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MAGNETIC FABRIC AS A TOOL TO DETERMINE KINEMATIC VORTICITY NUMBER OF THE HIGH-GRADE ROCKS FROM CHILKA LAKE AREA, EASTERN GHATS BELTS, INDIA

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ABSTRACT

The present study aims to determine the nature of strain in the high-grade rocks from Chilka lake area, Eastern Ghats Belt (EGB) by calculating the kinematic vorticity number using the relationship between the magnetic fabrics and the perceptible field fabrics. In the study, it is found that the nature of shear is dependent on the rock types. Here the granulites and migmatites that host the leptynite and anorthosite bodies have relatively lower values for kinematic vorticity number which proves the presence of pure shear component although simple shear component dominates. However, within the anorthosite and leptynite massifs the kinematic vorticity number approaches 1, pointing towards absolute simple shear.

INTRODUCTION

There is an accelerating use of Anisotropy of Magnetic Susceptibility (AMS) in the field of geosciences to handle problems. Magnetic fabrics within the high-grade rocks of the Eastern Ghats Belt remained unravelled until Chatterjee *et al*. (2016) gave a precise documentation of the magnetic fabrics in this area with special attentions in the Balugaon and Rambha Anorthosite Massif. Numerous phases of deformation in the studied area as stated by Das *et al*. (2012) proves that there is ample amount of strain accumulated in the high grade granulitic rocks of the Eastern Ghats Belt (EGB) and the intrusive anorthosite massifs. However, the degree of non coaxiality of strain accumulated in these regions are not characterised till date. Mamtani *et al*. (2013) performed vorticity analysis in the Chakradharpur Granite Gneiss using AMS data which yielded interesting and inferring results.

In the, present scenario, the authors present the magnetic fabric data, specially, the attitude of the magnetic foliation and correlate them with the fabrics studied in the field to calculate the kinematic vorticity number, which is on the other hand the parameter to characterize the degree of non-co-axiality of the strain.

General Geology of the Studied Area

The Eastern Ghats Belt (EBG) is a linear high-grade terrain which located along the Eastern Coast of India for a distance of about 1600 km starting from Cuttack, Odisha to Nellore, Andhra Pradesh. The EGB trends NE-SW and occupies an area of about 50,000 sq. km. The structural elements within the rocks of the EGB trends parallel to the NE-SW to NNE-SSW lengthening of the Eastern Ghats Belt (Kalia and Bhatia, 1981). The Western Margin of the EGB is marked by the coastal plain of the North Chennai. There exists an irregular contact between the granulite facies rocks of the EGB and the amphibolite facies rocks of the Bastar Craton. The Northern side of the Mahanadi rift valley marks the North-Eastern boundary of the EGB is marked by which is referred to as the Sukinda Thrust. Subdivisions of the EGB are suggested differently by different workers. Ramakrishnan *et. al*. (1998) gave a fourfold classification of the EGB, which are Western Charnockite Zone (WCZ), the Western Khondalite Zone (WKZ) the Central Migmatisation Zone (CMZ) and the Eastern Khondalite Zone (EKZ). However, Dasgupta and Sengupta (1998) suggested a simpler twofold classification of the EGB, the Southern Mobile Belt and the Northern Mobile Belt separated by the Godavari Rift.

Debates prevailed and still prevails regarding the metamorphism and deformation of the rocks of the EGB. Sen

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et al. (1995) states the rocks have underwent several stages of decompression and cooling under conditions of 1100°C and >10 K bar pressure, however, reviews of Dasgupta and Sengupta (2003) finds such an explanation was not a suitable one as the present case is considered. Raith *et al.* (2007) and Sengupta *et al.* (2008) provided petrological signatures of Ultra High Temperature (UHT) metamorphism near the Anorthosite Massifs but the problem was not completely solved.

Earlier workers suggested various views on the deformational events in this region. Bhattacharya *et al.* (1993, 1994) proposed presence of the three deformational events. Based on structural mapping and remote sensing data it was correlated that 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 demarcated the presence of the S_0 plane in terms of compositional bands.

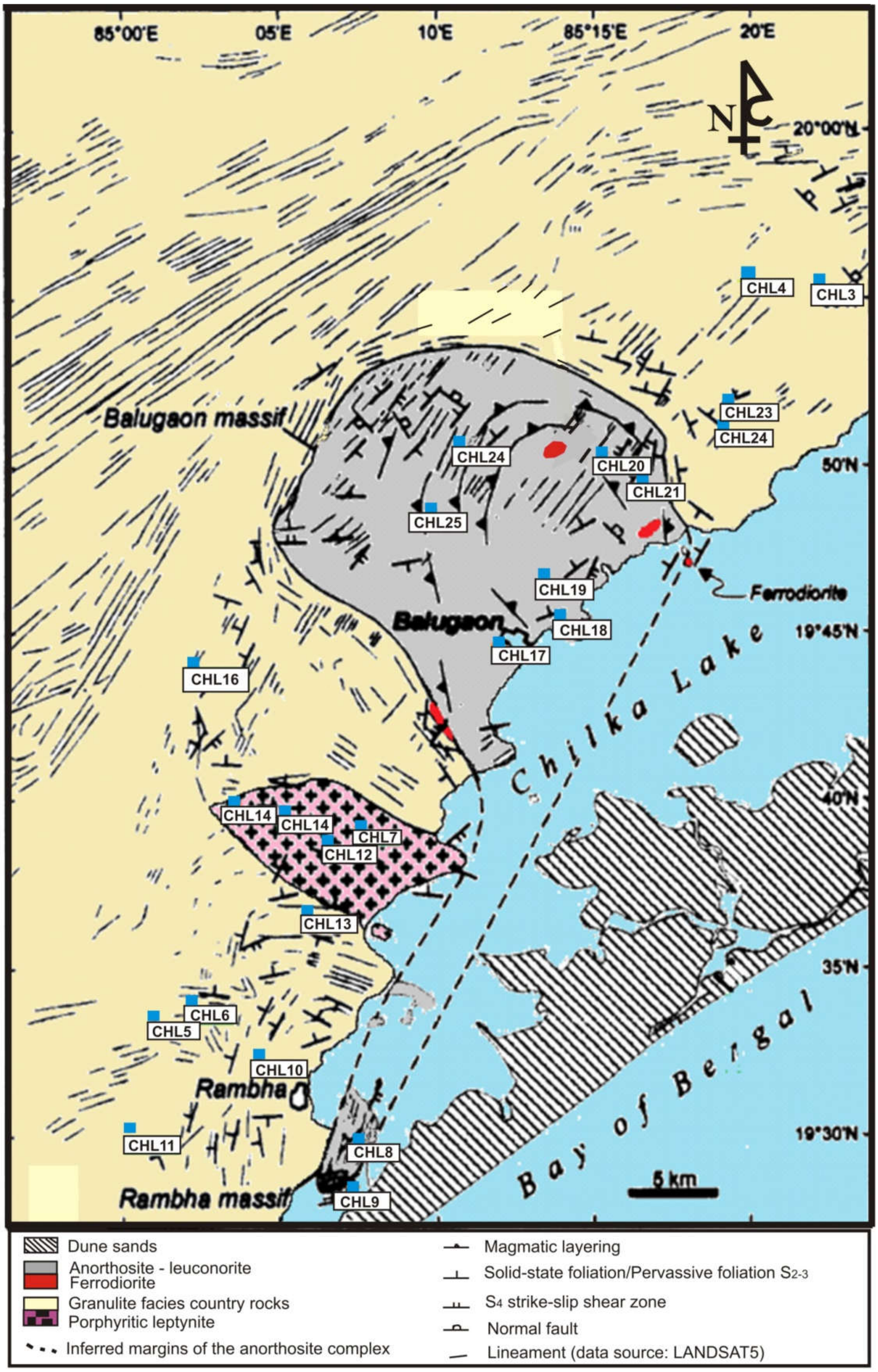

Figure 1 Generalised Geological map of the studied area with the blue dots marking the sampling locations (Chatterjee *et al*, 2016)

More recently, Das *et al.* (2012) represented interesting results regarding the metamorphism and deformation of the area. They narrated 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. These studies revealed that the M_1-D_1event predeceased the peak assemblage, M_2-D_2 the peak one and the M_3-D_3 and M_4-D_4 are post peak assemblages, *i.e.,* they are the manifestations from the retrograde stages of metamorphism. According to these workers, on the onset of the M_1-D_1 event, the primary depositional surface (S_0) was completely waived off leading to the development of the S_1 foliation, which is also preserved in microscopic scales only. The S_1 foliation further serves the purpose of form surface for the later deformational events. This S_1 foliation is folded during the D_2deformational event leading to the development of the S_2 foliation which is preserved in regional scale in all the rock units. This S_2 foliation is marked by the compositional banding of alternating of Garnet-Sillimanite-Cordierite and Quartzo-feldspathic bands. Field data reveals that the overall trend of the S_2 foliation varies from E-W through NE-SW to N-S which has fair accordance with the observations 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 succeeded by the M_3-D_3 event, which they suggested to be post peak event (as mentioned earlier), during which the S_2 foliation refolded to tight to isoclinal folds with gentle plunge of fold axes (18^0 to 26^0). The S_3 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 S_2 and the S_3 are almost parallel at the limbs of F_3 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 D_4 event, which led to the development of F_4 fold axis which has a plunge of 12^0-53^0, trending NW-SE, which was effective in causing a plunge reversal of F_3 axis (Das *et al*, 2012). However, the D_4deformation event failed to develop any penetrative planar structures except some spaced cleavages in the khondalites (Das *et al*, 2012).

Geochronological study on the Eastern Ghats Belt drew attentions of the scientists from the sixties. 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 berecognized as:

1. A metamorphism event at 3090 Ma from the Rb-Sr wholes-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 D_1, D_2 and D_3 deformations with the three earlier metamorphic events.

METHODOLOGY OF STUDY

The first step that needs to be taken to carry out AMS study is the collection of oriented in-situ core samples from suitable locations from the studied area, which extended form 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. 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 K_1, K_2 and K_3 ($K_1 \geq K_2 \geq K_3$). The plane passing containing the K_1 and K_2 is called the Magnetic Foliation and K_3 is the pole to that plane. For calculating the Kinematic Vorticity number, it is of utmost importance to determine the attitude of the magnetic foliation plane which can be considered as the ISA_{max} (Mamtani *et al*., 2013) and thus the nature of the foliation plane was obtained from the stereographic plots done using the Stereo-Nett software.

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.

Kinematic Vorticity and AMS

The degree of non-coaxiality of flow can be calculatedas the kinematic vorticity number (W_n; e.g., Means *et al*., 1980). Pure shear and simple shear are the two end members for which the extreme values ofW_n is 0 and 1, respectively (e.g., Passchier, 1988; Passchier and Trouw, 2005). According to Xypolias (2010), the end members can be treated as exceptions than general cases, and generally shearing takes place with contribution of both types. Several methods are summarised to determineW_n mathematically (Xypolias, 2010), one of which is by the equation W_n= sin 2€ (e.g., Passchier, 1988; Weijermars, 1991), where € is the angle between the extensional flow apophysis and the orientation of the ISA_{max}. Earlier, the orientation of ISA_{max} has been proxied by orientation of long axes of quartz neoblasts within an oblique foliation (Wallis, 1995; Xypolias and Koukouvelas, 2001; Xypolias, 2010). Also, in Fiordland (New Zealand), the amphibole defined foliation and plagioclase aggregates that makes an angle to the shear zone boundaries (and the main foliation visible in the field) has been considered to trace the orientation of the ISA_{max} (Daczko *et al*., 2001).

Based on the investigations by Mamtani *et al*, 2013 in the Chakradharpur Granite, they proposed that the magnetic foliation is analogous to an oblique foliation that develops parallel to the ISA_{max} on the onset of last stage syntectonic cooling. Thus, it may trace the direction of maximum stretching. Subsequent progressive deformation led to development of a foliation that is visible in the field that is parallel to the prominent field foliation, and thus proxies for the flow plane or the extensional flow apophysis.

In the present case of study, the dominant foliation in the field is S_2 (Das *et al*., 2012 and Chatterjee *et al*., 2016) which has a trend varying over the entire studied area. The magnetic foliation also has a varying nature over the area (Chatterjee *et al*., 2016) and thus the angular relation between the field foliation and the magnetic foliation will also vary and thereby causing a deviation in kinematic vorticity number among different study sectors of the study area.

Vorticity Calculation for the Studied Area

The attitudes of the magnetic foliations are calculated from the plots in the Stereo-Net and the attitude of the dominant field foliations were measured in the field itself. However, it should be noted that from each oriented block sample there were 6-8 cores extracted, each of which yielded a magnetic foliation plane. However, for vorticity calculation, the magnetic foliation attitude obtained from the best representative sample was used. As reported by Das *et al*. (2012), Chatterjee *et al*. (2016), Sengupta *et al*. (2008) the dominant foliation plane observed in the field was the S_2 foliation plane and herein in the present study the angular relationship between the magnetic foliation and the S_2 is used as a toll to calculate the kinematic vorticity number and characterize the nature of strain accumulated in the area. Table 1 represents the attitudes of the magnetic foliation plane, the dominant field foliation and thus the angle between them. For calculation of the regional vorticity number, average of all the data obtained are used.

However, for more precise and area-wise calculation of vorticity and strain characterization, data obtained from the various sectors of the study area are calculated.

The calculation of vorticity involves the following steps (Mamtani *et al*, 2013)

Average value of the angle between magnetic foliation and field foliation (€) = 54.375
Or, 2€ = 108.75
Or, sin 2€ = sin 108.75
Or, Kinematic Vorticity Number (W_n) = 0.934

Thus, the value of the average kinematic vorticity number of the area is approaching 1 and thus there is a dominance of the simple shear component.

Area-wise vorticity analysis

Although the average value of the kinematic vorticity number for the studied area is determined, on account of the fact that the area is composed of varied rock types (Chatterjee *et al*., 2016) the vorticity calculation on the basis of rock type and area stands relevant. Towards the North-East of the Balugaon massif, in the granulite rocks, the value of the kinematic vorticity number is about 0.7071 which has an implication towards the dominance of the simple shear over pure shear, although both the components are present. Further in the granulite facies country rocks at Rambha, the value of W_n is 0.7660. More towards South-West, in the Balugaon Anorthosite Massif the vorticity number reaches 0.9996 (nearly 1) which proves that the shear belongs to almost Pure Shear component in the Anorthosite massifs. This contention is corroborated by the high values of the vorticity number in the Rambha Anorthosite massif also (=0.976). The leptynite body towards the South-West of Balugaon also has a value approaching 1 depicting almost complete simple shearing in the area. The following Table 2 represents the area wise variation of the value of kinematic vorticity number throughout the study area.

Table 1 Database showing the steps involving vorticity calculation

Sl. No.	Sample No.	K_1(D/I)	K_2(D/I)	K_3(D/I)	Mag. Fol.	Str. Fol.	Angle between Mag. Fol. And Str. Fol.(Degrees)
1	CHL1.07	80.4/8.2	173.4/20.1	329.2/68.1	N70E	E30S	50
2	CHL2.05	281.8/4.2	191.4/5.5	49.1/83.1	W30N	N10E	70
3	CHL3.04B	33.8/4.4	125.0/15.5	288.7/73.9	N0E	N50E	50
4	CHL4.06	234.1/12.9	326.0/8.4	88.3/74.6	W80N	W10N	70
5	CHL5.02	307/3.4	37.7/11.2	200.3/78.2	W20N	N10E	80
6	CHL6.06	314.9/0.6	224.8/9.2	48.8/80.8	W45N	N15E	60
7	CHL7.05	314.9/0.1	45.0/41.5	224.8/48.5	W45N	W10N	35
8	CHL8.04	96.2/6.2	186.8/5.4	317.6/81.7	N80E	N30E	50
9	CHL9.06	16.1/0.6	106.2/2.5	272.3/87.4	N15E	N80E	65
10	CHL10.02	118.6/10.6	213.4/24.0	6.6/63.5	E15S	N40E	65
11	CHL11.01	292.3/6.3	22.4/0.9	121.0/83.6	W10N	W80N	70
12	CHL12.04	32.2/10.1	123.2/0.6	216.4/80.0	E30S	E10S	20
13	CHL13.02	22.5/2.7	292.5/1.3	176.7/87	W10N	N0E	80
14	CHL14.04	321.5/7.4	229.5/15.0	76.9/73.2	W80N	N20E	30
15	CHL15.01	284.1/5.1	14.5/4.5	145.8/83.2	N40E	E10S	60
16	CHL16.03	67.6/1.0	157.7/2.0	310.2/87.8	N70E	N10E	60
17	CHL17.01	250.9/6.7	160.0/8.3	19.5/79.3	E30S	N40E	80
18	CHL18.04	53.7/38.4	171.3/30.3	287.3/36.9	N15E	N30E	15
19	CHL19.05	41.7/1.6	311.7/1.8	172.9/87.6	N40E	N25E	15
20	CHL20.02B	23.4/14.7	290.9/9.4	169.3/72.4	W10N	W80N	70
21	CHL21.04A	317.3/3.2	226.4/15.5	58.5/74.2	W15N	W40N	25
23	CHL23.02	285.8/4.6	195.5/3.3	69.9/84.3	W30N	N10E	70
24	CHL24.01	5.9/32.9	274.5/2.9	180/57.0	N50E	W70N	80
25	CHL25.02	140.5/16.9	49.0/4.9	303.4/72.4	N25E	N60E	35

Table 2 Spatial distribution of kinematic vorticity in the study area

Study Sector	€	Kinematic Vorticity
Towards Tangi	67.5	0.7171
Balugaon	45.71	0.9996
Leptinite Body	45	1
Rambha	65	7660

DISCUSSIONS AND CONCLUSIONS

From the previous discussions it is quite obvious that the variation of the nature of shearing i.e. the kinematic vorticity number (W_n) is a parameter dependent on the rock types, at least in the present study area. The host granulite rocks within which the anorthosite and the leptynite bodies are intruded, are displaying relatively lesser values for the kinematic vorticity number ranging between 0.7-0.8 depicting that although simple shear dominates, the pure shear component is also not negligible. However, in the intruded anorthosite and leptynite massifs, the value for the kinematic vorticity number approaches 1 and thus complete simple shear dominates over these rocks and the pure shear component is negligible.

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