallikarjuna Rao, 2006; Kumar et al. 2001). The SGT lies between ~8° to 13°N and ~75° to 80°E and is divided into several tectonic blocks based on structural and tectonothermal histories. These are, from north to south: 1) Salem Block; 2) Madurai Block; 3) Trivandrum Block; and 4) Nagercoil Block (Plavsa et al. 2014). The SGT consists of Early Proterozoic (2600–2000 Ma) and Middle Proterozoic (2000–1500 Ma) mobile belts and a set of prominent faults/shear zones and high-grade supra crustal rocks and charnockites (Katz 1978; Drury and Holt 1980; Drury et al. 1984; Radhakrishna and Naqvi 1986).

Based on Landsat images, Drury and Holt (1980) suggested that the Archaean granulite terrain of southern Peninsular India (Fig. 1) is dissected by major Proterozoic shear zones, viz. Palghat-Cauvery Shear Zone, Moyar-Bhavani

Fig. 1 Simplified geological map of the Southern Granulite Terrain (SGT) displaying the areal distribution of the charnockite region (modified after Vijay Kumar et al., 2017). The filled red circles represent the sample sites
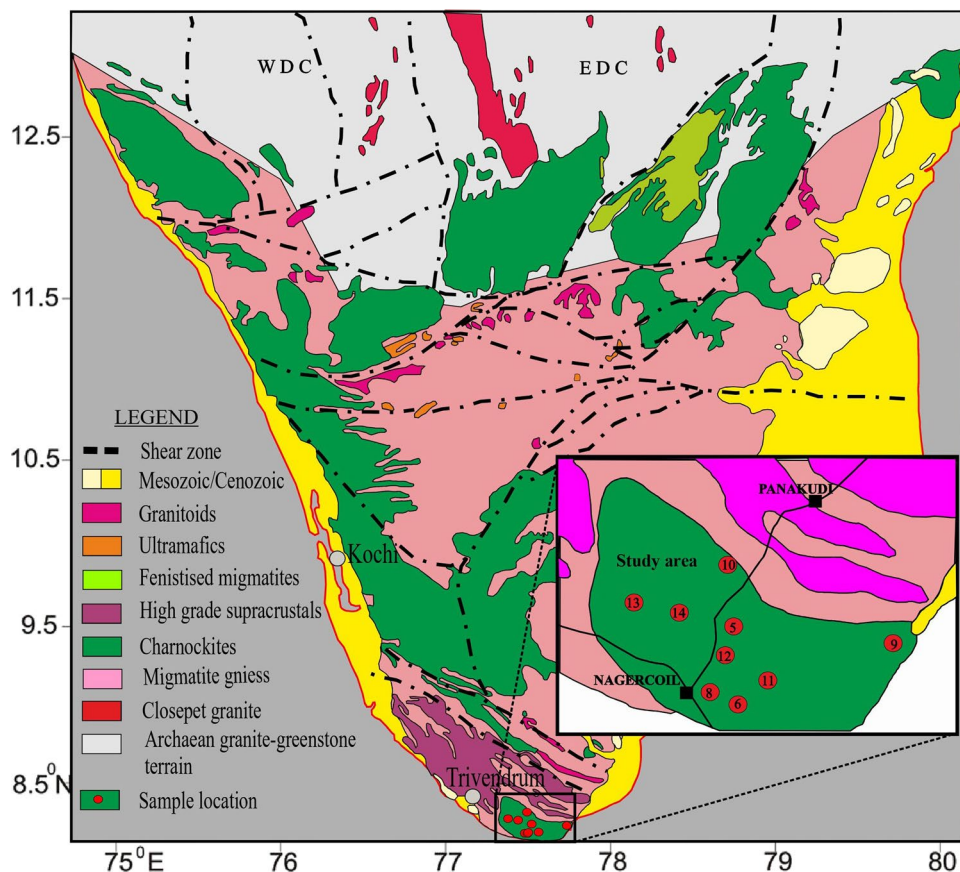
Shear Zone, Achankovil Shear Zone, and Attur Shear Zone (Bhadra, 1999). The Salem block occupies from Moyar, Bhavani, and Attur shear zone to the Palghat–Cauvery shear zone. The Madurai block covers from Palghat shear zone to Achankovil shear zone. The Kerala khondalite block or Ponmudi block and Nagercoil block occupy the north of Achankovil shear zone to the tip of the Southern Granulite Terrain (Plavsa et al. 2012; 2014). Charnockites are orthopyroxene-bearing granitoids (International Union of Geological Sciences nomenclature; Le Maitre 2002; Holland 1900; Harley 1989), including alkali feldspar, plagioclase feldspar, quartz, and magnetite (Piper et al. 2003).

Large charnockite massifs cover a substantial portion of the southern Indian granulite terrain. The older (late Archaean to early Proterozoic) charnockites occur in the northern part, and the younger (late Proterozoic) charnockites occur in the southern part of high-grade terrain. Among these, the older Biligirirangan hill, Shevaroy hill, and Nilgiri hill massifs are intermediate charnockites, with the Pallavaram massif consisting dominantly of felsic charnockites. The charnockite massifs from northern Kerala and Cardamom hill show a spatial association of intermediate and felsic charnockites, with the youngest Nagercoil massif consisting of felsic charnockites (Rajesh and Santosh 2004). A two-stage model is suggested for the formation of these charnockites. During the first stage, there was a period of basalt underplating, with the ponding of alkaline mafic magmas. Partial melting of this mafic lower crust formed the charnockitic magmas. Emplacement of hydrous basalt would result in melting at higher f_{H2O}, favoring the production of more siliceous felsic charnockites. Charnockites form a volumetrically significant lithology of the SGT, similar to many high-grade terranes elsewhere (Rajesh and Santosh 2012). Charnockites are the product of static regional metamorphic rocks at granulite facies and are formed at high temperature (T) and pressure (P). The mineral assemblages of metamorphic formation of charnockite occur at temperatures close to 800 °C and pressures of 7–9 kbars, implying depths of the order of 30–35 km (Piper et al. 2003; Raith et al. 1997; Condie et al. 1982; Weaver 1980). Petrographic studies have been done on orthogneisses of charnockites of Nagercoil Block comprising a framework of subhedral feldspars enclosed with orthopyroxene, clinopyroxene, hornblende, biotite, and quartz (Vijay Kumar et al. 2017).

A total of forty-eight oriented block samples were collected from nine sites of fresh outcrops (quarries and road cuttings) using a Brunton compass and spirit level in the field from massive charnockites at Nagercoil, Tirunelveli, and the surroundings. Before measurements in the laboratory, the samples were cut into standard cylindrical specimens (diameter 2.54 cm, height 2.2 cm) by non-magnetic tools, and the remaining parts were used for rock magnetic analysis. We have not recorded the local declination as the samples are magnetically not strong. Eighty-three specimens were obtained for anisotropy of magnetic susceptibility (AMS), isothermal remanent magnetization (IRM), and backfield studies from 48 block samples, and powder samples were also prepared for rock magnetic (hysteresis and thermomagnetic) studies.

AMS and experimental procedure

AMS is represented by an ellipsoid defined by three principal axes that lie along three orthogonal axes of the ellipsoid and are designated as maximum (K1), intermediate (K2), and minimum (K3) susceptibilities. These principal susceptibility axes are also used to determine alternative combinations of magnitude parameters such as the bulk susceptibility, $K_{mean} = (K1 + K2 + K3)/3$, the degree of magnetic lineation, $L = K1/K2$ (Balsley and Buddington, 1960), the degree of magnetic foliation $F = K2/K3$ (Stacey 1960), the degree of anisotropy $P = K1/K3$, and the shape parameter $T = ([2 \ln (K2/K3)/(\ln(K1/K3)]-1)$ (Jelinek 1981). The quality and quantity of magnetic fabric are determined by calculating the shape factor and the corrected degree of anisotropy. The P value is always greater than one and describes the sample anisotropy. The condition $0 < T < 1$ determines a planar fabric, which correspond to oblate (disk-shaped) shape, whereas $-1 < T < 0$ is valid for a linear fabric which corresponds to prolate (rod-shaped) shape. AMS measures all contributions due to dia, para, and ferromagnetic minerals averaged over a rock sample. These principal susceptibilities are combined with various ways to describe different features of the ellipsoid and the magnetic fabric it represents (Hrouda 1982). The shape of the ellipsoid and the orientation of its axes are interpreted in terms of flow direction for magmatic rocks and sediments (Hrouda 1982; Nomade et al. 2000). AMS is a physical property of rocks widely used for petrofabric studies and other related applications. AMS can also indicate the magma flow directions (Elwood, 1982; Knight et al. 1986; MacDonald and Palmer 1990).

Representative samples were selected for the rock magnetic study to identify the main magnetic carrier minerals. All the prepared standard specimens were measured for bulk susceptibility and low-field anisotropy of magnetic susceptibility using MFK1-FA Kappabridge (AGICO, Brno, Czech Republic) in a magnetic field of 200A/m and a frequency of 976 Hz. IRM and backfield measurements were done using a pulse magnetizer (Model MMPM-10, Magnetic Measurements, U.K.). Hysteresis loop and thermomagnetic (k-T) investigations were carried out using powder samples (weighing in the range of 300–600 mg) on an advanced variable field translation balance (AVFTB). Analysis of the data was done using Anisoft version 5.1.08 software. The mean normalized tensors were calculated

following the statistical procedures of Jelinek (1978). The statistic precisions were calculated with bimodal statistics (Bingham 1964). All the studies were conducted at the Paleomagnetism Laboratory of CSIR-National Geophysical Research Institute, Hyderabad, India.

Results

Rock magnetism

Thermomagnetic curves

Temperature-dependent magnetic susceptibility $(\chi - T)$ curves are commonly used to determine the magnetic minerals in samples using variations in the magnetic susceptibility during thermal treatment (Liu et al. 2005). Figure 2 shows
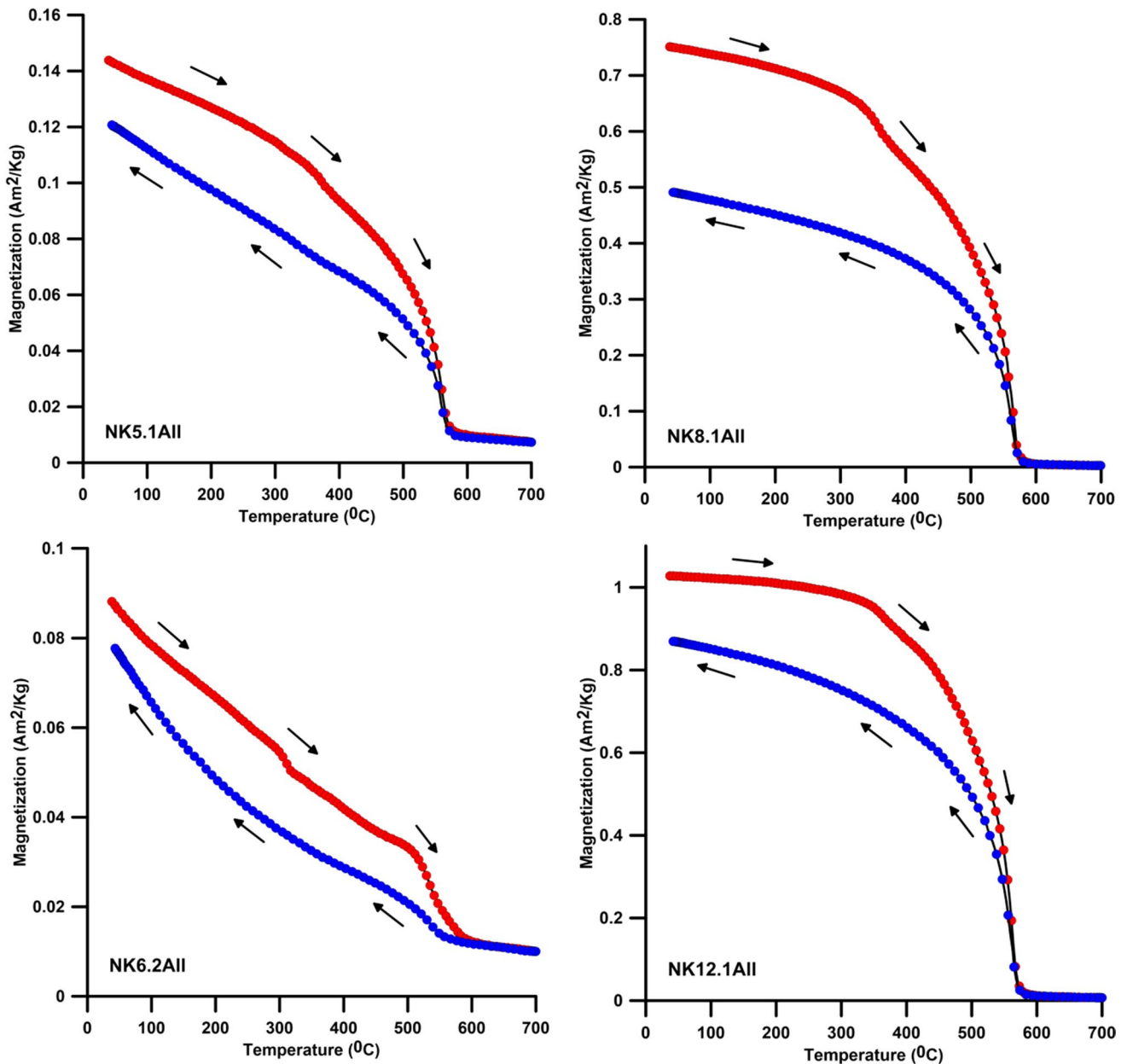

Fig. 2 Thermomagnetic curves of selected samples of Nagercoil charnockites. The red (blue) lines indicate the heating (cooling) cycle of the analysis

the thermomagnetic curves of the samples from Nagercoil charnockites. The measurement temperature was increased from room temperature to 700 °C. The thermomagnetic curves show Curie temperatures at 580 °C, indicating that the remanence carrier is magnetite in these samples. All the samples show a sudden drop in susceptibility at 580 °C except in a few samples where a prominent feature observed is that there were two dramatic drops in susceptibility at approximately 350 °C and 580 °C on the heating curves, indicating the presence of maghemite and magnetite in the samples, respectively. We used the first derivate technique to calculate the Curie temperature of all curves, as some curves show the transformation. The decrease in susceptibility from around 300 °C to 350 °C intervals could cause conversion from fine-grained maghemite to hematite (e.g., Deng et al. 2005; Liu et al. 2005), where few of the samples indicate this feature. The cooling curves of all samples show lesser susceptibility values than the heating curves. Thermomagnetic

curves from the charnockite belt of southern India show similar curves (Piper et al. 2003).

IRM acquisition curves

Isothermal remanent magnetization (IRM) acquisition curves are very useful for characterizing the ferromagnetic alignment in rocks, allowing the detection of the presence of phases with different coercivities. Therefore, we carried out IRM acquisition to know the main carrier material in Nagercoil charnockites, as one sample thermomagnetic curve shows transformation. The IRM and corresponding backfield curves for Nagercoil charnockites are shown in Figure 3. The IRM acquisition curves are significant in identifying the saturation magnetization of different rocks. The maximum applied magnetic field is 1 Tesla. All the samples show a fast initial rise in IRM acquisition curves with saturation at ~ 300 mT with minimal to no further IRM accumulation in higher fields. Inflections of these IRM curves show a low
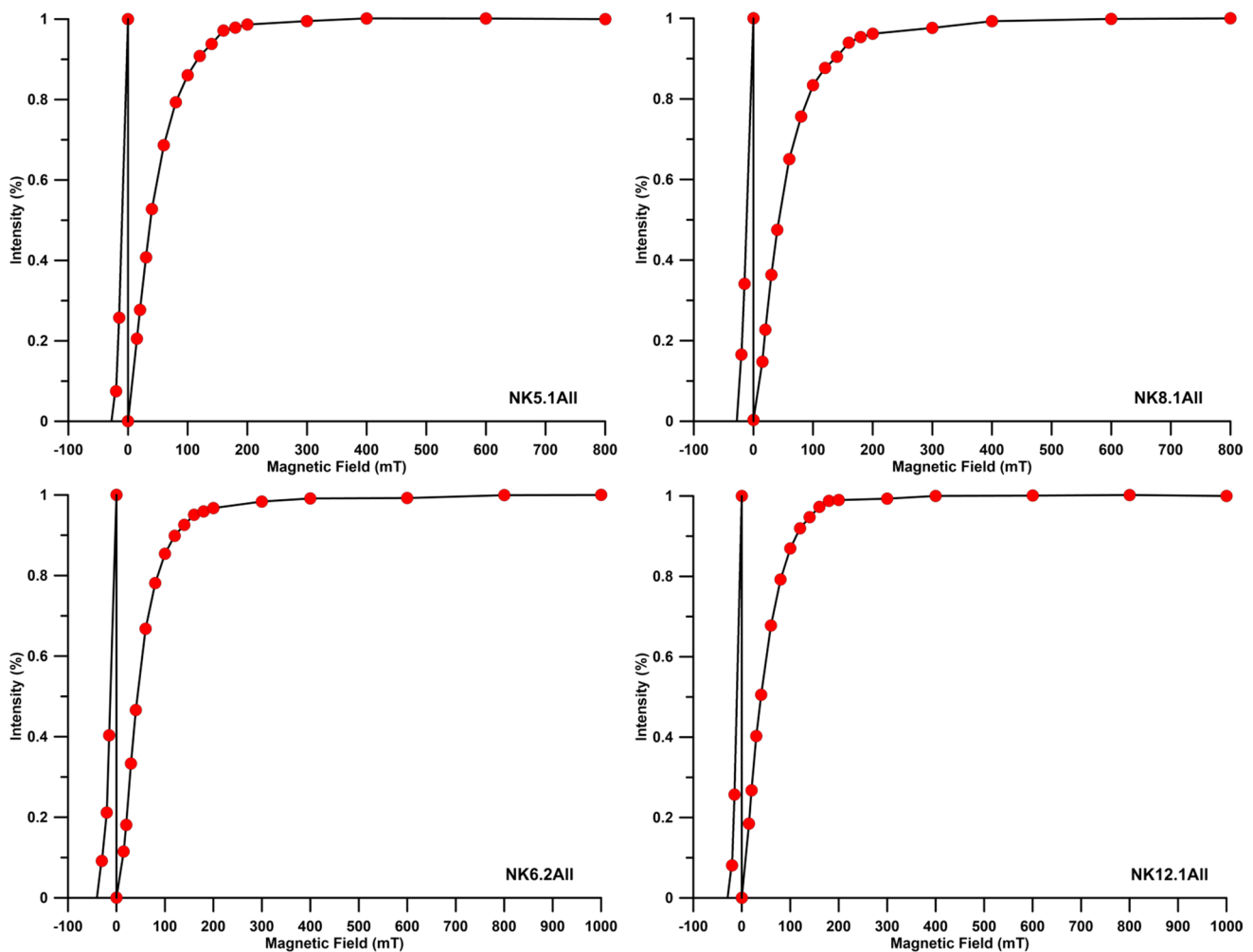
Fig. 3 Isothermal remanent magnetization (IRM) curves for representative samples from Nagercoil charnockites

coercivity, which deciphers the predominance of metamorphic magnetite. This is consistent with the thermomagnetic curves of all the samples showing temperatures 560–580 °C.

Hysteresis parameters

Most of the samples acquired a saturation at ~ 300 mT showing the presence of a low coercivity ferrimagnetic substance, i.e., magnetite. Hysteresis loops for all the sites are given in Fig. 4. Table 1 shows the hysteresis parameters derived from hysteresis loops of Nagercoil charnockite samples. M_{rs}/M_s ratios lie between 0.04 and 0.38 with an average of 0.12. The ratio of remanent coercivity and coercivity of remanence (H_{cr}/H_c) lies between 1.45 and 5.19, with an average of 3.86. Most of the studied hysteresis loops suggest the dominance of low coercive components, i.e., magnetite in the samples. Day plot (Fig. 5) drawn from the hysteresis parameters indicates the presence of single domain (SD), pseudo-single domain (PSD), and multidomain (MD) state for particles in all samples.
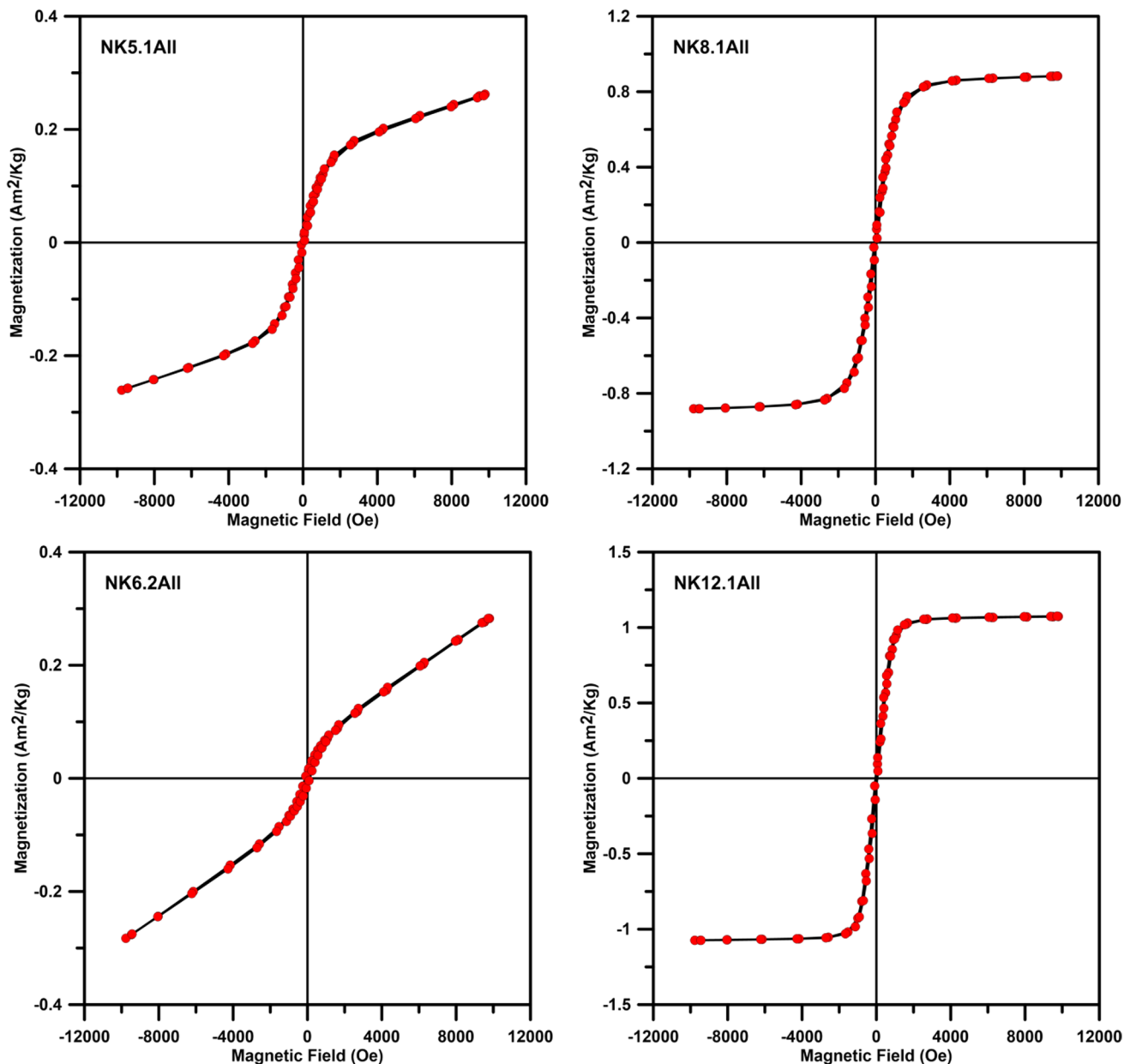

Fig. 4 Hysteresis loops of representative charnockite samples from Nagercoil charnockites, SGT

Table 1 Hysteresis parameters derived from respective hysteresis loops for Nagercoil charnockite samples

Sample ID	Mrs Am^2/Kg	Ms	Hcr mT	Hc	Mrs/Ms	Hcr/Hc
NK5.1aII	8.71	155.0	25.32	6.43	0.06	3.94
NK6.2aII	1.17	6.40	32.39	15.52	0.18	2.09
NK8.1aII	2.08	8.52	41.86	20.77	0.24	2.02
NK9.1aII	1.95	5.11	35.55	24.55	0.38	1.45
NK10.1aII	1.38	31.8	23.43	4.83	0.04	4.85
NK11.1aII	1.25	8.09	36.68	17.51	0.15	2.09
NK12.1aII	5.98	106.0	24.42	4.72	0.06	5.17
NK13.1aII	3.13	7.83	34.44	20.38	0.40	1.69
NK14.1aII	2.06	1.10	32.62	27.47	0.53	1.19
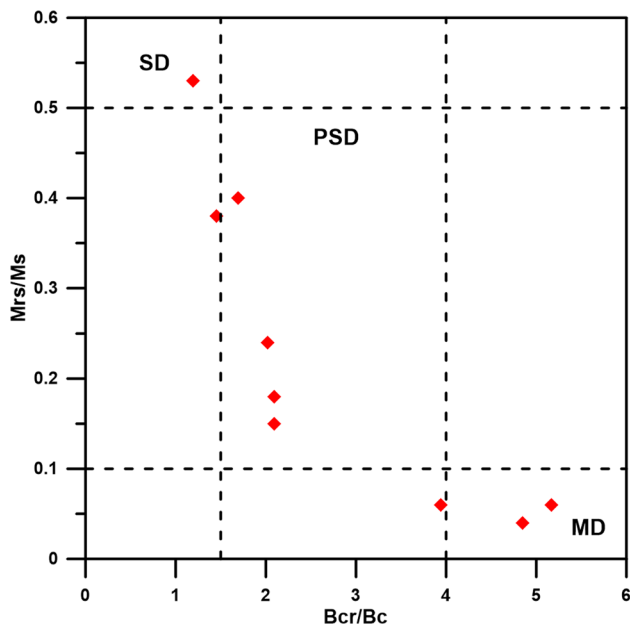
Fig. 5 Day plot (Day et al., 1977) showing the distribution of average magnetic grain size associated with different sites. M_s = saturation magnetization, M_{rs} = saturation remanent magnetization, H_c = coercivity, and H_{cr} = remanent coercive force. The plot is usually divided into regions: single domain (SD) for $M_{rs}/M_s > 0.5$ and $H_{cr}/H_c < 1.5$, multidomain (MD) for $M_{rs}/M_s < 0.05$ and $H_{cr}/H_c > 4$, and pseudo-single domain (PSD) in between

Anisotropy of magnetic susceptibility (AMS)

Bulk magnetic susceptibilities vary between 5.23×10^{-5} and 1.01×10^{-7} m^3/kg. As the rock magnetic results suggest that magnetite is the primary remanence carrier, the variation in susceptibility values is due to the differences in concentration of this mineral in the rock. The mean susceptibility (K_m) values of the Nagercoil charnockite samples ranged from 277×10^{-6} SI to $38,330 \times 10^{-6}$ SI (Table 2). AMS is represented by an ellipsoid defined by three principal axes along three orthogonal axes of the ellipsoid and is designated as maximum, intermediate, and minimum susceptibilities (K1,

K2, and K3). The magnitude of susceptibility is measured in 15 independent directions, enabling comment on the AMS ellipsoid, a standard least square fit method for the reliability of measurements (Cox and Doell 1967). Magnetic anisotropy in metamorphic and plutonic rocks is defined by ductile deformation and mimetic crystallization (Hrouda 1982). To understand AMS, the mean susceptibility (K_m), essential anisotropy factors like lineation (L), foliation (F), corrected anisotropy degree (P_j), and shape parameters (T) are to be studied. The AMS directional data were plotted in a comprehensive map together with the geological map to aid in the structural investigation (Fig. 6). The principal susceptibility axes (K1, K2, and K3) magnetic fabric data are summarized in Table 2. The K3 typically exhibits a north-to-northwest plunge and a magnetic lineation (K1) in the center (except site 10). K1 (magnetic lineation) and K2 trend to clusters in several locations, indicating the presence of triaxial ellipsoids with a clearly defined K3 (pole of the magnetic foliation). Figure 7 displays the stereonet with density plots of all sites with K1 (red), K2 (green), and K3 (blue) readings. The stereonet showing the maximum density contours of K1 and K2 is in the pole, while the density contours of K3 are situated near the center. In K1 and K2, the dense contours can be seen at north, east, and west, respectively. The mixed behavior of all individual sites of three principal axes, i.e., K1, K2, and K3 (Fig. 7), shows the lineations, and these are projected in various directions, indicating that the structure of this region was formed as a result of tectonic-related fabrics.

Discussion

Rock magnetic properties such as thermomagnetic curves, IRM, backfield demagnetization of IRM, and hysteresis loops show minor variations in Nagercoil charnockites. The Curie temperatures in thermomagnetic curves show 580 °C indicating the presence of magnetite in these samples (Fig. 2). In comparison, the rock magnetic studies of

Table 2 AMS results of the Paleoproterozoic Nagercoil charnockites, SGT, southern India

Site name	Site lat	Site long	N	K_m	F	L	Pj	T	K_{max}		K_{int}		K_{min}	
									D (°)	I (°)	D (°)	I (°)	D (°)	I (°)
NK 5	8.19	77.49	5	34,320	1.120	1.079	1.210	0.196	133	13	37	24	249	62
NK 6	8.18	77.50	5	28,040	1.016	1.040	1.059	− 0.418	64	28	163	16	279	59
NK 8	8.13	77.49	5	38,330	1.147	1.043	1.206	0.529	342	14	77	19	218	66
NK 9	8.18	77.73	5	547	1.048	1.020	1.072	0.405	284	3	14	7	170	83
NK 10	8.26	77.57	5	671	1.054	1.043	1.100	0.112	74	15	249	74	344	1
NK 11	8.13	77.52	6	277	1.031	1.005	1.039	0.739	228	3	319	1	62	87
NK 12	8.15	77.50	10	24,660	1.140	1.192	1.361	− 0.145	2	20	271	1	177	70
NK 13	8.21	77.36	5	509	1.032	1.164	1.216	− 0.655	357	15	257	34	106	52
NK 14	8.21	77.40	10	598	1.078	1.118	1.207	− 0.195	4	25	268	13	153	62

K_m bulk susceptibility (*10⁻⁶ SI units), F magnetic foliation, L magnetic lineation, P_j corrected anisotropy degree, T Jelinek shape parameter, D declination, and I inclination in degrees

*K_{max}, K_{int}, and K_{min} are the maximum, intermediate, and minimum susceptibility intensities, respectively
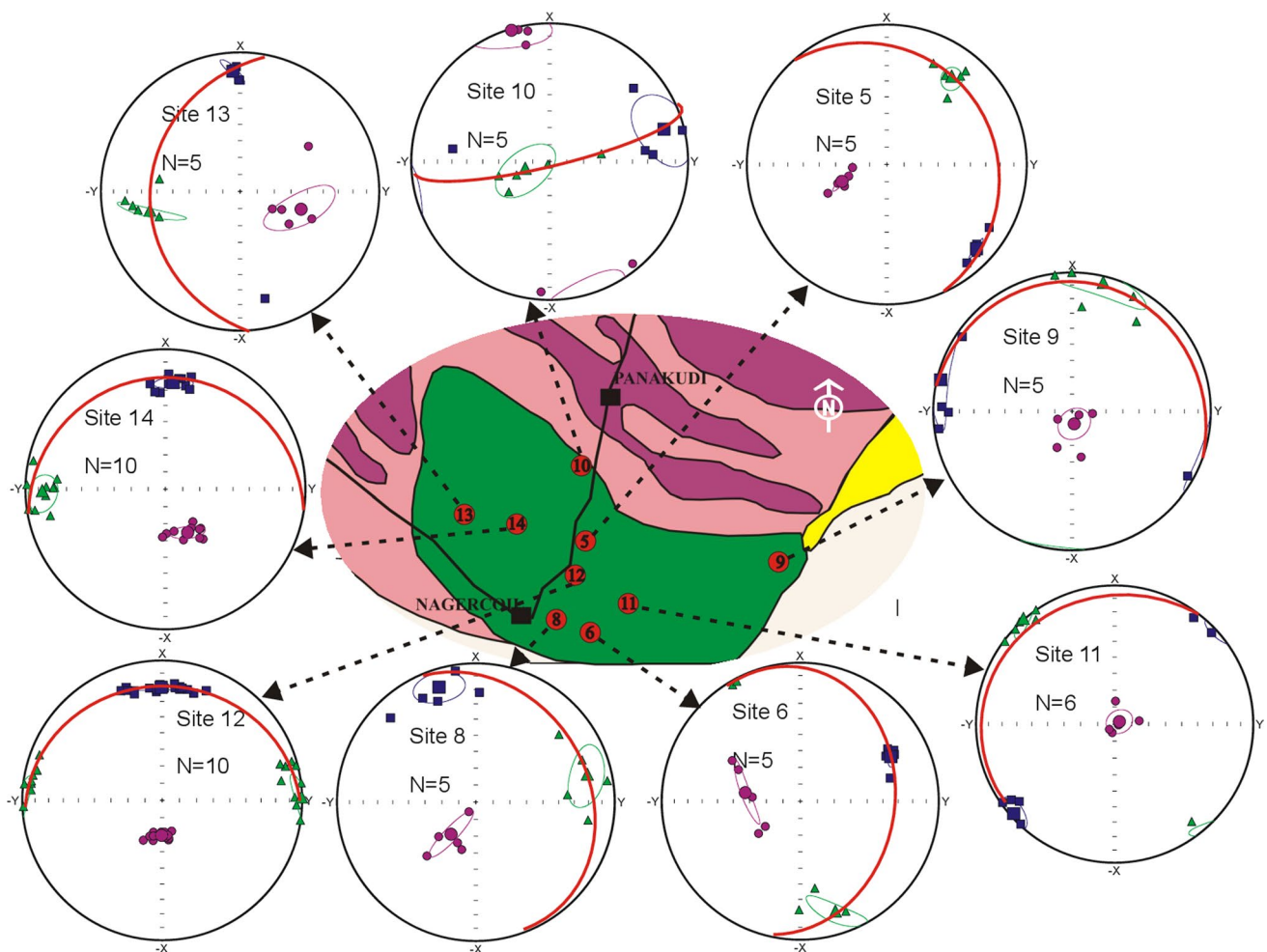
Fig. 6 Lower hemisphere projection of eigenvectors K1 (blue square), K2 (green triangle), and K3 (pink circle) for representative samples of Nagercoil charnockites

Dharmapuri charnockites (Piper et. al., 2003) show very
low-Ti metamorphic magnetite, a ubiquitous ferrimagnetic
mineral in all rock types. The heating and cooling curves are
semi-reversible and do not have a crossover.

The IRM acquisition curves of all the samples show a
significant rise with a saturation of intensity at ~300 mT
(Fig. 3). The coercivity spectra show coercivity values less
than 20 mT in all the samples analyzed, which deciphers
the predominance of low coercive magnetic minerals in the
samples and are in the pseudo-single domain (PSD) to multi-
domain (MD) except for one sample which shows a single
domain nature (Fig. 3).

Hysteresis loops are efficient and economical methods to
discriminate magnetic minerals with different coercivity in
a sample (Lowrie 1990; Deng et al. 2004). All the hysteresis
parameters, such as coercivity (H_c), saturated magnetiza-
tion (M_s), and saturated remanent magnetization (M_{rs}), were
calculated after subtracting the high-field paramagnetic con-
tribution. Remanent coercivity (H_{cr}) was acquired from the
backfield demagnetization curves (Fig. 4). A day plot drawn
from the hysteresis parameters suggests the presence of SD,
PSD, and MD states for all the samples (Fig. 5).

Nagercoil charnockite samples show shallow to inter-
mediate (less than 30°) dipping foliation toward N–S and
NE–SW (Fig. 6). All the sites show the intermediate fab-
ric with a girdle of stereonet; however, site 10 displays the
inverse fabric. The direction of minimum susceptibility (K3)
is vertical to intermediate, and the maximum susceptibility
axes (K1) plot near the horizontal to sub-horizontal. The
magnetic lineation of Nagercoil sites displays sub-horizontal
to horizontal and shows strong grouping along the north
and south direction (mean lineation/K_{max} 215/12 and 165/15,
and 186/22–Fig. 7a, b, c). The corrected anisotropy degree
(Pj) values show not much variation and range from 1.039
to 1.605 (Table 2). The shape parameter (T) is less variable
(−0.655 to 0.529) with Pj and T plot; the magnetic fabric is
dominantly prolate (Fig. 8). The anisotropy degree (P_j) vs
shape anisotropy parameter (T) diagram (Fig. 8a) indicates
that the anisotropy degree values of the samples are below
the value of 1.4. Most points are less than 1.05, indicating
relatively weak magnetic anisotropy fabrics (Tarling and
Hrouda 1993). The shape parameter of the AMS ellipsoid
(μ) is very important to know the directions and magnetic
carrier. For example, μ < 25 indicates the oblate, 25 < μ < 65
refers to triaxial, and μ > 65 shows prolate. The foliation and
lineation diagram (Fig. 8b) shows most of the points of our
AMS results situated in triaxial with principal susceptibili-
ties K_{max} > K_{int} > K_{min}. AMS fabrics in the Pallavaram region
of the Madras block show relatively weak fabrics reflecting
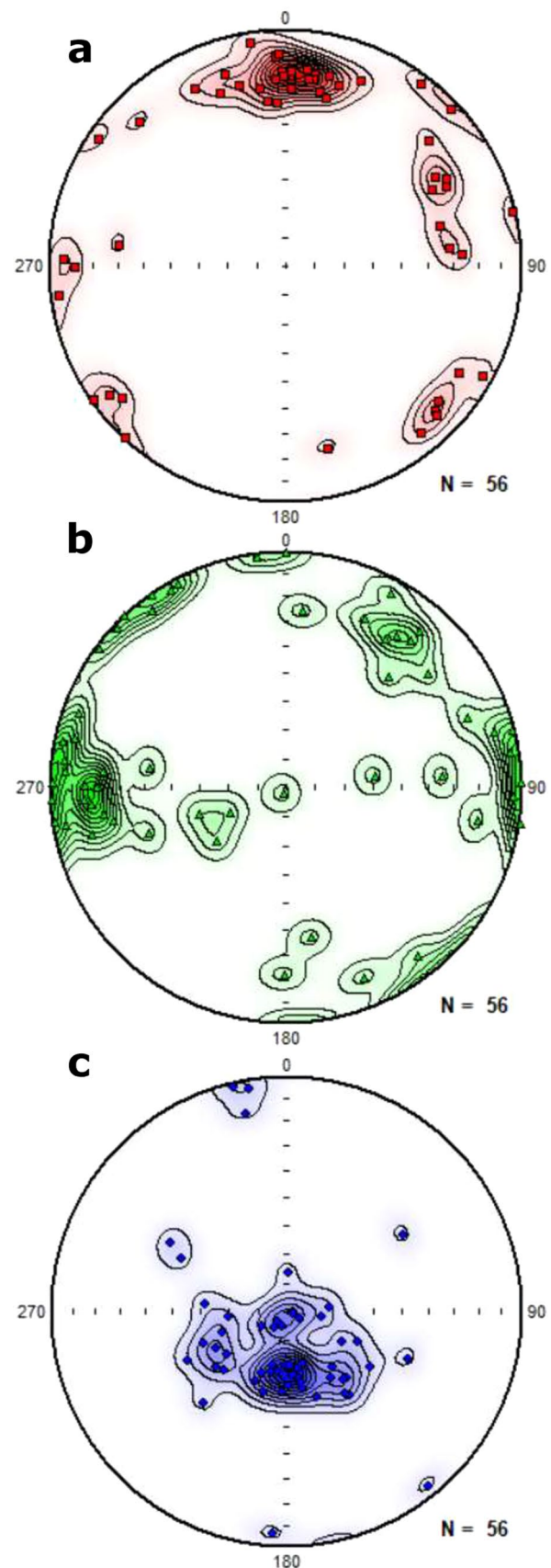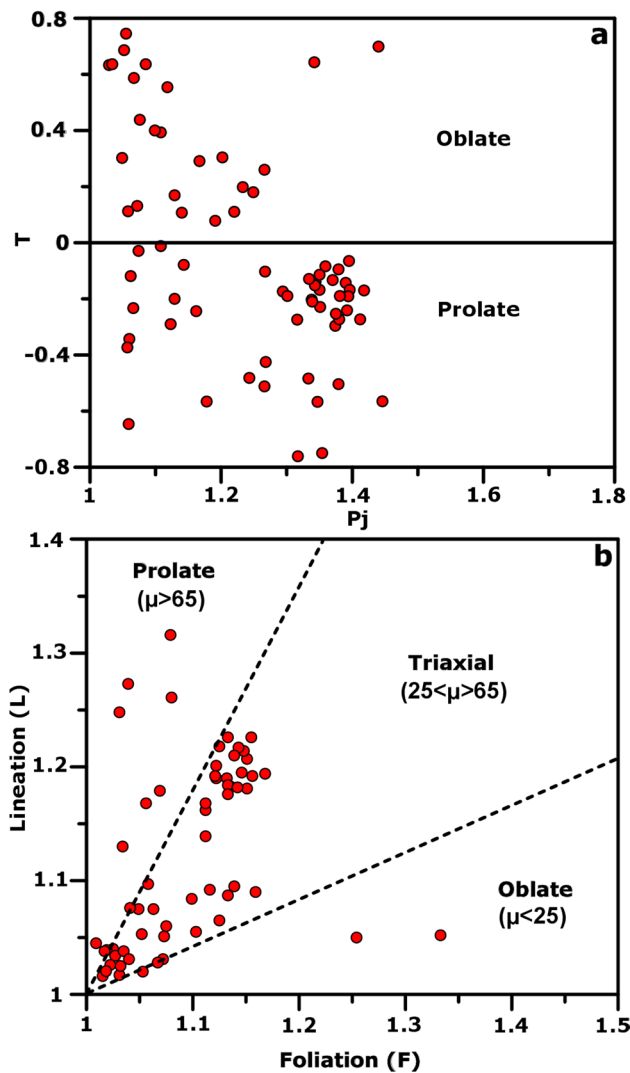
Fig. 8 (**a**) Plot of degree of magnetic anisotropy (Pj) versus shape anisotropy parameter (T) and (**b**) magnetic lineation (L) vs magnetic foliation (F) plot of all specimens for Nagercoil charnockites

the static nature of the dominant metamorphism. In contrast, in the Vandalur region, the fabric shows weak directional properties (Mondal et al., 2009). In Dharmapuri, anhydrous charnockite samples show the AMS directions essentially random and reflect the static nature of the charnockite metasomatism (Piper et al. 2003). Differences in K1 and K2 directions between sites possibly are due to differences in magma flow; however, in most sites, the AMS directions show the girdle of the stereonet with predominantly N–S directions (Fig. 7), which indicates the direction of magma flow. We assume that the reason for this girdle direction could be the compressive stresses exerted by the overlying crust. The AMS results of Nagercoil charnockite reveal that the magma flow (Magnetic grains aligned) was sub-horizontal to horizontal, and the magnetic fabric grains are from prolate to oblate in shape (Fig. 8).

Conclusions

The investigations of rock magnetism and anisotropy of magnetic susceptibility on Nagercoil charnockites resulted in the following:

(1) Rock magnetic study reveals magnetite (Fe_3O_4) as the primary magnetic remanence carrier in Nagercoil charnockite samples. Most of the sample's IRM curves show saturation at ~300 mT, and the coercive force ranges from 24 to 41 mT, establishing the presence of a low coercivity ferrimagnetic substance, i.e., magnetite. The hysteresis ratio of remanence (M_{rs}/M_s) ranges from 0.04 to 0.53, and the coercivity ratio (H_{cr}/H_c) is between 1.19 and 5.17, indicating SD, PSD, and MD state in day plot. The thermomagnetic curves show the Curie temperature at 580 °C, indicating that the remanence carrier is magnetite in these samples.

(2) The AMS results define the magma flow from subhorizontal to horizontal, and the deformed crystalline charnockite rocks show the flow direction in N–S lineation. Nagercoil charnockite sites show shallow to intermediate (less than 30°) dipping foliation toward N–S and NE–SW.

An extensive sampling with a more significant extent of study is needed to strengthen this inference further.

Declarations

Conflict of interest The authors declare no conflict of interest.

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