Anisotropy of Magnetic Susceptibility (AMS) Studies on Quartzites of Champaner Group, Upper Aravallis: An Implication to Decode Regional Tectonics of Southern Aravalli Mountain Belt (SAMB), Gujarat, Western India

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Abstract Here we present, Anisotropy of Magnetic Susceptibility (AMS) studies on quartzites of Champaner Group, Gujarat, Western India. As quartzites are dominantly present within each formation of the Champaner Group, they have been selected for the study. Our study on AMS signifies two prominent striking planes of magnetic foliation within the rocks. The rocks have (i) ENE-WSW to E-W and (ii) N-S to NE-SW trends. The former trend matches with the regional magnetic foliation of Godhra Granites (GG) and neighboring Banded Gneisses (BG), while the later one does not match with any of the trends resulted due to last phase of deformation within Southern Aravalli Mountain Belt (SAMB). Such heterogeneity among the later trends signifies further continuation of emplacement of GG after syn-tectonic pulse and regional deformation. This latter phase of granite led to the development of broad open N-S trending folds within the supracrustals along with its basement and doming up of sequences towards the eastern periphery of the Champaner Group.

Keywords AMS · Champaner Group · Godhra Granites · SAMB

1 Introduction

Rock samples when subjected to external magnetic field, certain minerals within the sample show same strength of induced magnetization in all directions and are considered as "magnetically isotropic". On the contrary, there are few minerals in the rocks, which have different strength of induced magnetization in preferred directions are called as "magnetically anisotropic". Such minerals have an Anisotropy of Magnetic Susceptibility (AMS). Variation in susceptibility in preferred directions creates susceptibility ellipsoid (Tarling and Hrouda 1993), having three principal axes—long, intermediate and short. These axes are the principal susceptibility axes represented

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in SI units as K1, K2 and K3, where K1 ≥ K2 ≥ K3. The axes of susceptibility ellipsoid generally show a preferred orientation of principal axes of the strain ellipsoid in tectonically deformed rocks (Hrouda and Janak 1976; Rathore 1979, Borradaile and Tarling 1981, 1984; Hrouda 1982; Borradaile and Mothersill 1984; Borradaile 1987, 1991; Borradaile and Alford 1987; Borradaile and Henry 1997).

In the present paper, we provide AMS data generated on quartzites of Champaner Group belonging to the Aravalli Supergroup with an aim of demonstrating the last deformation imprint recorded within this rock. With the help of the AMS data, strong correlation has been established between the deformation signatures pertaining to the Champaner Group along with its basement and the neighboring Pre-Cambrian stratigraphic units. The present attempt is to explore the AMS fabrics from Champaner Group of rocks, particularly quartzites, as emphases regarding the emplacement record of granite, to understand the SAMB tectonics operated at its southern margin.

2 Geological and Structural Setting

The Champaner Group, a part of upper Aravallis is exposed at the eastern most fringe of Gujarat, India (Gupta et al. 1997) (Fig. 1). It bears an important link between the main Aravalli domains with the Central Indian Tectonic Zone (CITZ). The Champaner Group consists variety of rock types such as quartzites of manganiferous and non-manganiferous variety, polymict and oligomict metaconglomerates, carbonaceous phyllites and schists, spotted slates, hornfelses, manganiferous phyllites, biotite schists, dolomitic limestones, calc-silicate rock and meta-greywackes, which overlies the Paleo-Proterozoic Pre-Champaner Gneissic Complex (PCGC) located at Chhota Udepur region–i.e. "considered basement", comprising granite-gneisses, quartzites and pelitic gneisses (Gupta et al. 1992, 1997; Merh 1995; Srikarni and Das 1996; Karanth and Das 2000; Das 2003) (Fig. 2). The Champaner rocks show greenschist facies metamoprhism and hornfelses are developed at the contact aureole with granite intrusive. (Das et al. 2009; Joshi and Limaye 2018; Joshi 2019a, b). Granites located in and around Champaner Group indicate syn-to-post emplacement record. Timing of granites suggest a wide span of dates from 1.1 to 0.93 Ga (Joshi and Limaye 2018).

Structurally, the rocks including quartzites, show poorly deformed signatures having three phases of deformation, viz. D_1, D_2 and D_3. The three phases of deformation have resulted into F_1, F_2 and F_3 folds, respectively. D_1-D_2 resulted into F_1-F_2 are coaxial having ESE-WNW and E-W trend, respectively, while the D_3 shows folds having NNW-SSE to NNE-SSW trend. Combination of $F_{1\text{-}3}$ folds have resulted into various interference fold patterns on regional as well as on the outcrop scale. The Type-III interference fold pattern has formed on account of regional deformation resulted due to combinations of $F_{1\text{-}2}$ folds, whereas the Type-I interference pattern superimposed orthogonally over Type-III, which led to the development of domes. This last axial trace generated on account of superimposition is produced by later granitic pulse, represents F_3 folds (Joshi 2019a, b). In addition, there has

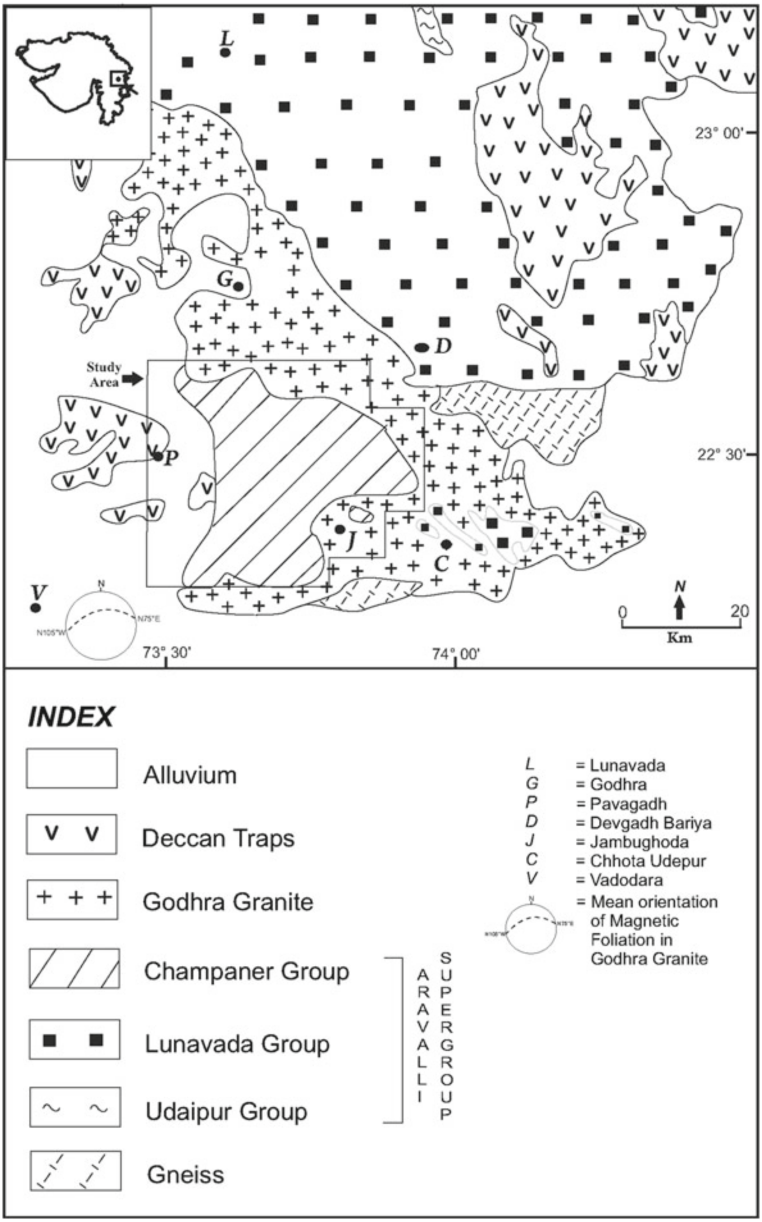

Fig. 1 lithostratigraphic map of SAMB, NW, India, specifying location of the Champaner Group. Modified after Mamtani and Greiling (2005). Square indicates the study area magnetic foliation data presented within Godhra granite is after Mamtani (2014)

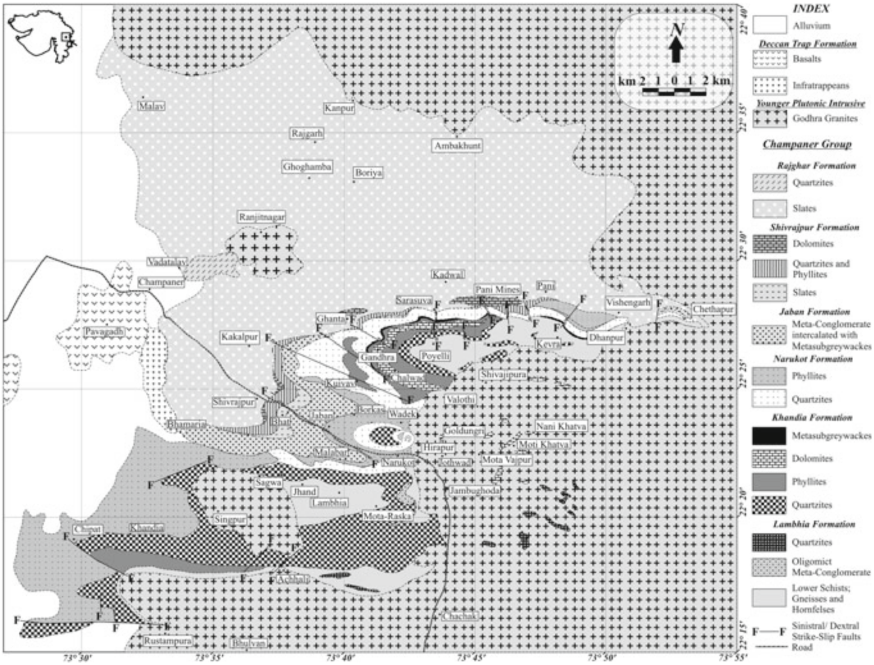

Fig. 2 Geological map of the Champaner Group, after Joshi 2019b

been observed evidences of out-of-sequence deformation (i.e. trends, which not concomitant with F_1, F_2 and F_3) demonstrate varied trends and meso-scale interference patterns inside the detached and isolated patches of calc-silicates, caught up within the granites (Joshi and Limaye 2018).

3 Anisotropy of Magnetic Susceptibility Studies on Quartzites, Principle and Methodology

Quartzites of the Champaner Group are hard, massive, compact; at times flaggy and whitish to dark grey and/or black in colour. They are highly jointed with variable grain size from fine to coarse and display varieties of primary sedimentary structures at different locations of the study area. By and large quartzites of the study area exhibit E-W to NW-SE strikes with variable dip directions. Petrographic study of quartzites reveal granoblastic polygonal, mosaic with two granular boundary varieties (i.e.) in-equigranular interlobate and seriate interlobate. The former type is observed in the quartz grains showing sutured boundaries with large scale variability in grain size, whereas the latter shows less size variation with sutured grain boundaries. At places the grains show inclusions of mica flakes especially Mn-rich-muscovite having colourless to faint green pleochroism (Patel et al. 2016).

The present section deals with the Anisotropy of Magnetic Susceptibility (AMS) studies carried out on quartzites of the Champaner Group. Oriented samples were collected at 12 localities across the Champaner Group and more than 60 cores were analyzed for the AMS study. These measurements were done using KLY-4 Kappabridge at Department of Geology and Geo-physics, Indian Institute of Technology, Kharagpur. The instrument gave the results for the following parameters: (1) the magnitude and orientations of three principal axes of the susceptibility ellipsoid viz. K1, K2 and K3, where K1 $\geq$ K2 $\geq$ K3; (2) mean susceptibility (km); (3) degree of anisotropy (Pj); (4) shape parameter (T); (5) magnitude of foliation (F) and (6) lineation (L) (Table 1). The quartzites of the study area reflect low Km values, having the mean susceptibility as 47.37×10^{-6} SI units. Some quartzites reveal exceptionally high mean susceptibility values more than 250×10^{-6} SI units, due to the presence of biotite content.

4 Result and AMS Data Interpretation

The orientations of all three principal axes K1, K2 and K3 have been plotted using lower hemisphere stereographic projection. The plane passes through K1-K2 and essentially matching with K3 pole defines the magnetic foliation (F). The F plane in the given figure is plotted with the dotted line. The stereographic net is also aided with the planar structure S_0 (bedding plane) acquired through field and has been depicted by means of continuous line (Fig. 3). There are total 12 samples, viz. SN1-4, SN6, CPR1, CPR3-5 and CPR7-9, out of which 61 cores have been analyzed.

As mentioned in the geological and structural setting section, the Champaner Group shows three phases of deformation, viz. D_1, D_2 and D_3, of which first two phases were co-axial (F_1 ~ ESE-WNW; F_2 ~ E-W) and the last phase of deformation has N-S trend. The response of all three phases of deformation has been recorded within the quartzites of the Champaner Group. The samples collected from the southern part of the study area, viz. CPR1, 3, 4 and 5 show dominance of F_1 and F_2 folds. The CPR1 sample has a dominance of F_1 fabric on an outcrop scale due to the presence of mesoscale folds, but shows dominance of magnetic foliation in nearly E-W direction. The superimposition of F_2 fabric over F_1 is clearly seen in the sample collected from NW of Masabar (CPR1). CPR3 sample from the F_2 limb portion show oblique relationship of the magnetic foliation with the bedding. CPR4 and 5 collected from F_2 limb, depicts similar trend of bedding and magnetic foliation. These samples show the effect of F_2 folds present in the southern part of the study area. The signatures of F_3 fold or preferred orientation along N-S direction are not seen in the present samples. This suggests that the last episode of deformation did not show any mineral alignment in the southern part of the study area.

CPR 7 and SN2 sample collected from the eastern part of the study area from Narukot dome clearly signifies similar relationship of S_0 and S_1 in these quartzites.

Table 1 AMS data of the quartzites of the Champaner Group

Sample No.	K_m (10^{-6} SI units)	F	L	P_j	T	K_{max}	K_{int}	K_{min}	K_{max}—D/I	K_{int}—D/I	K_{min}—D/I
SN1	10.80	1.623	1.722	1.101	0.107	1.074	0.967	−0.573	284/45	15/2	107/45
SN2	6.67	6.676	1.619	1.302	0.335	1.158	0.883	−0.644	319/78	134/12	225/01
SN3	2.30	1.912	1.092	1.021	0.726	1.215	1.041	0.744	280/07	13/18	170/71
SN4	95.40	1.030	1.042	1.074	−0.084	1.037	0.989	0.974	275/09	19/55	179/33
SN6	180.0	1.057	1.026	1.087	0.349	1.035	1.008	0.957	300/35	58/36	178/37
CPR1	162.0	1.122	1.015	1.153	0.775	1.045	0.999	0.956	86/44	279/46	182/07
CPR3	20.00	2.331	1.113	1.412	0.419	1.021	0.569	0.723	281/28	13/03	109/62
CPR4	0.0833	1.193	0.957	1.403	−0.052	−0.030	−0.289	−0.450	75/21	320/48	181/34
CPR5	19.20	1.717	1.104	2.014	0.553	1.015	0.652	0.732	292/39	77/45	187/18
CPR7	7.41	1.393	1.817	2.642	0.109	−0.353	−0.472	−0.975	265/80	63/09	154/04
CPR8	145.00	1.050	1.049	1.107	−0.084	1.019	1.066	0.974	154/52	16/31	273/21
CPR9	28.70	1.090	1.042	1.143	0.010	1.023	0.235	0.863	310/35	128/55	219/01

K_m = mean susceptibility; F = magnetic foliation; L = magnetic lineation; P_j = degree of anisotropy; T = shape parameter; K_{max}, K_{int}, K_{min} = represent magnitudes of maximum, intermediate and minimum axis of the magnetic ellipsoid, D/I = the direction and inclination of principle axes of magnetic ellipsoid in degrees

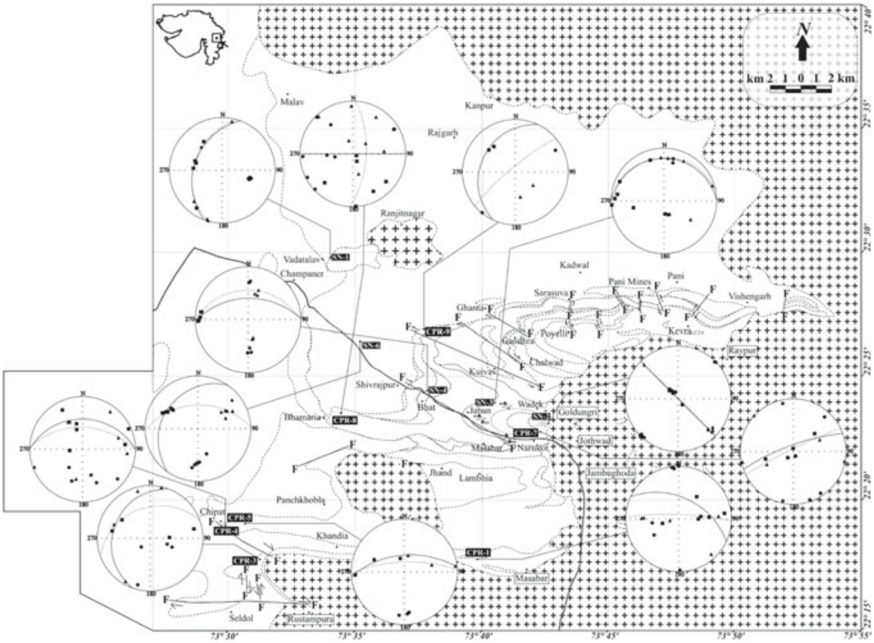

Fig. 3 AMS orientation data plotted as lower hemisphere projections for the Champaner Group. Dotted great circles represent the magnetic foliation, whereas continuous great circles represent the S_0 reading recorded from the field. Filled square, triangle and circle indicate orientations of K1, K2 and K3 respectively

The SN2 sample collected from F_1 fold limb and CPR 7 sample from F_2 limb gives nearer results of F_1 and F_2 fabric. It suggests that although, there is a dominance of N-S deformation in the eastern part of the study area, the preferred magnetic fabric parallel to F_3 is absent. Such condition has occurred due to the presence of F_2 fold dominance in the Narukot area. Further to the west of the Narukot dome, the samples collected along the axial trace of the F_2 fold (SN3, SN4 and SN6), show prominence of E-W magnetic foliation. The D_2 imprint recorded within these rocks clearly suggests that the central part of the Champaner Group has a dominance of N-S shortening. The western and northern part of the study area shows the magnetic fabric parallel to the D_3 deformation of the Champaner Group in the samples viz. CPR 8, CPR 9 and SN1. This magnetic fabric ranges from N-S to NE-SW; however there is no mesoscopic scale imprint of the late deformation in the present localities.

Jelinek plot (Pj vs. T) (Fig. 4), suggest that majority of the cores fall in the oblate field (flattening field) and few cores from the quartzites show their affinity towards prolate field (constrictional field). In order to examine the type of strain, the available AMS data has been plotted as Flinn diagram (F vs. L), which holds good correlation with the Jelinek plot. Most of the AMS data of cores from quartzites of the Champaner Group represented in the Flinn diagram concentrated in the oblate

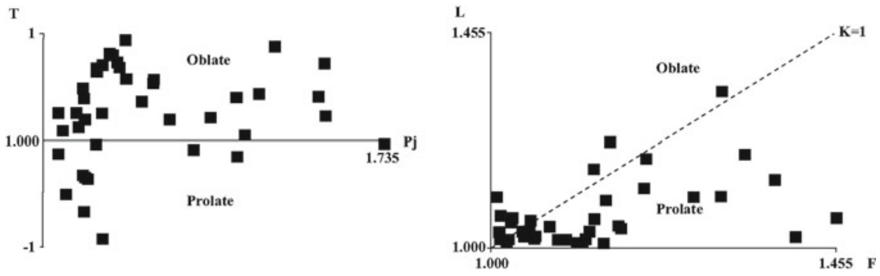

Fig. 4 Jelinek plots (at left) and Flinn diagram (at right) for the quartzites of the Champaner Group

field and few around K = 1 line, which separates the prolate and the oblate field. This is an indication of the plane strain condition (Fig. 4).

5 Discussions

5.1 Significance of AMS Study for the Study Area

The AMS data results from quartzites of Champaner Group indicate that there exist two prominent striking planes of magnetic foliation, viz (i) ENE-WSW to E-W and (ii) N-S to NE-SW. The former range of strikes represent the first two phases (i.e. D1 = F1 ~ ESE-WNW and D2 = F2 ~ E-W), while the later orientation matches with the third deformational phase (i.e. D3 = F3 ~ NNW-SSE to NNE-SSW) recorded within the Champaner Group along with its basement.

Advancement in the present technique indicate that the Anisotropy of Magnetic Susceptibility (AMS) studies have been used to deduce the time relationship between emplacement/fabric development and regional deformation (Mamtani and Greiling 2005); in kinematic analysis and vorticity quantification of syn-tectonic granitoids (Tarling and Hrouda 1993; Benn et al. 1998, 1999, 2001; Majumder and Mamtani 2009; Mamtani et al. 2013); to capture imprints of superposed deformation in granitoids (Mondal 2018; Mamtani et al. 2019). In the light of this extensive work on Godhra and other granitoids, authors posit their AMS data set generated on quartzites by correlating it with the existing literature on structural and magnetic records related to the SAMB.

5.2 AMS of Adjoining Areas

The structural records from Pre-Cambrian stratigraphic units of SAMB, viz. (1) the Banded Gneisses (BG); (2) the Lunavada Group (LG); (3) the Champaner Group

(CG) along with its basement (Pre-Champaner Gneissic Complex-PCGC); (4) the Godhra Granites (GG); signifies that each of the unit that belongs to the SAMB, except GG have underwent at least three phases of deformation (Table 2). Moreover, the magnetic records derived through BG, LG and GG, by the earlier workers state that these magnetic trends are coeval with the last phase of deformation (having strikes ~ WNW to WSW and plunge ~ NW to W), recorded within the SAMB (Mamtani and Greiling, 2005). Unlike in the case of CG, where the latest magnetic foliation (having strikes ~ N-S to NE-SW), demonstrating the last phase of deformation within CG, show a distinct heterogeneity in terms of trends recorded during the waning phase of SAMB. In addition, the strain estimation derived with the help of degree of magnetic anisotropy value (P′ or P_j) from Godhra granite samples, suggest that southern part of GG, in proximity to CITZ tends to show inflated P′ or P_j values, implying the rocks have accommodated higher strain condition than their northern

Table 2 Summary of deformation events recorded in neighbouring Precambrian Supracrustals and its relationship with the Champaner Group along with its basement

The Banded Gneisses (BG)	The Lunawada Group (LG)	The Pre-Champaner b Complex (PCGC)	The Champaner Group (CG)	Godhra granite (GG)
D_1 and D_2 coaxial having axial trace trend NE-SW to ENE-WSW	D_1 and D_2 coaxial having axial trace trend NE-SW	D_1 having axial trace trend N-S of recline folds	–	–
D_3 having axial trace trend ESE-WNW to ENE-WSW	D_3 having axial trace trend E-W to NW-SE	D_2 and D_3 having axial trace trend E-W with different fold morphology (a. recline & b. upright)	D_1 and D_2 coaxial having axial trace trend F1 ~ ENE-WSW F2 ~ E-W	Preferred orientation of feldspar laths trend ESEWNW; magnetic foliation trend ESE-WNW to ENE-WSW
–	–	*D_4 having axial trace trend N-S upright warps and kinks*	*D_3 having axial trace trend NNW-SSE to NNE-SSW + out-of-sequence deformation trend NE-SW*	–

Structural records from the Banded Gneisses and the Lunawada Group (Mamtani 1998; Mamtani and Greiling 2005); the data from the Pre-Champaner Gneisses (Karanth and Das 2000); Godhra granite magnetic data and preferred orientation of feldspar laths (Mamtani and Greiling 2005; Mamtani et al. 2002; Sen and Mamtani 2006). The columns in italics indicate correlatable axial trace trends within Champaner Group and its basement, which are unmatched with the last phase of deformation associated to the Southern Aravalli Mountain Belt (SAMB). Modified after Joshi 2019b counter parts (Mamtani et al. 2019). However, the quartzite samples collected from the eastern part of the Champaner Group, having predominantly N-S to NE-SW magnetic foliation reflects higher P′ or P_j value, suggests that the eastern part of the CG have accommodated high strain condition than any of the other direction (Table 1).

In order to understand the heterogeneity in terms of magnetic records, the study of granite located in and around the CG becomes vital. On the basis of structural data proposed by Joshi and Limaye (2018), suggests that the granites located in and around the Champaner region shows evidences of prolong emplacement records. One such evidence has been proposed by a field photograph published in Joshi and Limaye (2014), where, the coarse grained later pulse having intrusive relationship with the comparative fine grained granite variety. Also, the evidences suggested by Joshi (2019a) on genesis of interference fold patterns within CG, explained forceful emplacement of granite deforming the country rocks along N-S trend, on the basis of the model suggested by He et al. (2009) for Fangshan pluton, SW Beijing, China. In addition to that, the existing geo-chemical data of granites located in and around CG is in favor of two pulses revealing prior 'S' type granite (Goyal et al. 1997) and later the 'A' type variety representing transitional or post-orogenic uplift (suggested by Maithani et al. 1998 and Goyal et al. 2001). Finally, the Geophysical studies carried out within this terrain corroborate to the fact that there lies a sub-surface pluton beneath the CG, which has eventually up rooted the country rocks along with the pre-existing granitic pulse during the later stages (Joshi et al. 2018).

Hence based on the above facts it can be stated that the possibility of prolong emplacement record, which governed the tectonics of SAMB from its southern margin cannot be ruled out. At the end of regional deformation the granite pulse was still active at the southern margin deforming the Champaner metasediments along with its basement, to give rise different trends. These trends being restricted to the Champaner Group and its basement, have not been recorded in the neighboring supracrustals and thus how show heterogeneity in terms of last deformation imprint within the SAMB (Table 2).

6 Conclusion

1. The AMS studies on quartzites from Champaner Group indicate two prominent striking planes of magnetic foliation, viz (i) ENE-WSW to E-W and (ii) N-S to NE-SW. These trends matches with the three deformational phases occurred within the present group, along with its basement (i.e. D1 = F1 ~ ESE-WNW and D2 = F2 ~ E-W; D3 = F3 ~ NNW-SSE to NNE-SSW).
2. Correlating these magnetic fabrics of CG with the available structural and magnetic records from SAMB, suggest that there lies a distinct heterogeneity in case of latest trends of CG and SAMB.

3. Degree of magnetic anisotropy value (P′ or P_j) from quartzite samples indicate that the eastern part of the Champaner Group has accommodated high strain condition than any of the other directions.
4. The above facts are in favor of indicating the prolong emplacement record of GG, which governed the tectonics of SAMB from its southern margin.
5. During the waning phase of regional deformation of CG, the emplacement was still continued to deformed the Champaner metasediments along N-S trend, along with its basement.
6. As this latest trend was confined to the CG and its basement, have not been recorded with the neighboring supracrustals of SAMB.

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