Magneto-Mineralogy Characterization and Analysis of Magnetic Fabrics of the High Grade Rocks from Chilka Lake Area, Eastern Ghats Belt, India

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Abstract

The present study is an integrated approach consisting of field observations, petrography, rock magnetism and Anisotropy of Magnetic Susceptibility (AMS) measurements which are used to determine the magneto-mineralogical characteristics and the nature of the magnetic fabrics of the high grade rocks from the Chilka Lake Area, Eastern Ghats Belts, India. Petrographic study reveals the textural relationship of the magnetic minerals with that of the silicates. The study of the thin-polished sections under reflected light microscope depicted the presence of magnetite, titanomagnetite and ilmenite as the dominant magnetic minerals. More than one generation of these minerals was found in these sections corresponding to different conditions of temperature that prevailed during their oxidation. The different generations of the magnetic minerals have significant tectonic results and points towards crustal upliftment. IRM and hysteresis curves were obtained which show the presence of both the ferromagnetic and paramagnetic minerals. Further, the determination of the Curie temperature confirmed the presence of magnetite and haematite. However, haematite was not observed in the petrographic/ore-petrographic studies. AMS studies unravelled the overall nature of the magnetic fabrics in the region. The susceptibility ellipsoids were dominantly oblate in the region as evident from the F-L and the P_j - T_j plots. The magnetic foliation plane has a highly variable strike varying from NE-SW to NW-SE with a moderate amount of dip. The magnetic lineation, *i.e.* the maximum susceptibility axes (K_1) showed clusters in the NE, SW and the NW quadrants having close accordance with that of the F_3 and F_4 fold axes pointing towards the structural controls of the magnetic fabrics.

Keywords: Eastern Ghats Belt (EGB), Anorthosite massifs, Fe-Ti-Oxide, Anisotropy of Magnetic Susceptibility (AMS).

Introduction

The northern and the north-eastern parts of the Eastern Ghats Belt (EGB) in India contains exposure of a number of a multiply-deformed, poly-metamorphic high grade rocks of the Grenvillian age (1.1-0.95 Ga) as stated by Bhattacharya *et al.*, 1998; Krause *et al.*, 2001 and Dobmeier and Raith, 2003. These rocks are further intruded by some anorthositic massifs mainly the Balugaon and Ramnha Anorthosite massifs (Fig. 1). The exposures of all these rocks in the Chilka-Balugaon-Ramnha region, Odisha are excellent for the concerns of the present study. They occur exclusively in high grade terrain, north of the Palaeozoic Godavari Rift and form complexes of varying size within a poly-deformed association of ultrahigh to high grade rocks of sedimentary or magmatic precursor. The entire granulite facies rocks of the Eastern Ghats Belt of India represents an uplifted portion of the Earth's crust from a depth of about 25km and cooled in the late Archean to Proterozoic time (Fermor, 1936). These Proterozoic plutonic terrains are the ideal for study of the uplift related magnetizations on account of their slow rate of upliftment in comparison with that of the

Phanerozoic orogenic belts (Watson, 1976). Determination of various stages of magnetic minerals, corresponding to the different temperatures will help us predict the tectonic events that drive their formation. In spite of these characteristics of the rocks under present consideration, the Magneto-mineralogical characteristics and the nature of the magnetic fabrics of the rocks remained unravelled. Here in the following sections we will be discussing about the magnetic-remanence carriers, magneto-mineralogical characteristics and the nature of magnetic fabrics of the rocks. Further the nature of the Anisotropy of Magnetic Susceptibility (AMS) data was analysed to correlate magnetic fabrics with the deformational history of the region.

General Geology and Deformation History of EGB

General Geology of the EGB:

The Eastern Ghats Belt (EBG) is a linear high grade terrain which is aligned along the Eastern Coast of India for a distance of about 1600 km starting from Cuttack in Odisha to Nellore in Andhra Pradesh. The EGB has a broad trend of NE-SW encompassing an area of about 50,000 sq. km. The maximum width of the EGB is 300 km which is found in Odisha in the north and as it proceeds towards the south it tapers down to tens of kilometres near Andhra Pradesh. The trends of the structural elements within the rocks of the EGB are parallel to the NE-SW to NNE-SSW elongation of the belt (Kalia and Bhatia, 1981). Coastal plain of the North Chennai marks the Western Margin of the EGB. Irregular contact exists between the granulite facies rocks of the EGB and the amphibolite facies rocks of the Bastar Craton. The North-Eastern boundary of the EGB is marked by the Northern side of the Mahanadi rift valley which is sometimes partly referred to as the Sukinda Thrust. Disruption of the Gravity profile of the EGB occurs as it is intersected by the Godavari rift, which indicates that movement has occurred on the rift after the development of the EGB (Naqvi and Rogers, 1987). Subdivisions of the EGB are suggested differently by different workers. Ramakrishnan *et al.* (1998) proposed a fourfold classification of the EGB, namely the Western Charnokite Zone (WCZ), the Western Khondalite Zone (WKZ) the Central Migmatization Zone (CMZ) and the Eastern Khondalite Zone (EKZ). However, Dasgupta and Sengupta (1998) suggested a twofold classification of the EGB, the Southern Mobile Belt and the Northern Mobile Belt separated by the Godavari Rift.

Metamorphism and Deformational History:

Debates and uncertainty prevails regarding the metamorphism of the rocks of the EGB. According to Sen *et al.* (1995), the rocks have several stages of decompression and cooling starting from a temperature of about 1100°C and >10 K bar pressure, however, reviews of Dasgupta and Sengupta (2003) finds such an explanation was not a viable one from that particular study and also from later works. Raith *et al.* (2007) and Sengupta *et al.* (2008) provided petrological evidences of Ultra High Temperature (UHT) metamorphism near the Anorthosite Massifs but the problem was not completely revived. Earlier researchers have suggested various views on the deformational events in this region. Bhattacharya *et al.* (1993, 1994) argued for the presence of the three deformational events. On the basis of the structural mapping and remote sensing data they correlated the NE-SW trending S_1 foliation plane (developed during the D_1 deformation) with that of the overall trend of the EGB. Bhattacharya *et al.* (1994) also reported the presence of the S_0 foliation plane in terms of compositional banding. Recently, Das *et al.* (2012) presented an interesting idea regarding the metamorphism and deformation of the area. They found four phases of penetrative deformation in the area namely D_1 , D_2 , D_3 and D_4 . The corresponding metamorphic events are M_1 , M_2 , M_3 and M_4 . Their studies revealed that the M_1 - D_1 event was prior to the peak

assemblage, M₂-D₂ the peak one and the M₃-D₃ and M₄-D₄ are post peak assemblages, *i.e.*, they are the signatures of the retrograde stages of metamorphism. According to them, during the M₁-D₁ event, the primary depositional surface (S₀) was completely waived leading to the formation of the S₁ foliation, which is also lost is large scale but preserved in microscopic scale defined by the alignment of the biotite-sillimanite-plagioclase-quartz assemblage developed during the M₁-D₁ event. The S₁ foliation further acts as form surface for the later deformational events. This S₁ foliation is folded during the D₂ deformational event leading to the development of the S₂ foliation which is preserved in regional scale in all the rock units. This S₂ foliation is defined by the compositional banding of alternations of Garnet-Sillimanite-Cordierite and Quartzofeldspathic bands. Field data suggests that the overall trend of the S₂ foliation varies from E-W through NE-SW to N-S which has good accordance with the studies of Das *et al.* (2012). This is the peak metamorphic event, as suggested by Das *et al.* (2012), with a characteristic assemblage of orthopyroxene-garnet-plagioclase-cordierite. This was followed by the M₃-D₃ event, which they suggested to be post peak event (as mentioned earlier), during which the S₂ foliation was folded to develop tight to isoclinal folds with gentle plunge of fold axes (18° to 260°). The S₃ axial planar fabric that is developed during this post peak event has its attitude varying with the rock types. Das *et al.* (2012) also found that the S₂ and the S₃ are almost parallel at the limbs of F₃ folds whereas they are at high angles at the hinge zones. They found that besides these structural alterations, there were partial or complete decompositions of the peak assemblage minerals leading to the formation of the intergrowths. This was succeeded by a weak D₄ event, which led to the development of F₄ fold axis which has a plunge of 12°-53°, trending NW-SE, which was effective in causing a plunge reversal of F₃ axis (Das *et al.*, 2012). However, the D₄ deformation event failed to develop any penetrative planar structures except some spaced cleavages in the khondalites (Das *et al.*, 2012).

Age of the EGB:

Geochronological study on the Eastern Ghats Belt was initiated in mid-sixties. Since then, although considerable amount of information regarding age of rock has been gathered, most of the generated data lack proper correlation with tectono-thermal, thermal, and tectonic perturbations in the history of the belt. The geochronological data from the Eastern Ghats rocks show a wide spread (3100 – 500 Ma) in the Rb-Sr whole rock, Sm-Nd isochron, and K-Ar biotite ages. Some of the geochronological results on this belt determined by different workers are discussed here.

Lal *et al.* (1987) pointed out that several episodes of metamorphism and magmatism can be identified from the age dating. Taking cognizance of acquired data, these can be recognized as:

1. A metamorphism event at 3090 Ma from the Rb-Sr whole-rock age of a khondalite (Perraju *et al.*, 1979);
2. An event of felsic and basic magmatism at ~3000-2900 Ma from model Nd (TDM) age (Paul and Ray Barman, 1988);
3. A metamorphic event at 2600±100 Ma from Rb-Sr whole-rock age of a khondalite (Vinogradov *et al.*, 1964);
4. A metamorphic and magmatic event in late Proterozoic Rb-Sr age of 1400 Ma from anorthosite (Sarkar *et al.*, 1981); Rb-Sr age of garnetiferous gneisses between 1370

- and 1100 Ma (Perraju *et al.*, 1979); Pb-Pb whole-rock isochron age for carbonatite and alkaline rocks (Clark and Subba Rao, 1971); Rb-Sr whole-rock age of 1211 Ma for leptynite (Perraju *et al.*, 1979); Pb-Pb ages between 1700 and 1000 Ma (Grew and Manton, 1986); and
5. A metamorphic event between 600 and 450 Ma as indicated by the K-Ar biotite age (Aswathanarayana, 1964).

These above mentioned episodes show that the Eastern Ghats granulites witnessed four metamorphic events at ~3100 Ma, 2600±100 Ma, 1400-1000 Ma and 600-450 Ma and magmatic events occurred at ~3000-2900 Ma and ~1400-1200 Ma. Sarkar *et al.* (1981) correlated the D₁, D₂ and D₃ deformations with the three earlier metamorphic events. The youngest metamorphic event has been correlated with the Indian Ocean orogenic cycle (Lal *et al.* 1987).

Methodology of Study

The first step that needs to be taken to carry out AMS study is the collection of oriented core samples from suitable locations in the studied area, which extended from Rambha in the South Western part and up to Tangi in the North-Eastern part. About 25 locations were selected, from which 6-8 oriented cores were drilled out in the field itself, which has a diameter of 2.54 cm and height of 2.2 cm. Thin-polished sections were prepared from the samples collected for petrography and magneto-mineralogy study. Powdered rock samples were prepared and used for generating the rock magnetism data and obtaining the Thermo-magnetic and Hysteresis Curves for characterizing the nature of magnetic minerals present within the rocks of the studied area. The rest of the cores were used for the measurement of the Magnetic Susceptibility and related parameters. This yielded the magnitude and directions of the three principal axes of the susceptibility ellipsoid K₁, K₂ and K₃ (K₁≥K₂≥K₃). The plane passing containing the K₁ and K₂ is called the Magnetic Foliation and K₃ is the pole to that plane. The magnitudes of K₁, K₂ and K₃ are useful in determining values of various parameters such Mean Susceptibility, Magnetic Foliation, Magnetic Lineation and Degree of Anisotropy. The values of these parameters are calculated as follows:

Mean Susceptibility (K_m) = (K₁+K₂+K₃)/3 (Nagata, 1961)

Magnetic Lineation (L) = K₁/K₂ (Balsley and Buddington, 1960)

Magnetic Foliation (F) = K₂/K₃ (Stacey *et al.*, 1960)

Degree of Anisotropy (D) = K₁/K₃ (Nagata, 1961)

Eccentricity (E) = K₂²/K₁K₃ (Hrouda *et al.*, 1971a, b)

Jelinek (1981) and Hrouda (1982) proposed a set of few other parameters which are designated as Corrected anisotropy degree (P_j) of the susceptibility ellipsoid and Shape (T_j) of the ellipsoid which he calculated as follows:

$$P_j = \exp \{2[(n_1 - n_m)^2 + (n_2 - n_m)^2 + (n_3 - n_m)^2]\}^{1/2}$$

$$T_j = (2n_2 - n_1 - n_3) / (n_1 - n_3); \text{ where } n_i = \log K_i$$

Fig.1: Simplified map illustrating the geological setting and the structural features of massif type anorthosites at Chilka Lake Area. (Dobmeier and Simmat, 2001). The geology is largely based on Bhattacharya *et al.*, 1998 and Sarkar *et al.*, 1981. The blue dots indicate the points from which samples were collected.

Besides this there are few other parameters also given by Granar (1958), Graham (1960). However, their applications remained limited to the studies of the unconsolidated sediments.

These parameters are useful in determining the shapes of the susceptibility ellipsoid (Susceptibility Ellipsoid in analogous to strain ellipsoid with K_1 , K_2 and K_3 as the axes). Flinn (1962) introduced a plot, designated here as the Flinn-type plot where the Magnetic Foliation is plotted on the x-axis and the Magnetic Lineation is plotted on the y-axis. The line passing through the origin making an angle of 45° with the positive direction of the x-axis is defined as the line of plane strain. Shape of the ellipsoid here is determined by dominance of Magnetic Foliation or Magnetic Lineation in a particular set of data. Here, in the present study we will be using both Flinn type plot and P_j - T_j plot for determining the shape of the ellipsoid so that the results from both the graphs can be verified.

The Thermo-magnetic curves were obtained using Curie Balance and the Hysteresis curves were obtained using VSM (Vibrating Sample Magnetometer) at the Geomagnetism Laboratory, Department of Earth Sciences, University of Liverpool, Liverpool, UK. The Susceptibility related measurements were performed using the Bartington Susceptibility Meter (MS-2) (which works synchronously with the software AMS-BAR, which is programmed to calculate the Anisotropy and other related parameters) in the Geophysics Laboratory, Department of Geological Sciences, Jadavpur University, Kolkata, India. Isothermal Remnant Magnetization (IRM) curves were obtained by applying the magnetic field using Pulse Magnetizer and the acquired magnetism was measured by Spinner Magnetometer.

Petrography and Magneto-mineralogy

Petrography:

Transmitted Light study were performed in order to identify the rock mineralogical and textural characteristics of the rock and particularly to define the textural relationships of the silicates with that of the opaque (magnetic minerals). The dominant rock types present in the studied area are enderbite, calc-Silicate Granulite, Khondalite and Anorthosite. Brief mineralogical and textural details of these rocks are given below.

Enderbite consists of plagioclase, clinopyroxene and orthopyroxene as the major minerals in decreasing order of abundance. Beside these there are some amount of sphene (titanite), biotite and opaque minerals. Plagioclase and pyroxene grains show two dominant grain size (*i.e.* Bimodal distribution of grain size). The finer grains are present within the spaces between the coarse grains (Fig. 2a). Effect of deformation in the rock is confirmed by the presence of deformed/wedge shaped twins within the plagioclase grains (Fig. 2b). The pyroxene grains show similar bimodal distribution of grain size as plagioclase. Deformation of the rock is also depicted by the variety of the interference colours shown by clinopyroxene. Exsolution lamellae are observed within the clinopyroxene grains. They are present along the (100) plane and are Ca-poor pyroxenes (Sengupta, *et al.*, 2008) (Fig. 2c). Fractures within the pyroxene grains are invaded late stage fluid and caused the crystallization of garnet in the fractures (Sengupta *et al.*, 2008) (Fig. 2c). Some enderbites are extremely garnetiferous (~40% garnet). Garnetiferous samples are found to be present in the vicinity of the leptynite body. Biotite occurs within the intergranular spaces and is devoid of its typical lath shape (Fig. 3f). Calc-silicate granulites are characterised by the plagioclase, clinopyroxene,

wollastonite and some small amount of quartz in some places. Wollastonite grains at places are embayed by later formed calcite grains. The scapolite grains are further replaced by extremely fine grained intergrowths of Calcite+plagioclase. Kandalites of the studied area consists of Sillimanite, Garnet, Biotite, Alkali feldspar and high amount of opaque minerals. The rock shows gneissic banding with alternate garnet rich and sillimanite rich layers which is earlier suggested by Das *et al.* (2012). Myrmekitic textures are observed where the k-feldspar grains are being replaced by plagioclase and thereby forming worm like or bleb like intergrowth of quartz grains from the excess silica in k-feldspar within the plagioclase grain. Pure anorthosites are extremely rare and thus these rocks cannot be designated as *sensu stricto* Anorthosite (*i.e.* contains <95% plagioclase). Anorthosite samples contains about 60-70% of coarse grained plagioclase along with clinopyroxene and minor amount of quartz and opaque minerals. Typical protoclastic to granoblastic texture of anorthosite is being displayed in thin-section study of the samples. Clinopyroxene shows recrystallised textures. Recrystallization has occurred due to the high temperature shear deformation at >600°C temperature of metamorphism (Brodie and Rulter, 1985). Plagioclase grains here are devoid of any deformational feature and are extremely euhedral in nature. However, some pyroxene grains here are twinned (lamellar twinning). The rock can thus be designated as pyroxene bearing meta-anorthosite. The opaque minerals show more than one mode of occurrences. Within the meta-anorthosites and the enderbites they are found to be associated with the pyroxene and the plagioclase grains at their boundaries, also, replacing them in some cases (Fig. 2d). Garnetiferous enderbites has opaque minerals occurring along the garnet grain boundaries and within the grains as inclusions (Fig. 2e). Beside these, the opaque minerals are found along the cleavage planes of the biotite grains (Fig. 2f).

Magneto-mineralogy:

The magneto-mineralogical study under the reflected light microscope revealed the presence of magnetite (or titanomagnetite more specifically) and ilmenite Fe-Ti oxides. During prolonged period of metamorphism, magnetite and ilmenite has a tendency to undergo oxidation and make stable phases of all Fe-Ti oxides. Two such oxidation states are found- Low temperature and high temperature depending on the temperature conditions. In the studied sections, both low temperature (<350°C) and high temperature (>600°C) oxidation states of these minerals are encountered. Haggerty (1976) proposed a classification of the high temperature oxidation states of the Fe-Ti oxides, following which the high temperature oxidised grains in the studied sections can be classified into “C-3” (Fig. 3e) and “C-5” (Fig. 3f) stages, where “C” stands for cubic phase and the suffixes (*viz.* 1, 2, 3 etc.) are proportional to the degree of high temperature oxidation “C-3” stage is characterised by densely crowded ilmenite lamellae within the host titanomagnetite grain. Development of incipient banding (sandwich like structure) of the ilmenite and titanomagnetite bands demarcates the presence of “C-5” stage.

Johnson and Hall (1978) classified the low temperature oxidation states of the Fe-Ti oxides into five stages (Stage 1 to Stage 5) based on the nature of cracks which stands to be their characteristic feature, which they termed as “shrinkage cracks”, because these cracks develops due to cation deficiency resulting from the migration of the Fe-ions out of the titanomagnetite-spinel lattice (Prevot *et al.*, 1968; Akimoto *et al.*, 1984). Among these five stages as proposed by Johnson and Hall (1978), “Stage-3” (Fig. 3a and 3b), “Stage-4” (Fig. 3c) and “Stage-5” (Fig. 3d) are found within the studied sections with rare and doubtful

Fig. 2: **A.** Bimodal grain size distribution of pyroxene and plagioclase grains; **B.** Wedge shaped (deformation) twins in plagioclase; myrmekite texture; **C.** Exsolution lamellae of Ca-poor pyroxene in a host grain of Ca-pyroxene; **D.** Opaque minerals forming by replacing the plagioclase and pyroxene grains; **E.** Opaque minerals present as inclusions within garnet and along their grain boundaries; **F.** Opaque minerals present within the cleavages of biotite grains (XPL, 40x).

occurrences of “Stage-2”. “Stage-1” is basically un-oxidised grains without any development of cracks. Development of microscopic to sub microscopic cracks at the periphery of the grain occurs when low temperature oxidation initiates, signifying the occurrence of “Stage-2”. “Stage-3” is reached when the degree of low temperature oxidation increases and the cracks starts migrating from the periphery towards the centre of the grains with subsequent filling of the cracks by silicates. With further increase in the degree of low temperature oxidation, a network of these cracks is formed with the relict titano-magnetite within it, revealing a “droplet” like structure.

Rock Magnetism and AMS Studies

IRM, Magnetic Hysteresis and Thermo-magnetic Studies:

IRM studies were done to selected samples of the studied area to obtain saturation curve. Samples were subjected to applied Magnetic field (using Pulse Magnetizer) with gradually increasing strength up to 10000 Oe (1000mT). The acquired magnetism was measured at each step and was plotted against the applied magnetic field. Saturation of the acquired magnetic field occurred when the applied magnetic field CHL-4.06 and CHL-12.03 respectively showing ferromagnetic nature was about 500-800 Oe (Fig. 4a and 4b). For hysteresis study samples were subjected to cycled magnetic fields of strength 1000mT in a VSM. Hysteresis curves with varying properties were obtained. Some curves showed evidences of both saturation of magnetization and remnance (Fig. 5a and 5b). Some samples also generated hysteresis curves with neither saturation of magnetization nor remnance (Fig. 5c). Apart from these, interestingly, some of the samples shows both unsaturated nature and remnances (Fig. 5d). Thermomagnetic studies were carried out to study the behaviour of the saturation magnetization with temperature changes, both in heating and cooling phases, and to obtain the curie curves for the studied samples. The Curie temperatures were obtained from these curves which lies on two points (a) $\sim 680^{\circ}\text{C}$ (Fig. 6a and 6b) and (b) $\sim 580^{\circ}\text{C}$ (Fig. 6c and 6d).

AMS Studies:

AMS studies were carried out in order to determine the nature and attitude of the magnetic fabrics, for which the magnetic susceptibility and related parameters were calculated. The parameters related to AMS were obtained from the combined operation of the Bartington Susceptibility Meter (MS-2) and the AMS-BAR software. We obtained the values of Mean Susceptibility, Magnetic Lineation (L), Magnetic Foliation (F), Degree of Anisotropy and Eccentricity (E). The mean magnetic susceptibilities of the rocks range from 2.6 to 286.9 CGS units. The values of F range from 1 to 2.1 and L ranges from 1 to 1.9, with few exceptions of higher values. The value of F and L were used in determining the Flinn-plot plots (Fig. 7), with F being plotted on the horizontal axis and L on the vertical axis.

This graph clearly depicts the dominance of a particular fabric (planar or linear) over the other. The values of D do not show such significant variation across the different parts of the study area. The degree of anisotropy (P_j) lies between 1.066 and 3.111. The shape parameter (T_j) is positive in maximum of the samples with few samples showing negative values. The plot of P_j - T_j (Jelinek, 1981), also supports the fact that the shape of the susceptibility ellipsoids is oblate. The value of P_j is higher (about 1.8-2.0) at the anorthosite

Fig.3: Low temperature oxidation showing: **A.** and **B.** Infiltration of silica along fractures (Stage-3); **C.** Extensive veins of silica along cracks (Stage-4); **D.** Droplets of magnetite formed within the host silica (Stage-5). High temperature oxidation of magnetite showing: **E.** 2-3 laths of ilmenite in titanomagnetite (C-3); **F.** Thick laths of ilmenite in titanomagnetite (C-5). Secondary occurrence of the ultrafine grains of magnetite: **G.** Along grain boundary and **H.** Along cleavage. (PPL, 40x).

Fig. 4: IRM curves showing ferromagnetic nature of the sample: **A.** Sample no: CHL - 4.06and; **B.** Sample no: CHL – 12.03.

Fig. 5: A. and B. Strong hysteresis curve of samples CHL-12.03 and CHL-4.06 respectively showing ferromagnetic nature; **C:** Strong hysteresis curve of sample CHL-7.07 showing paramagnetic nature; **D:** Strong hysteresis curve of sample CHL-15.03 showing unsaturated ferromagnetic nature.

Fig. 6: A and B: Strong field thermo-magnetic curve of samples CHL -7.07 and CHL-15.03 respectively showing paramagnetic nature; **C and D:** Strong field thermo magnetic curve of samples.

massifs and their vicinity. Similar is the case for the values of F and L. The value of F is about 1.5-1.6 or even higher near and at the anorthosite massifs whereas it is about 1.2-1.3 at the other locations. Similarly, value of L is within 1.1-1.4 at and around Rambha and Balugaon massifs with lower values ranging between 0.9 and 0.1.

In the present study it is seen that the plots are mainly within the F dominated field *i.e.* the AMS ellipsoid shows oblate (or disc shaped) nature. The value of E, which is greater than 1, also corroborates the contention. The K_1 , K_2 and K_3 axes were plotted on Lower Hemisphere Circular Diagram (Fig. 9a). The minimum (K_3) susceptibility axis remained concentrated to the center where as the maximum (K_1) and intermediate (K_2) susceptibility axes showed variation. The Magnetic foliation plane (plane passing through the K_1 and K_2) strikes variably from NE-SW to NW-SE with low to moderate amount of dips. The magnetic lineation (K_1) forms girdle in the NE and SW zones (Fig. 9b). In some cases the K_1 axes are found to cluster in the NW zone of the circular diagram (Fig. 9b).

Results and Discussion

Results from Petrography and Magneto-Mineralogy:

Petrographic studies reveals that the rocks of the studied area high grade metamorphic rocks, mainly enderbite, kondalite, calc-silicate granulite. All these rocks contains varying

amount of magnetic minerals which shows a wide range of textural relationship with the silicate minerals. The ore-microscopic studies revealed the presence of both the high temperature and low temperature oxidation states of the titano-magnetite grains, along with the presence of some fine grained emulsion drop like secondary titano-magnetite grains (Fig. 3). Evidently these two markedly different states of oxidation are developed during two different combinations of pressure-temperature conditions. The high temperature oxidation states of the titano-magnetites were developed during the increasing temperature and pressure of metamorphism leading to the development of the “C-3” to “C-5” stages of the high temperature oxidation *i.e.*, these were developed during the attaining of the peak condition of metamorphism.

Fig.7: Foliation vs. lineation plots for all samples (Flinn type plot).

Das *et al.* (2012) suggested that the M_2 - D_2 stage of metamorphism was the peak condition of metamorphism, thus the primary high temperature oxidation (Fig. 3e-3f) was syn-tectonic with that of the D_2 deformation stage. The low temperature primary oxidation state (Fig. 3a-3d), which forms at a much lower temperature (300-350°C) must have developed during the post peak metamorphic conditions and thus the primary low temperature oxidised grains are post tectonic with respect to M_2 - D_2 of Das *et al.* (2012). They also suggested that the garnet decomposition has occurred during the D_3 deformation stage, and also fracturing occurred within them, which implies that the secondary magnetic minerals associated with the fractures of the garnet grains (Fig. 2e) are either syn-tectonic or post-tectonic with respect to D_3 . Secondary magnetic minerals are also associated with the cleavages of the biotite grains (Fig. 2f and 3h). However, the biotite grains are formed during the M_4 - D_4 deformation stage pointing towards the syn-tectonic occurrence of the secondary magnetic minerals within biotite with respect to D_4 .

Fig. 8: P_j vs. T_j plots for all samples (Jelinek type plot).

Table- 1: Database containing the different parameters of magnetic fabric from few selected samples in the studies area

Sl. No.	Sample No.	K_m	F	L	D	$K_1(D/I)$	$K_3(D/I)$	P_j	T_j
1	CHL1.07	32.9	1.1	1.1	1.2	80.4/8.2	329.2/68.1	1.215	0.077
2	CHL2.05	22.8	1.2	1.1	1.3	281.8/4.2	49.1/83.1	3.111	0.295
3	CHL3.04B	26.2	1.2	1.3	1.3	33.8/4.4	288.7/73.9	1.299	0.437
4	CHL4.06	17.1	1.4	1.1	1.5	234.1/12.9	88.3/74.6	1.499	0.56
5	CHL5.02	286.9	1.6	1.1	1.7	307/3.4	200.3/78.2	1.823	0.676
6	CHL6.06	163.1	1.5	1.1	1.7	314.9/0.6	48.8/80.8	1.783	0.572
7	CHL7.05	14.9	1.0	1.0	1.1	314.9/0.1	224.8/48.5	1.066	0.566
8	CHL8.04	26.6	1.3	1.0	1.4	96.2/6.2	317.6/81.7	1.409	0.843
9	CHL9.06	22.6	1.3	1.0	1.3	16.1/0.6	272.3/87.4	1.38	0.752
10	CHL10.02	127.1	2.1	1.0	2.1	118.6/10.6	6.6/63.5	2.356	0.958
11	CHL11.01	123.9	1.7	1.0	1.8	292.3/6.3	121.0/83.6	1.877	0.871
12	CHL12.04	12.7	1.5	1.0	1.6	32.2/10.1	216.4/80.0	1.66	0.818
13	CHL13.02	12.8	1.4	1.1	1.5	22.5/2.7	176.7/87	1.576	0.765
14	CHL14.04	9.1	1.2	1.1	1.3	321.5/7.4	76.9/73.2	1.343	0.298
15	CHL15.01	14.9	1.2	1.1	1.3	284.1/5.1	145.8/83.2	1.276	0.366
16	CHL16.03	150.3	1.1	1.4	1.5	67.6/1.0	310.2/87.8	1.517	0.612
17	CHL17.01	2.6	1.8	1.7	3.1	250.9/6.7	19.5/79.3	3.376	0.067
18	CHL18.04	4.0	1.2	1.1	1.3	53.7/38.4	287.3/36.9	1.331	0.336
19	CHL19.05	18.4	1.4	1.1	1.5	41.7/1.6	172.9/87.6	1.508	0.62
20	CHL20.02B	6.4	1.2	1.1	1.4	23.4/14.7	169.3/72.4	1.359	0.331
21	CHL21.04A	29.6	1.2	1.1	1.4	317.3/3.2	58.5/74.2	1.367	0.153
22	CHL22.07	36.6	1.8	1.4	2.5	289.3/7.7	156.3/78.8	2.491	0.302
23	CHL23.02	407.1	1.4	1.4	1.8	285.8/4.6	69.9/84.3	1.836	0.008
24	CHL24.01	7.8	1.1	1.1	1.2	5.9/32.9	180/57.0	1.236	0.298
25	CHL25.02	3.9	1.3	1.5	1.9	140.5/16.9	303.4/72.4	1.946	0.234

Fig. 9: A. Plots of K₁, K₂ and K₃ on lower hemisphere circular diagram; **B.** Contours showing the variation in the density of distribution of the K₁ axes. **C.** Contours showing the density of the distribution of the F₃ and F₄ fold axis.

From the Hysteresis measurement, it can be suggested that both ferromagnetic and paramagnetic minerals are present within the studied samples. The Hysteresis curves with no remnance and saturation marks the occurrence of the paramagnetic minerals (Fig. 5c) and those with evidences of both saturations and remnances are signatures of the ferromagnetic minerals (Fig. 5a and 5b). The IRM studies show that the saturation of the acquired magnetic field occurs at an applied field of 800-1000 Oe (Figs. 4a and 4b). This value of applied field is typical for the Magnetite-Ilmenite series (Lowrie, 1990). The curie curves more precisely help to identify the nature of the magnetic minerals. From the curie curves (Fig. 6), it is seen that Fig. 6c and 6d have their convexity away from the origin and have a curie point at $\sim 580^{\circ}\text{C}$ which marks the presence of the ferromagnetic magnetite. However, the curves in

Figs. 6a and 6b have their convexity towards the origin with a curie point at $\sim 680^{\circ}\text{C}$, which depicts the presence of paramagnetic haematite. However, petrography does not show any evidence of haematite in the studied sections.

Results from AMS Study:

The plot of F versus L (Flinn plot) shows that the shapes of the Susceptibility ellipsoids are dominantly oblate. The results from Jelenik plot also reveal the same. The plots of the susceptibility axes show that the maximum and the intermediate axes have girdles at the NE and SW zones. Considering field data, the dominant field foliation is the S_2 foliation (as discussed earlier) plane which is further folded leading to the development of the F_3 fold axis. The F_3 axis has trends of 18° and 260° and this inversion of trend occurs due to the D_4 deformation stage (Das *et al.*, 2012) which shows that the orientation of the maximum susceptibility axis mimics the orientation of the F_3 fold axis (Fig. 9c). Apart from these, a cluster of K_1 susceptibility occurs in the NW quadrant which is similar to that of the trend of the F_4 fold axis. Thus, the magnetic lineation is parallel to the F_3 fold axis and in some cases it is parallel to the F_4 axis. The values of P_j , F , L are higher near the anorthosite massifs and their vicinity which is due to the higher anisotropy of magnetic susceptibility prevailing in those areas and also the magnetic foliations and lineations are more intensely developed there. Hrouda and Janak (1976) suggested that during the earlier stages of deformation of rocks, the primary oblate ellipsoid changes its shape to prolate and with further increase in intensity of deformation the shape of the ellipsoid further changes to oblate. The oblate shape of the susceptibility ellipsoids in the studied area most likely depicts similar deformation history. The NE-SW and NW-SE trends of the K_1 axes are almost perpendicular to the directions of shortening during the D_3 and D_4 deformation events, which are WNW-ESE and NNE-SSW respectively as suggested by Das *et al.* (2012). This helps to reach a conclusion that the K_1 axes are parallel to the direction of maximum elongation in a particular deformation event (Rathore, 1979; Goldstein, 1980; Mondal *et al.*, 2009).

Conclusions

The above studies point towards the conclusion that the rocks of the studied area show both ferromagnetic and paramagnetic characteristics. The ferromagnetic property is contributed by the magnetite grains of both primary and secondary generations. The contributors towards the paramagnetic property are a bit dubious. Ore-petrographic study of the thin-polished sections suggests the presence of paramagnetic ilmenite but the Curie curves show the presence of paramagnetic haematite. The presence of the high temperature oxidation stages with ilmenite laths and incipient bands within titanomagnetite suggests a prolonged period of high temperature metamorphism and the presence of ultrafine grains of secondary magnetite, which occur as droplets along silicate grain boundaries as well as along the cleavage planes of silicate grains, are indicative of upliftment or exhumation. However, the evidences such as high temperature metamorphism and also the primary high temperature oxides, suggest that the rocks under study had an extremely deep-seated occurrence. For reaching their present sub-surficial level from such deep-seated conditions they must suffer a tectonic upliftment and not exhumation. Also the ultra-fine grains of the secondary magnetic minerals corroborate the contention *i.e.* if exhumation would have been the case, the secondary magnetic minerals would have been much coarser. Now, the AMS study reveals that the tectonic lineations (F_2 and F_3 fold axes) are parallel to the magnetic lineation (K_1 susceptibility axis) which points towards the development of the observed magnetic fabric of the studied rocks during the D_3 and D_4 stages of deformation (Fig. 8). Thus, it can be concluded that the magnetic fabric of the region is tectonically controlled. Generally it is

considered that when the presence of more than 0.1 volume percentage leads to the controlling of the magnetic fabrics by those ferromagnetic minerals only. However, here the scenario is quite different. The presence of paramagnetic haematite and the number of deformation events has over written the ferro-magnetically controlled magnetic fabric, leading to the development of an ultimate tectonically controlled magnetic fabric. Also, the various parameters related to susceptibility are thus controlled by tectonics. Considering the scope of further studies it is ensured that these rocks are suitable for palaeo-magnetic studies for determining the Apparent Polar Wandering (APW) path.

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