Interpretation of magnetic fabrics in the Dalma volcanic rocks and associated meta-sediments of the Singhbhum Mobile Belt

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The present work deals with the generations of Fe–Ti oxides and the variation in magnetic fabrics of the Dalma lavas and associated meta-sediments of the Singhbhum Mobile Belt (SMB) in relation to tectonics. Generations of the Fe–Ti oxides are different in meta-sediments and volcanics, the former preserving upliftment related oxidised grains, whereas the latter contains fresh grains prompting towards their upliftment due to plume upwelling before the volcanic eruption. In the meta-sediments, the magnetic fabric has close accordance with D_2/F_2 event revealing synchronous development with D_2 . The Dalma thrust developed a sudden break in the homogeneity of the magnetic fabrics of the rocks where the magnetic foliations are all parallel to the Dalma thrust. This also causes P_j to be highest in this sector. The magnetic fabrics of volcanic rocks are different from the meta-sediments and record no signature of deformation. The pattern of distribution of susceptibility axes are in accordance with the subaerial lava flows. However, their K_1 and K_2 dispersed throughout the periphery with K_3 clustering at the centre. This infers towards the fact that although the volcanism took place in a subaerial environment, calm aqueous environment was locally present where the oblate grains settled on the eruption surface with their K_3 vertical.

Keywords. Anisotropy of Magnetic Susceptibility (AMS); Dalma; East Indian Shield; Fe–Ti oxide; magnetic fabric.

1. Introduction

All igneous, sedimentary and metamorphic or tectonically deformed rocks consist of a spatial and geometrical arrangement of their constituent minerals referred as a fabric. Such arrangements correspond to any geological process, or, to tectonic

phenomena on a larger scale (Tarling and Hrouda 1993; Borradaile and Henry 1997; Parés and Pluijm 2002; Mamtani *et al.* 2004; Praveen *et al.* 2009; Mamtani *et al.* 2012). Thus, fabric analysis plays a crucial role in solving geological problems. Anisotropy of Magnetic Susceptibility (AMS) is an intrinsic property of any material that describes the

directional non-uniformity of the induced magnetization with respect to the applied field (Chatterjee *et al.* 2017, 2018a,b; Mondal *et al.* 2017). The salient features that make AMS a powerful tool in fabric analysis are: (a) have the capability of recording very low intensities of deformation, (b) large volumes of rock can be analysed, and (c) analysis of many grains possible in a single sample (Parés and Pluijm 2014). These are useful for the information regarding geological processes that impinged the fabric within the rock both during genesis and subsequent deformation (Hrouda 1982, 1991; Sagnotti and Speranza 1993; Borradaile and Henry 1997). AMS is generally represented mathematically as a symmetric second rank tensor and geometrically represented as a three-axis ellipsoid (Borradaile and Henry 1997).

Despite sporadic studies on AMS in various parts of the Singhbhum Craton and mobile belt of the (Mamtani *et al.* 2004, 2013; Mukherjee *et al.* 2004; Ghosh *et al.* 2010; Mamtani and Sengupta 2010) the Dalma volcano-sedimentary belt remained virgin in terms of AMS studies. The core objective of the present study is to perform AMS analysis and determine the following: (a) generation of the Fe–Ti oxides and the acquisition of the magnetic fabric elements in the Dalma volcano-sedimentary

belt; (b) the relationship between the meso-scale, micro-scale and magnetic fabrics; (c) interpret the magnetic fabrics in terms of the tectonics of the studied area. As the Dalma volcano-sedimentary sequence is composed of a wide range of rock type, the orientation of the magnetic fabric elements will also vary depending on the rock type. Such variations throughout the studied area are also discussed herein. Besides, many ideas are available till date regarding the tectonic evolution of the Dalma volcanics and associated meta-sediments which are exclusively based on petrological and geochemical characteristics. The present study thus also aims towards unfolding the tectonics of the area as evident from the geophysical studies.

2. Geological setting

The nearly 150 km east–west trending Dalma range comprises the medial spine of the Proterozoic Singhbhum Mobile Belt (SMB) and is flanked by meta-sedimentary rocks both on the north and on the south (figure 1). The SMB meta-sediments and the associated Dalma lavas are bounded by the Chottanagpur Gneissic Complex (CGC) towards the north and the southern margin is delineated

Figure 1. Geological map of the Singhbhum Mobile Belt and associated rock units (Mazumder 2005).

Figure 2. Generalised geological map of the studied area (after [Sarkar and Saha 1983](#)). The blue squares mark the sampling locations.

by the Singhbhum Shear Zone (SSZ) separating the rocks from the Archean nucleus ([Mazumder 2005](#)). On the northeast of the Dalma volcanic range, the elliptically outcropped Kuilapal granite massif occurs within the terrain of largely volcanics and sediments ([Misra 2006](#)).

The present study was conducted within the latitudinal extents of $22^{\circ}30' - 23^{\circ}00'N$ and longitude $86^{\circ}00' - 86^{\circ}45'E$. The area belongs to the eastern part of the nearly NW–SE trending Dalma volcano-sedimentary range of the East Indian Shield, extending from Belpahari (West Midnapore district, West Bengal) in the east up to Chandil (East Singhbhum district, Jharkhand) in the west (figure 2). The rock units consist of thick sequences of mafic–ultramafic volcanic rocks, lenses of basaltic agglomerate, meta-pelitic schists, phyllites, carbon phyllites, carbon phyllite-tuff along with some intercalated quartzite bands ([Chakraborti 1980](#); [Gupta et al. 1980](#); [Chakraborti and Bose 1985](#); [Bose 1994](#); [Singh 1997, 1998](#); [Sengupta and Mukhopadhyay 2000](#); [Mazumder 2005](#); [Misra 2006](#)). The meta-volcanics splay out into many

bands that are trapped within the schists and phyllites ([Iyengar and Banerjee 1964](#)). The rocks are metamorphosed to greenschist facies ([Mazumder 2005](#); [Mazumder et al. 2015](#)). The agglomerates consist of numerous angular clasts and blocks of sedimentary rocks (viz., sandstone) entrapped within the basaltic lava (figure 3a). Besides, the basaltic lava flow displays spectacular outcrops of pillow structures (figure 3b).

It is pertinent that the Dalma lavas and the SMB sediments have suffered four phases of deformation ([Naha 1956, 1959](#); [Sarkar and Saha 1962](#); [Saha 1994](#)). The original bedding (S_0) was folded during F_1 deformation which led to the development of S_1 ([Sarkar and Saha 1963](#)). Further folding of S_1 during D_2 deformation led to the development of the observed mesoscopic foliation in the field with nearly E–W striking axial planes (figure 3c; also see [Chatterjee and Bhattacharya 2013](#) and references therein). Field observations of the present study shows that the southern limb of F_2 folds strikes 095° and dips $75^{\circ} \rightarrow S$ and the northern limb strikes 120° and dips $76^{\circ} \rightarrow N$. The orientation of S_2 is almost

Figure 3. (a) Clasts/blocks of sandstones in basaltic matrix, (b) exposure of pillow lava near Chakulia, (c) folds in the volcanic rocks at Chakulia, and (d) phyllites from near Tamlia with puckered near-vertical schistosity.

similar throughout the study area with strikes 090 dipping 80–90° towards N or S. The fold axis (F_2) plunges 20° → 100°. The S_2 is puckered locally (figure 3d; also see Sarkar *et al.* 1969). The intersection lineation of the foliation (S_2) and localised thrust plane plunges 75° → SW. Slicken-side lineation on this thrust plane pitches 71° → 230°. The F_3 folds are superposed on F_1 and F_2 and are penetrative throughout the study area (Chatterjee and Bhattacharya 2013). The axial planes of F_3 fold strikes NE–SW and are expressed by joint sets in Galudih area (Mamtani *et al.* 2004). The F_4 deformation event is represented by the large-scale ESE–WNW folds (Saha 1994). However, the last two events of deformation are mainly concentrated towards the south of the SMB, i.e., towards SSZ and dies out towards north (Bhattacharya and Sanyal 1988). Faults trending NNW–SSE and NNE–SSW have displaced the Dalma rocks in the Asanbani and Tamlia sectors, the former being more common. The Dalma rocks in the easternmost part, i.e., near Belpahari, are interrupted by NW–SE trending Dalma thrust. The field data observed in the study area is represented on lower hemisphere equal area projections (figure 4).

The tectonic evolution of the Dalma volcano-sedimentary belt is debated throughout the last decade. Dunn and Dey (1942) and De (1964) suggested a continental origin of the Dalma volcanic rocks. However, Naha and Ghosh (1960) hypothesized an island arc setting for the Dalma basaltic volcanics. Again Bose *et al.* (1989) and Bose (1994) found that the LREE patterns with the Dalma basalts are comparable with that of MORB and thus claimed a close analogy with the basalts of back-arc basin. Gupta *et al.* (1980) presented the idea of distension of the protocontinental crust leading to the formation of Chaibasa basin and the rising geotherms associated with almost complete melting produced the Dalma volcanic rocks (Mukhopadhyay 1984, 1994; Bose 1994). Based on sedimentary history, geochemical evidences and magmatic characterization, however, Gupta *et al.* (1980) doubted the genetic relationship of Dalma volcanism and mantle plume upwelling. More recently, Acharyya (2003) stated that the distribution of the volcanic rocks at Chandil (north of Dalma) and the absence of 1500–1600 Ma old charnockites in the southern part of CGC that flanks the Dalma volcanics does not

Figure 4. Lower hemisphere equal area projection of the F_2 components (left); contour diagram representing the attitudes of F_2 (centre); contour diagrams representing poles to S_2 with the great circle representing the average attitude of S_2 (right).

support the origin of Dalma volcanic rocks during the mid-proterozoic (~ 1600 Ma) global plume related uplift, as stated by Roy *et al.* (2002). However, Roy *et al.* (2002) correlated the positive ΔNb values of the volcanic rocks of Dalma belt with their mantle plume origin. Besides, pillow structures within the Dalma are indicative of sub-aerial flows locally entering stream or fluid channel (Dillard *et al.* 1999; Mazumder 2005) with the overlying entirely terrestrial (fluvial-aeolian) deposits of Dalbhum formation. Based on these studies and the fact that the Dalma volcano-sedimentary sequence is entirely bounded by terrestrial deposits it is supported that the origin of Dalma volcanics is due to plume activity in continental rift basin (Gupta *et al.* 1982; Mukhopadhyay 1990, 1994; Eriksson *et al.* 1999; Mazumder *et al.* 2000; Roy *et al.* 2002; Mazumder 2003).

3. Methodology

For AMS studies, the oriented block samples collected were drilled to 6–8 number of cores (2.54 cm in diameter and 2.2 cm in height) by vertical drilling on the top surface of the sample. The samples were drilled at the Department of Geology and Geophysics, IIT Kharagpur, India, with non-magnetic drilling, but fitted to a geared drilling rod. The AMS measurements for these cores were carried out using the KLY-4S Kappa bridge (Czech Republic) housed at the Fabric Analysis Laboratory (FAL), Department of Geology and Geophysics, IIT Kharagpur, India.

This yielded the magnitude and directions in space for the three principal axes of the susceptibility ellipsoid K_1 , K_2 and K_3 ($K_1 \geq K_2 \geq K_3$) and the corresponding bulk susceptibility values. These values are useful in determining values of various parameters such as mean susceptibility, magnetic foliation, magnetic lineation and degree of anisotropy. The values of these parameters are calculated as follows, and were thereby interpreted:

Mean susceptibility

$$(K_m) = (K_1 + K_2 + K_3)/3 \text{ (Nagata 1961)} \quad (1)$$

Magnetic lineation

$$(L) = K_1/K_2 \text{ (Balsley and Buddington 1960)} \quad (2)$$

Magnetic foliation

$$(F) = K_2/K_3 \text{ (Stacey et al. 1960)} \quad (3)$$

Degree of anisotropy

$$(D) = K_1/K_3 \text{ (Nagata 1961)} \quad (4)$$

Eccentricity

$$(E) = K_2^2/K_1K_3 \text{ (Hrouda et al. 1971a, b).} \quad (5)$$

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:

$$P_j = \exp\{2[(n_1 - n_m)^2 + (n_2 - n_m)^2 + (n_3 - n_m)^2]\}^{1/2} \quad (6)$$

$$T_j = (2n_2 - n_1 - n_3)/(n_1 - n_3); \quad \text{where } n_i = \log K_i. \quad (7)$$

For microscopic studies, polished thin sections were prepared from slices cut from drilled cores extracted by drilling the oriented blocks. As the cores are oriented, the sections were also prepared in similar orientations which help in correlative studies of micro-scale fabrics and AMS. The sections were studied at the Image Analyser Laboratory, Department of Geological Sciences, Jadavpur University using Leica DM 2700 microscopes.

4. Petrography, micro-structures and generations of Fe–Ti oxides

4.1 Petrography and micro-structures

The Dalma rocks are represented by quartz-mica schists, phyllites, with minor intercalated quartzite bands (also see Mazumder 2005). The schists are porphyroblastic with quartz, mica or opaque as porphyroblasts set within a matrix of fine grained quartz, feldspar, muscovite, sericite, biotite, sphene and variable amount of opaque minerals (figure 5a). Relicts of the younger schistosity are preserved locally which are defined by the athwart grains of muscovite (figure 5a). Further, S_2 suffered puckering (figure 5b) and micro-faults disrupted the schistosity (figure 5c).

The intercalated quartzites consist of ~95% medium to coarse grained sub-rounded to angular quartz with minor biotite and opaque minerals. Sheared portions within the quartzite consist of undulose, polygonal and elongated quartz grains (figure 5d). Intense shearing at places has resulted in pulverization of the quartz grains. Also, at places micro-fracture planes have developed which are further invaded by opaques and quartz (figure 5e).

Most of the Dalma volcanic is metamorphosed to greenschist facies forming chlorite schists (Chakravorty 1961). However, relict textures are also common. The volcanic rocks are porphyritic in nature, defined by phenocrysts of amphibole, plagioclase and quartz placed within a matrix of finer quartz, feldspar, and abundant amount of devitrified glasses consisting of crystallites and microlites. The texture can be more precisely termed as ‘vitrophyric’ on account of the abundance of the glassy matrix. Locally such texture is glomero-porphyritic also, where the phenocrysts are clustered together of coarser hornblende, opaque and plagioclase crystals are clustered together. Remnants of pyroclasts are quite prominent in the volcanic rocks of

Chakulia and Asanbani areas (figure 5f). This implies towards subaerial eruption of the Dalma lavas (Singh 1997).

4.2 Generations of Fe–Ti oxides

The purpose of dealing with the generations and modes of occurrences of Fe–Ti oxides (mainly titanomagnetite here) and their modes of occurrence is to unravel the control of ferro-magnetic oxides on the magnetic fabrics and to bring out the correlation of the regional tectonics (Rochette 1987; Rochette *et al.* 1992; Archanzo *et al.* 1995; Cañon-Tapia *et al.* 1995; Chatterjee *et al.* 2016, 2018b). The generations of Fe–Ti oxides can be classified into three broad categories: primary high temperature ($>600^\circ\text{C}$), primary low temperature ($<350^\circ\text{C}$) and secondary (Haggerty 1976; Johnson and Hall 1978; also see Akimoto *et al.* 1984). Haggerty (1976) classified the high temperature primary generations of titanomagnetite into seven stages (C-1 to C-7), the suffix increasing with the increasing degrees of exsolution of ilmenite from homogeneous titanomagnetite. Johnson and Hall (1978) classified the low temperature primary generations of titanomagnetite into five stages (stage-1 to stage-5) based on the degrees of migration of highly mobile ferrous and ferric ions from titanomagnetite and subsequent enrichment by Si^{4+} ions (see Akimoto *et al.* 1984).

4.2.1 Modes of occurrence of magnetic minerals in schists and phyllites

The titanomagnetites in the schists are present in two generations which are: (a) coarse-rounded to square shaped porphyroblasts wrapped by S_2 , which are oxidised at low temperature to stage-2 to stage-4, with some intermediate stage-3 according to the classification of Johnson and Hall (1978) (figure 6a); and (b) fine elongated grains parallel S_2 (figure 6b). Besides these primary low temperature oxidised titanomagnetites, some secondary titanomagnetite grains are also present which are very closely associated with dissolution of primary titanomagnetite grains and ‘haematite-pigmentation’ (figure 6c). These are present as veins of secondary oxide minerals which can be traced throughout the sections. These veins are present along fractures planes and are ubiquitously associated with the secondary biotite.

Figure 5. (a) Muscovite porphyroblast rotated along the schistosity (XPL, 50 $\times$), (b) evidences of puckering in S_2 (XPL, 100 $\times$), (c) micro-fault causing the disruption of the thinner dark colour band (XPL, 50 $\times$), (d) preferentially aligned quartz grains within the deformed quartzites from Asanpani area (XPL, 100 $\times$), (e) recrystallized grains of deformed quartzite which conceives a folded vein of quartz (XPL, 100 $\times$), and (f) pyroclastic grain in basalt embedded within glassy matrix with the long axis (LA) parallel to S_2 (PPL, 50 $\times$). K_1K_2 represents the trends of the magnetic foliation.

4.2.2 Modes of occurrences in quartzites

The proportion of the oxide minerals are much lower in the quartzite and are hardly present associated with the polygonal quartz grains. Very rare occurrences are found which belong to low temperature oxidation stages 3 and 4. Mostly the Fe–Ti oxides are present along fracture planes developed within the quartzites which are principal sites for secondary titanomagnetite occurrence

(figure 6d). Some are extremely oxidised to higher degrees representing stage-5 of low temperature oxidation of the titanomagnetites.

4.2.3 Modes of occurrences in volcanics and meta-volcanics

Titanomagnetite grains constitute a much larger proportion in the volcanic and meta-volcanic rocks and are present in almost unaltered primary phases

Figure 6. (a) Porphyroblastic titanomagnetite within schists oxidised to stage-2 at low temperature (PPL, 100 $\times$), (b) schistosity defining titanomagnetite oxidised at low temperature (PPL, 100 $\times$), (c) fracture planes containing primary dissolved titanomagnetites developing pigmentary haematite within which ultra-fine secondary grains of titanomagnetite have crystallised (PPL, 100 $\times$), (d) secondary titanomagnetite along fractures in quartzites of Chandil area (PPL, 100 $\times$), (e) titanomagnetite oxidised at high temperature to C-1 within the volcanic rocks of Chakulia, and (f) relict phenocryst of titanomagnetite oxidised at low temperature to stage-1 within the volcanic rocks of Burudih area (PPL, 100 $\times$).

like C-1 or stage-1 (Haggerty 1976; Johnson and Hall 1978). The high temperature grains are present as coarse relict euhedral phenocrysts with sharp grain boundaries (figure 6e). The low temperature components are very feebly oxidised (figure 6f), most likely to stage-1. The oxides are abundant in the sections parallel to the horizontal top of the exposures.

5. Results from AMS studies

For representation of the AMS data from the rock samples of the studied area, the values of F , L , P_j , T and K_m were calculated from the raw susceptibility data and were represented in the various diagrams mentioned in the previous sections. The values of the different AMS parameters are

Table 1. Database consisting of the AMS data for the selected sampling locations of the studied area.

Sample no.	Rock type (area)	$K_1(D^0/I^0)$	$K_3(D^0/I^0)$	F	L	P_j	T	$K_m(\times 10^{-4}SI)$
DL 3.2	Schist (Chandil)	123.2/57.7	10.1/13.9	1.111	1.002	1.131	0.96	8.85
DL 6.3	Phyllite (Chandil)	127.2/23.7	16.6/38.8	1.261	1.483	1.885	− 0.259	9.8
DL 29.2	Schist (Tamlia)	111.1/16.1	212.4/34.1	1.45	1	1.176	0.994	5.87
DL 30.1	Phyllite (Tamlia)	329.6/26.1	217.2/37.8	1.162	1.611	2.319	0.678	3.2
DL 16.4	Schist (Tamlia)	134.3/17.3	231.9/23.0	1.407	1.025	1.506	0.865	2.16
DL 17.4	Schist (Galudih)	225.1/23.5	148.9/32.7	1.111	1.127	1.252	− 0.062	4.33
DL 19.3	Schist (Galudih)	239.1/1.4	116.5/87.4	1.181	1.023	1.23	0.756	6.92
DL 25.5	Metavolcanics (Burudih)	90.6/32.6	270.6/57.4	1.99	1.144	2.416	0.673	5.37
DL 9.5	Quartzite (Chandil)	124.1/24.5	12.7/38.7	1.032	1.029	1.061	0.056	1.81
DL 18.1	Quartzite (Galudih)	147.8/1.9	356.9/87.8	1.117	1.029	1.159	0.587	0.732
DL 18.6	Quartzite (Galudih)	21.9/0.9	272.1/87.4	1.186	1.021	1.234	0.783	0.683
DL 23.2	Quartzite (Burudih)	133.2/35.5	261.3/41.0	3.636	1.775	9.798	0.385	4.1
DL 23.4	Quartzite (Burudih)	164.5/40.2	289.4/34.0	1.923	1.68	3.479	0.115	6
DL 13.3	Volcanics (Chakulia)	176.4/0.0	266.4/65.7	1.028	1.005	1.036	0.712	6.74
DL 14.2	Volcanics (Chakulia)	16.9/54.5	138.8/20.7	1.021	1.017	1.039	0.111	6.12
DL 14.3	Volcanics (Chakulia)	13.7/52.8	124.3/14.9	1.025	1.015	1.041	0.228	5.77
DL 15.3	Volcanics (Chakulia)	172.2/2.8	1.7/87.2	1.274	1.046	1.362	0.689	37.3
DL 28.1	Volcanics (Chakulia)	245.0/3.5	37.9/86.0	1.457	1.123	1.457	1.123	34.9
DL 26.4	Volcanics (Burudih)	338.7/0.9	246.9/63.8	1.065	1.078	1.148	− 0.091	7.95
DL 27.1	Volcanics (Burudih)	236.1/0.4	145.3/63.1	1.255	1.165	1.465	0.196	25.8

Table 2. Distribution of the values of AMS parameters over the different rocks of the studied area.

Rock type	Mean F	Mean L	Mean P_j	Mean T	Mean $K_m(\times 10^{-4}SI)$
All Samples	1.469	1.133	1.902	0.451	9.12
Schists	1.481	1.165	1.857	0.581	4.968
Quartzites	1.718	1.165	2.574	0.557	4.24
Volcanics/metavolcanics	1.207	1.068	1.276	0.216	18.153

mentioned in table 1. For convenience we are discussing the mathematical parameters and directional characteristics separately.

5.1 Magnitude and shape parameters of the AMS data

The mean susceptibility (K_m) of the rocks are low with an average value of 9.120, but in the volcanic rocks, it is notably higher ranging within 14.612×10^{-4} SI and 21.694×10^{-4} SI. The average degree of anisotropy (P_j) is about 1.902, which is >1.05 , the critical value that determines whether the magnetic fabrics are typically primary or deformational (Dvořák and Hrouda 1975). In the schists, the average value of P_j is 1.857. However, the schists of Chandil and Burudih have higher values, which are respectively 2.212 and 2.346, whereas it is much lower values in Tamlia and Banduan areas. In the quartzites, the P_j is quite higher

(2.574) than in the schists, as the value of P_j in Dharagiri area is as high as 5.062. The P_j values of the volcanics are higher in the volcanic rocks of the Burudih area (1.396) than those of the Chakulia area where it is 1.155. The average magnitude of foliation (F) is 1.469 and that of lineation (L) is 1.133, i.e., $F > L$ which points towards a largely oblate fabric (table 2). This is also evident from the Jelinek plots (figure 7). However, some exceptions are present which lies within the prolate field. Consideration of individual rock type and sampling area for AMS analysis yields more precise results (Tarling and Hrouda 1993). Hence the lithological and spatial variations of the values of the AMS parameters are provided in tables 2 and 3.

From the plots of the P_j – F graph there exists a direct proportional relationship between P_j and F (figure 8a). However, the value of L remains almost constant with the change of the P_j value

Figure 7. P_j – T plots (Jelinek plots) for (a) all samples, (b) schists, and (c) volcanic rocks, and (d) quartzites.

Table 3. *Spatial distribution of the values of the AMS over the different rocks (area wise) of the studied area.*

Rock type	Mean F	Mean L	Mean P_j	Mean T	Mean $K_m(\times 10^{-4}\text{SI})$
Schist (Chandil)	1.399	1.313	2.212	0.793	5.475
Schist (Tamlia–Pardih)	1.434	1.148	1.734	0.682	4.589
Schist (Asanpani)	1.121	1.081	1.137	0.124	4.435
Schist (Burudih)	1.969	1.116	2.346	0.729	5.373
Quartzite (Chandil)	1.132	1.038	1.188	0.521	3.437
Quartzite (Asanpani)	1.358	1.045	1.472	0.739	5.13
Quartzite (Burudih)	2.664	1.411	5.062	0.412	4.067
Volcanics (Chakulia)	1.105	1.033	1.155	0.358	14.612
Volcanics (Burudih)	1.309	1.103	1.396	0.074	21.694

Figure 8. Plots of (a) P_j vs. F and (b) P_j vs. L for the rocks of the studied area.

(figure 8b). Thus, with increasing degree of deformation, the values of F increase and that of L remains constant, i.e., the shape of the susceptibility ellipsoid becomes more and more flattened

(oblate) with increasing degree of deformation. From the K_m vs. P_j plots of the samples (figure 9), it is observed that the degree of anisotropy is independent of the mean bulk susceptibilities.

Figure 9. K_m vs. P_j plots for (a) all samples, (b) schists, (c) quartzites, and (d) volcanic rocks.

5.2 Directional characteristics of the AMS data

For the directional analysis of the AMS data, lower hemisphere equal area projections of the principal susceptibility axes were obtained, firstly for all samples and then more precisely for different rock types (figure 10). The principal purpose of plotting these susceptibility axes on the lower hemisphere circular diagram is to determine the distribution of the susceptibility axes in different rock types of the area, and more precisely to develop an idea regarding the attitudes of magnetic lineation (K_1) and magnetic foliation (plane passing through K_1 and K_2). Figure 10 represents the lower hemisphere equal area projections for K_1 , K_2 and K_3 for all samples and rock type.

First, from the cluster and contour diagrams of the K_1 axes of all the samples in the studied area (figure 11a, b), it is observed that the dominant cluster of the magnetic lineation in the area is in the NW–SE trend. However, some samples show a completely opposite trend of NE–SW. In the schists, despite the widely dispersed K_1 (figure 11c, d), their dominant orientation is NW–SE with a very few exceptions of K_1 plots in the SW sector. From the distribution of K_1 in the quartzites it is very clear that the magnetic lineation within the quartzite (figure 11e, f) typically follows the NW–SE trend and displaying a cluster. In the volcanic rocks, it is very interesting to be observed that both the K_1 and K_2 are distributed throughout the periphery with low to moderate inclinations

(figures 10 and 11g, h), which point towards a near-horizontal magnetic foliation plane.

6. Discussions

A combined study of the generations of Fe–Ti oxides and the nature of the magnetic fabrics have an appraisal towards the tectonics of the area. However, in the present study area, the magnetic fabric is quite inhomogeneous which is represented in the *magnetic fabric maps* (figures 12 and 13, respectively). Such variations in the magnetic fabric may be triggered by bulk susceptibility values of the rocks, preferred orientation of fabric element due to deformation or even due to variable concentration of ferro-magnetic mineral (Robion *et al.* 1995; Lehman *et al.* 1996; Chadima *et al.* 2006). In the following sections, the variation of magnetic fabrics and their geological implications in the study area are discussed.

6.1 Interpretation of the planar magnetic fabrics

There is close agreement of the magnetic foliations and S_2 in the schists (both trending NW–SE to WNW–ESE) in Chandil Tamlia and Asanpani areas. The S_2 in turn is defined by the paramagnetic phyllosilicates (viz., muscovite, biotite). This points towards the dominance of paramagnetic susceptibility over ferromagnetic in the schists and consequent development of magnetic

Figure 10. Lower hemisphere equal area projections for the principle susceptibility axes of (a) all samples, (b) schists, (c) quartzites, (d) volcanic rocks.

Figure 11. Lower hemisphere equal area projection for magnetic lineation (K_1) of (a) all samples, (b) schists, (c) quartzites, (d) volcanic rocks. Figures (e), (f), (g), and (h) represent the respective contour diagrams for the magnetic lineation in all samples, schists, quartzites and volcanic rocks.

fabrics within the schists syn-kinematic to D_2 (also see Lamali *et al.* 2013; Parés and Pluijm 2002). The oblate fabric in the schists, the independence of

anisotropy degree and bulk susceptibility and the high values of P_j further points towards similar inferences. Towards the east, near Burudih and

Figure 12. (a) Magnetic foliation map. Contour diagrams respective to each sector the poles to foliation (K_3) in the corresponding area. Figures (b), (c), (d), and (e) are the contour diagram of K_3 and the area wise average foliation planes (great circles) for all samples, schists, quartzites and volcanic rocks, respectively.

Dharagiri, the schists have phyllosilicate defined S_2 strike varying from NE–SW in the eastern limb of Bankati depression to NW–SE in the western limb. However, the magnetic foliation trends from NW–SE to NNW–SSE strictly. Interestingly, this magnetic foliation trend parallels the Dalma thrust pointing towards the synchronous development of magnetic fabric with the Dalma thrust.

In the quartzites, the bulk susceptibilities are much less than 50×10^{-6} SI; however, the orientation of the principal susceptibility axes, i.e., K_1 , K_2 and K_3 , have tectonic implications (Hrouda 1986). It is also established that the quartzite which possesses bulk susceptibilities greater than 50×10^{-6} SI ($= 0.5 \times 10^{-4}$ SI) have their nature of magnetic fabrics controlled by the paramagnetic/ferromagnetic minerals rather than diamagnetic quartz (Hrouda 1986, 2004; Mamtani and Vishnu 2012). At the western end near Chandil and at Dharagiri in the east, the quartzites have the susceptibilities $>0.5 \times 10^{-4}$ SI and thus can be expected to possess a magnetic fabric controlled by

the paramagnetic and ferromagnetic minerals. But according to petrography the quartzites are not that rich in primary titanomagnetite, which can define a prominent magnetic foliation. The chief occurrences of titanomagnetite in these quartzites are veins of secondary titanomagnetite. Thus, the magnetic foliations within these quartzites are necessarily the replications of the orientations of the secondary veins which are otherwise not traceable in the field. However, the quartzites of Asanpani area possess K_m value lower than the threshold 0.5×10^{-4} SI with a mesoscopic foliation trending like the magnetic foliation (NW–SE). This eventually relates to the development of the magnetic fabric in this sector due to quartz grain alignment which is also prominent in the micro textures.

It is worth mentioning that the magnetic fabrics of the volcanic rocks are very difficult to characterize genetically (i.e., whether primary or deformational) due to smaller influence of the cooling stress (Ade-Hall *et al.* 1971). The volcanic rocks possess magnetic fabrics which is quite different from that

Figure 13. (a) Magnetic lineation map. Contour diagrams respective to each sector are the distributions of K_1 in the corresponding area. Figures (b), (c), (d), and (e) represents the contour diagrams of the K_1 for all samples, schists, quartzites and volcanic rocks, respectively.

of the associated meta-sediments. Although, the attitude of the magnetic foliation is highly variable, it is having low dips as evident from the widely dispersed K_1 and K_2 near the periphery of the equal area projections. This nature of magnetic fabric is indicative of volcanic eruption in subaerial conditions (Ellwood 1978). However, the volcanic rocks where the K_1 and K_2 are dispersed at the periphery and K_3 clusters at the centre, planes of simple shearing within the flow layers are described by the plane perpendicular to the K_3 cluster, i.e., the magnetic foliation (Cañón-Tapia and Pinkerton 2000; Cañón-Tapia 2001). This plane trends NE–SW in near Chakulia and Asanbani and in Burudih sector it trends NNW–SSE with moderate dips.

6.2 Interpretation of linear magnetic fabrics

The magnetic lineations (K_1) within the schists have two very strong trends which are sub-equally dominant. The plots towards the east and south-east sectors are obvious manifestations of F_2 .

The crude dispersions towards SW are probable weak replications of F_3 . The magnetic lineations within the quartzites are exactly subparallel to F_2 throughout. The plunges of the magnetic lineation are low to moderate. Sengupta and Chattopadhyay (2004) reported that the F_2 plunges gently in the Northern part of the SMB and becomes steeper towards South but in the same direction due to increase in non-coaxiality towards South. Mamtani and Sengupta (2010) reported a much steeper plunge of magnetic lineation towards southern part of SMB. In the present study area, which lies towards the northern part of SMB, the magnetic lineation plunges gently to sub-horizontal towards SE which undoubtedly proves that the magnetic fabric in the meta-sediments of SMB is necessarily the fossilised D_2 .

In the volcanic rocks, the projection of the susceptibility axes on the lower hemisphere equal area diagram displays a typical scatter which is characteristics of pre-quaternary volcanic terranes (Tarling and Hrouda 1993). The distribution of the

K_1 axes cannot be considered as flow parameters in these volcanic rocks. Interestingly, although the K_1 here describes wide dispersions but the K_3 clusters towards the centre of the equal area diagram. This implies that although the maximum and intermediate susceptibility axes of the volcanic rocks are haphazardly oriented on a near-horizontal plane, the K_3 is vertical. Thus, even though the volcanism took place in an overall subaerial environment, quiescent aqueous environment prevailed where the oblate grains (as evident from the P_j – T plot) settled on the eruption surface with their minimum susceptibility axes vertical.

7. Conclusions

The present study is conclusive towards the generation of Fe–Ti oxides and acquisition of magnetic fabrics in the SMB meta-sediments and the associated Dalma lavas and its relationship with the regional tectonics. The meta-sediments (schists and quartzites), although have a magnetic fabric synchronous to D_2 , the equal area projection of their susceptibility axes is dispersed rather than clusters pointing towards a haphazard and weak pre-deformational (depositional) fabric. These sort of haphazard fabrics are characteristics of rift basins with polymodal sources (Renault and Ashley 2002). Thus, the sedimentation in the SMB was initiated in an inter-continental rift basin. After the deposition of these sediments, there was an upliftment. The presence of low temperature oxidised titanomagnetite and ultrafine grains of secondary magnetite, occurring with haematite pigments are indicative of upliftment of with slow cooling as during upliftment and/or exhumation there occurs release of pressure which led to the development of cracks within the oxide minerals which further gets filled in by silicates and thus these features can be attributed towards upliftment of the deposited sediments and slow cooling (Chatterjee *et al.* 2016, 2018b; also see Akimoto *et al.* 1984). However, these features are absent in the volcanic rocks where the titanomagnetite grains are fresh and are almost devoid of upliftment related oxidation processes. Hence the entire process of deposition of the SMB sediments and their subsequent upliftment was prior to the mafic volcanism and thus the development of rift basin and upliftment can be attributed towards the pre-eruption rise of large volume of mantle rocks supporting plume related volcanism which is debated till date (Mazumder

2005 and references therein). These set of events were succeeded by volcanism and the corresponding volcanic rocks have magnetic fabrics which are analogous to fabrics of subaerial lava flows with at least localised aqueous environment. Presence of pillow lavas also supports the same. These localised aqueous environments are due to the endorsement of drainage network during plume related upliftment (Cox 1989).

Sedimentation and volcanism in rift setting was followed by multiple phases of deformation, which, although have imposed a near-homogeneous mesoscopic fabric, have failed to control the patterns of magnetic fabric. The meta-sediments which possessed weak depositional fabrics were easily converted to tectonic ones during D_2 event. Post D_2 , the deformation events were not intense enough to change the magnetic fabric patterns. The deformations D_3 and D_4 were not intense enough to develop any penetrative fabric element in the terrain except some local replication of F_3 by K_1 in the schists. But, the disagreement of the magnetic fabrics with D_2 in the eastern part near Burudih and neighbouring areas are due to the interference of the Dalma thrust, where there occurred rotation of the D_2 controlled magnetic fabric in a direction parallel to the thrust itself. Thus, although the rocks towards the south of the Dalma thrust are virtually unaffected by it, have their magnetic fabrics developed synchronous to the Dalma thrust. The high value of P_j in Burudih and Dharagiri areas for all the rock types corroborates the contention. Evidently, the effect of the Dalma thrust is limited to the eastern most part of this volcano-sedimentary belt. The volcanic rocks on the other hand have fossilised their primary depositional fabric throughout the terrain. The reason for this is the presence of high concentration of ferro-magnetic minerals (titanomagnetite) in the mafic volcanics, which can retain the magnetic fabric imposed to them during eruption despite overprinting by polyphase mesoscopic deformation events (Tarling and Hrouda 1993). As this is proved that the magnetic fabric in the volcanic rocks are primary in origin defined by oblate titanomagnetite grains, it can be safely stated that the titanomagnetite grains are present on the near-horizontal magnetic foliation along which lava flowage and shearing during flow has taken place. The abundance of the titanomagnetite grains on the horizontal lava flow exposures supports the same. This proves that although magnetic fabric is already established as a robust tool in studying deformation, rocks with extreme

high concentration of ferro-magnetic mineral may retain their mineralogically controlled primary fabric without recording deformation.

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