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Magnetic fabric, shape preferred orientation and regional strain in granitic rocks

Koushik Sen, Manish A. Mamtani*

Department of Geology & Geophysics, Indian Institute of Technology, Kharagpur 721302, West Bengal, India

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Abstract

Since granites do not preserve easily mappable foliations, lineations, and strain markers, determining the degree of shape preferred orientation (SPO) in them is challenging. The aim of this paper is to present a methodology for determining variation in the degree of SPO in granites and to test the feasibility of correlating the same with regional strain. The case of the Godhra Granite located in the southern parts of Aravalli Mountain Belt (India) is taken as an example. Degree of SPO is determined using two different techniques (a) anisotropy of magnetic susceptibility (AMS) and (b) strength of mineral lineation determined by calculating the concentration parameter (κ) of von Mises distribution by digital image analysis of biotite (κ_{bi}) and feldspar (κ_f) in thin sections prepared parallel to the magnetic foliation plane. SPO data obtained using the above two techniques from 20 samples distributed across the entire granite are analysed. Samples with a higher κ also have a stronger magnetic fabric (magnetic lineation, L and degree of magnetic anisotropy P'). Also, the degree of SPO is greater for granites from the southern parts as compared to the northern parts. It is argued that this variation in degree of SPO cannot be attributed to rheological differences or strain resulting from difference in aspect ratios. Regional strain is inferred as the dominant factor. Since the emplacement of the Godhra Granite is synchronous with the tectonic rejuvenation along the Central Indian Tectonic Zone (CITZ) that lies to its south, the higher degree of SPO in the southern parts is attributed to its proximity to the CITZ. Whilst caution needs to be exercised to directly apply magnetic data as a measure of strain-intensity on a regional scale, it can be a useful guide to select samples for detailed SPO analysis using some alternative technique, especially for granites and other magmatic rocks that are devoid of mesoscopic strain markers.

Keywords: Anisotropy of magnetic susceptibility; Shape preferred orientation; Strain; Granite; Aravalli Mountain Belt; India

1. Introduction

Shape preferred orientation (SPO) in geological materials can be measured using different techniques such as, the intercept method that uses digital images of thin sections (e.g. Launeau et al., 1990; Launeau and Robin, 1996). The degree of magnetic anisotropy (P') obtained from Anisotropy of Magnetic Susceptibility (AMS) measurements is another parameter that is used for petrofabric studies to gauge the strength of preferred orientation of magnetic minerals (e.g. Tarling and Hrouda, 1993; Borradaile and Jackson, 2004). P', which describes the eccentricity of the magnetic susceptibility ellipsoid, has been equated with strain in a number of studies (e.g. Borradaile and Alford, 1987; Hrouda, 1993; Mukherji et al., 2004), although the one-to-one correlation is not always obvious (e.g. Archanjo et al., 1995; Borradaile and Henry, 1997; Borradaile and Jackson, 2004). Another method for measuring the degree of an SPO is by statistically determining the strength of a lineation in the foliation plane as defined by the concentration parameter, κ (Masuda et al., 1999; Piazolo et al., 2002), which increases with the strength of preferred orientation.

Several laboratory experiments have been performed to understand the relationship between degree of SPO, processes of SPO development and strain. Experiments by Ildefonse et al. (1992a,b) revealed that in case of rigid body rotation, SPO development depends on finite strain and on the concentration of

* Corresponding author. Tel.: +91 3222 283 388; fax: +91 3222 255 303/282 700.
E-mail address: mamtani@gg.iitkgp.ernet.in (M.A. Mamtani).

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the fabric forming material i.e., the rigid particles (also see Piazolo and Passchier, 2002). To understand the development of biotite fabrics in magmatic rocks Arbaret et al. (1997) carried out analogue experiments under simple shear and found that fabrics remain constant in orientation and magnitude with increasing strain and that the fabric strength does not depend on strain magnitude. On the other hand, Ildefonse et al. (1997) reviewed aspects of SPO development in magmatic rocks and concluded that although SPO's point to the local flow direction, there is no simple relationship between the intensity and orientation of the fabric, and finite strain. Numerous studies on rock analogues as well as numerical analyses have been carried out to understand the development of SPO and behaviour of groups of rigid particles under different deformation conditions (e.g., Bhattacharya, 1966; Pennacchioni et al., 2001; Piazolo et al., 2002; Cañón-Tapia and Chávez-Álvarez, 2004; Mandal et al., 2005). Based on these studies it is now well established that the degree of SPO is influenced by several parameters like strain, aspect ratio, rheology of the matrix material, type of flow, concentration of rigid objects and extent to which rigid particles interact with each other. Despite this information, there are only a few studies where the applicability of these results has been tested to understand SPO in naturally deformed rocks. Piazolo and Passchier (2002) carried out detailed field studies on the development of lineation strength in shear zones of Cap de Creus (Spain) and concluded that whilst strain is an important factor that controls the strength of a lineation (and hence SPO), other factors such as dynamic recrystallisation, metamorphic reactions and rigid body rotation can also play an important role. As stated earlier, rigid body rotation is also known to be controlled by strain in laboratory experiments (Ildefonse et al., 1992a,b).

In granitic rocks, petrofabrics have commonly been analysed using AMS studies (e.g. Bouchez et al., 1990; Bouchez, 1997; Hrouda et al., 1999; Benn et al., 2001; de Wall et al., 2001; Mamtani and Greiling, 2005). Archanjo et al. (1995) compared magnetic data and SPO determined using the intercept method on magnetite-bearing granite. They found that biotite and magnetite SPOs were sub-parallel to the magnetic lineation (K_1 direction) that defines the direction of maximum elongation of the magnetic susceptibility ellipsoid, although biotite SPO was closer to K_1 than that of magnetite. Also, a positive correlation was found between fabric strength and P' for biotite but not for magnetite. This was attributed to a possible influence of clustering of magnetite. Therefore, it was suggested that P' values may not be used to gauge strain-intensity in magnetite-bearing rocks. Launeau and Cruden (1998) combined AMS and image analyses data from syenites and found that the intensities, shapes and principal direction orientations of the resulting intercept ellipsoids were generally similar to the corresponding AMS ellipsoids. They also found that grains with higher aspect ratio tend to have a larger degree of alignment.

Apart from these and a few other works (e.g., Archanjo et al., 2002; Pignotta and Benn, 1999), not many studies compare magnetic fabric in granites with some other non-magnetic technique. Moreover, such an approach has not been attempted on a regional scale to identify strain gradients in naturally deformed granitic rocks and thus test: (a) the applicability of AMS in gauging regional strain variations; and (b) the extrapolation of some of the experimental and numerical results about SPO development in these rocks. This paper aims at filling the gap and at evaluating the relationship between the intensity of magnetic fabric, SPO degree and regional strain in natural geological situations. For this purpose samples from the Godhra Granite (Aravalli Mountain Belt, India) have been chosen and a general methodology is proposed to determine the degree of SPO in granites (and other magmatic rocks). The data are also used for regional interpretations.

2. Geology of the sampled area

The Godhra Granite is situated in the southern parts of the Aravalli Mountain Belt, NW India (Fig. 1) and is dated at 955 ± 20 Ma (Gopalan et al., 1979). It is flanked by the metasedimentary rocks of the Lunavada and Champaner Groups in the N and SW parts respectively, while a banded gneiss lies to its E and SE. Some of the contacts between the granite and the country rocks are high strain zones (Mamtani and Greiling, 2005). The granite is dominantly coarse to porphyritic with quartz, K-feldspar, plagioclase and biotite as the major minerals. A few samples also contain some hornblende along with biotite. Sphene, apatite, magnetite and ilmenite occur as subsidiary minerals. Fine-grained varieties occur at a few places, generally cutting through the coarser varieties. Inside the granite pluton, a fabric defined by preferred orientations of feldspar laths is noted at places. It trends between 110° and 140° and is prominent in the vicinity of Devgadh Bariya and around Godhra and to its north. Magmatic structures, such as magmatic shear zones and magmatic folds, are also observed in the vicinity of Godhra and to its north (Fig. 2). In contrast, the southern part of the granite around Chhota-Udepur is totally devoid of similar magmatic structures.

A study of 100 thin sections from spatially distributed samples from the entire granite reveals that a high-T fabric defined by chessboard pattern in quartz is present throughout the granite. However, a difference in the dominant fabric in different parts of the granite is noted. Magmatic microstructures like oscillatory zoning in plagioclase (Fig. 3a), perthites in K-feldspar and evidence of melt present deformation such as fracture in K-feldspar healed by sodic rims joining an adjacent plagioclase grain (Bouchez et al., 1992) (Fig. 3b) dominate the granites from the NW part of the granite (around Godhra and to its north). The region around Devgadh Bariya in the central part of the granite (Mamtani and Greiling, 2005) preserves good evidence of superposition of high-T solid-state fabric over a magmatic fabric. This part is also marked by subgrain rotation recrystallisation in quartz, some recrystallised feldspars and a few kinked biotites. Low-T solid-state fabrics defined by deformation twins in plagioclase (Fig. 3c) and kinked biotite crystals (Fig. 3d) are very prominent in the granites from the southern part (around Jhoj and to its south). Interestingly, zoned feldspars and other magmatic to sub-magmatic microstructures are absent in this southern part of the Godhra Granite, in contrast to the fabric that dominates the northern part.

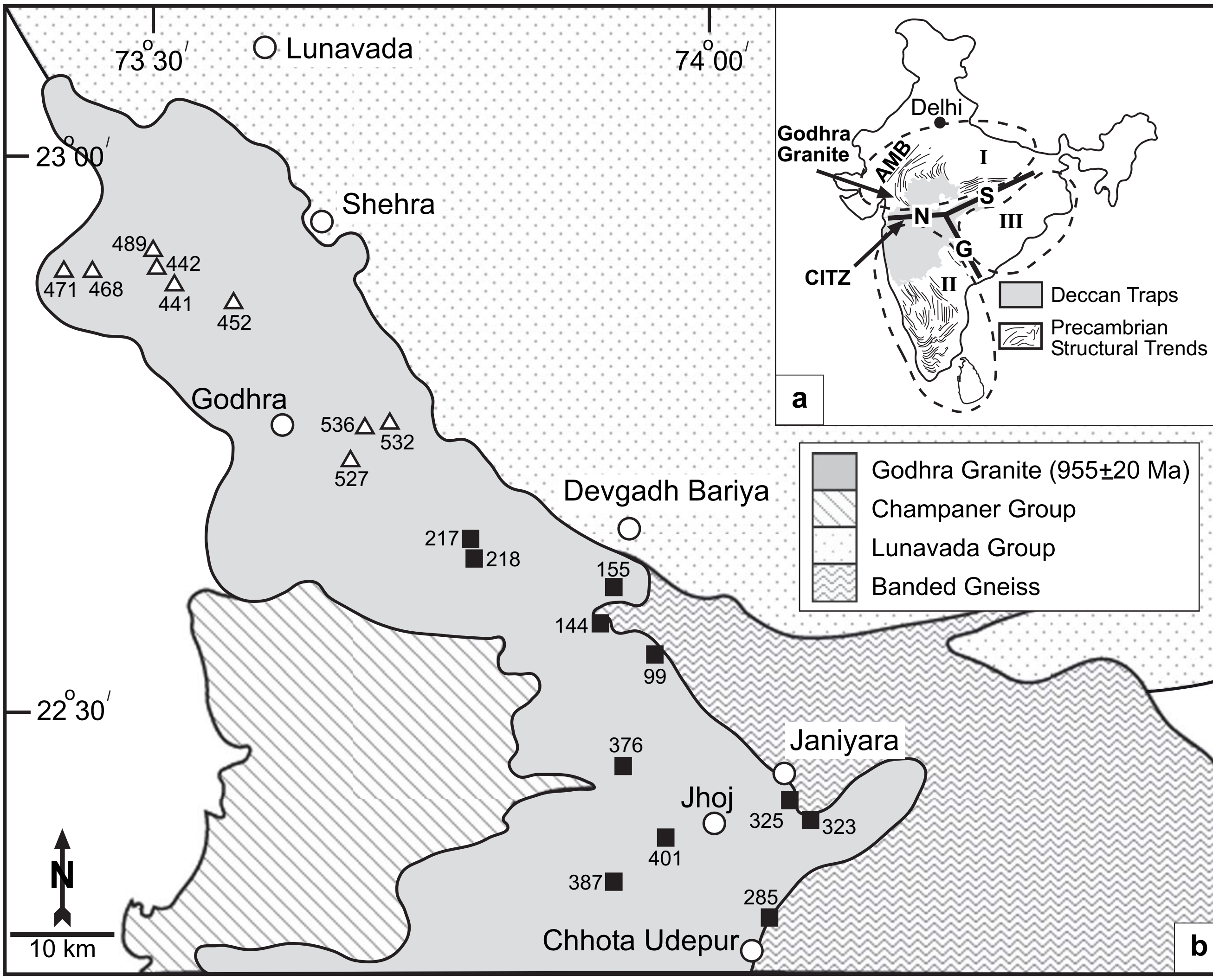

Fig. 1. (a) Map highlighting the position of the Aravalli Mountain Belt (AMB) and the Godhra Granite in the southern parts of AMB. I, II and III are the Aravalli, Dharwar and Singhbhum Protocontinents that are believed to have accreted during the Proterozoic period to form the Indian shield along the Y shaped Narmada (N), Son (S) and Godavari (G) lineament (Naqvi et al., 1974). The region in the vicinity of N and S lineament has been redefined as the Central Indian Tectonic Zone (CITZ) inferred to have formed by amalgamation of the North Indian Block and the South Indian Block (Yedekar et al., 1990). (b) Geological map of study area around Godhra Granite in the southern parts of AMB. The triangles and filled squares show the sample locations to the north and south of Devgadh Bariya respectively; oriented thin sections of these samples were investigated to determine the degree of shape preferred orientation (SPO) in the present study.

The above field and microstructural observations indicate that the southern part of the Godhra Granite is deficient in magmatic fabric and has a stronger solid-state deformation fabric in comparison to the northern part. Mamtani and Greiling (2005) inferred the emplacement of this granite to be synchronous with the tectonic rejuvenations along the CITZ that lies to the south of the granite. Therefore, the difference in the fabric between the northern and southern parts of the granite maybe related to regional strain. This warrants a systematic analysis of the degree of SPO in the granite to identify any possible relationship with regional strain.

3. SPO analysis: techniques

In the present study degree of SPO in the Godhra Granite samples has been determined using the AMS technique and the calculation of the strength of lineation.

3.1. AMS measurement

The anisotropy of magnetic susceptibility (AMS) was measured with the KLY-4S Kappabridge (AGICO, Czech Republic) in the Magnetic Laboratory of the Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur (India). Oriented cylindrical cores having 25.4 mm diameter and 22 mm height were used for measurements in the spinner mode. The database gives the orientation and magnitude of the three principal axes of the magnetic susceptibility ellipsoid ($K_1 \geq K_2 \geq K_3$). The magnetic lineation is attributed to K_1 and the pole to the magnetic foliation (K_1K_2 plane) to K_3. The magnitudes of these principal directions are used to calculate different parameters: K_m (mean susceptibility), P' (degree of magnetic anisotropy, which is a measure of the eccentricity of the magnetic susceptibility ellipsoid), L (magnitude of magnetic lineation), F (magnitude of magnetic

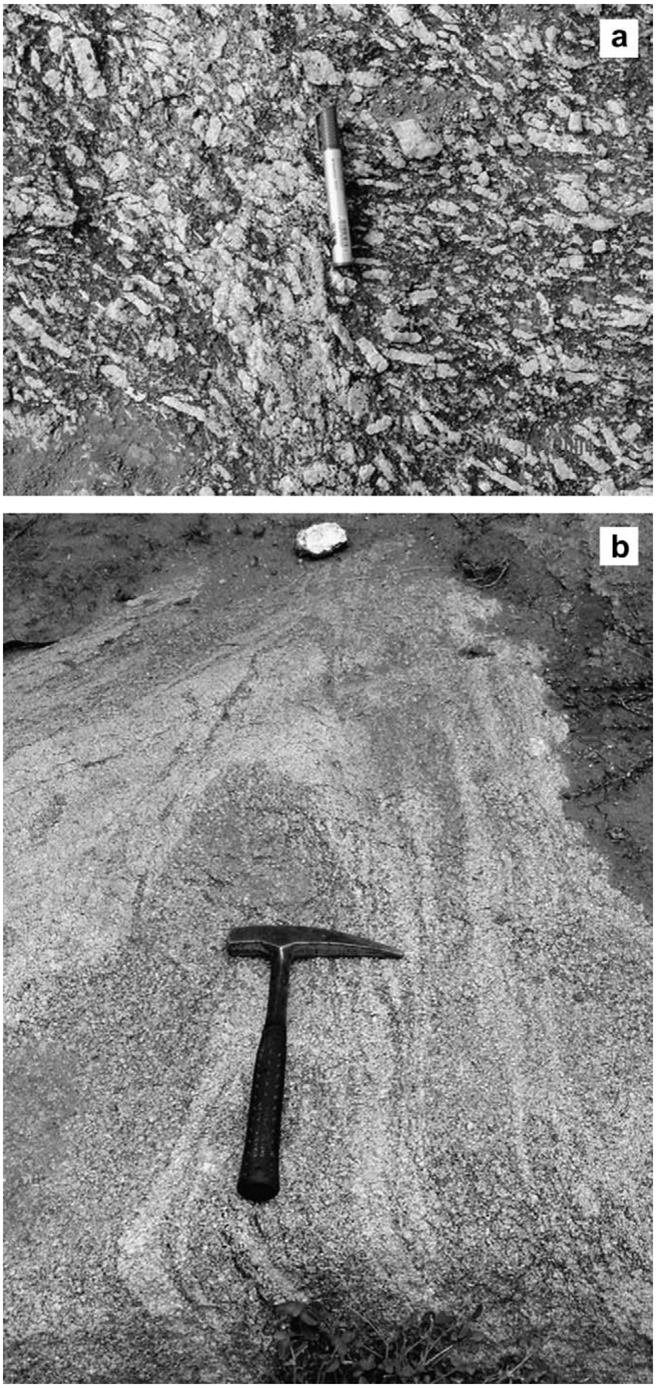

Fig. 2. Field photographs of magmatic structures in the Godhra Granite observed in the vicinity of Godhra town. (a) Magmatic shear zone defined by systematic curving of euhedral K-feldspar laths into a new orientation; camera looking to the north. (b) Magmatic fold in the granite. The fold has a reclined geometry; the axial plane strikes 225° and dips steeply towards NW (camera faces 210°).

foliation) and *T* (shape parameter that describes the oblate/prolate shape of the magnetic susceptibility ellipsoid). Tarling and Hrouda (1993) give the formulae of the above parameters. The software SUFAR attached to the KLY-4S Kappabridge was used to automatically calculate the above parameters. A total of 615 cylindrical cores from 248 sites spatially distributed throughout the Godhra Granite were analysed. *Supplementary Data-1* shows the map with locations of sites in the Godhra Granite from where samples were taken for AMS analyses.

3.2. SPO measurement in thin sections

Shape preferred orientations (SPOs) were quantified by calculating the strength of lineation, κ in 20 oriented thin sections prepared along the magnetic foliation i.e., K_1K_2 plane. Biotite (Bi) is the dominant elongated (flaky) mineral in the Godhra Granite. It is therefore a primary choice for determination of κ. Out of the 20 samples, 4 samples (nos. 285, 323, 325x and 527) also contain some hornblende (Hb). In samples 285, 323 and 325x, Hb comprises $<17\%$ of the flaky minerals while $>83\%$ of flaky minerals are biotite. A higher proportion of Hb is present in sample 527. Therefore, the data of Hb are treated as a part of Bi. Moreover, from field studies it is known that feldspar crystals tend to have a preferred orientation in some areas. Therefore, feldspar was the other mineral species that was found suitable for determining κ. The calculations were done using the Excel Worksheet of Piazolo and Passchier (2002). Masuda et al. (1999) have the statistical details. The following procedure was followed.

A frame from an oriented thin section was captured using a digital camera attached to the microscope. For Bi, and for Bi + Hb in the 4 samples mentioned above, each frame was captured in plane polarized light (PPL) while feldspar (F) was captured under crossed nicols (XN). Leica Qwin software was used for digital image analysis of each captured image frame. Although binarizing of images can be done automatically and very quickly using this software, e.g. by identifying the brown colour of Bi in PPL, a different method was used. In each frame, the boundary of an individual crystal of the desired mineral was mapped using the above software and the crystal was binarized. This process was repeated for a number of crystals of the same mineral in that particular frame (*Supplementary Data-2*). Throughout this process the position of the slide on the microscope stage was not changed till all the crystals of the desired mineral from the frame had been mapped. This allows checking of the mineral being mapped. Although this process of binarizing an image takes a longer time than the automatic method, it reduces the errors in mineral identification (e.g. Bi in PPL and feldspar in XN in the present case). Further statistical analyses were performed automatically using this binary image with the help of the same software. The basic statistical data generated were: (a) the aspect ratio (R) of each individual grain; and (b) the angle θ between the long axis of each grain and a reference axis of the microscope stage.

To obtain statistically meaningful data for an entire thin section, several frames were captured from each thin section. Since the thin section was fitted within an XY object guide on the microscope stage an identical orientation was maintained while capturing various frames. The above procedure of converting a frame into a binary image and subsequent statistical analysis was repeated for every frame. Finally, the data obtained from different frames of a particular thin section were

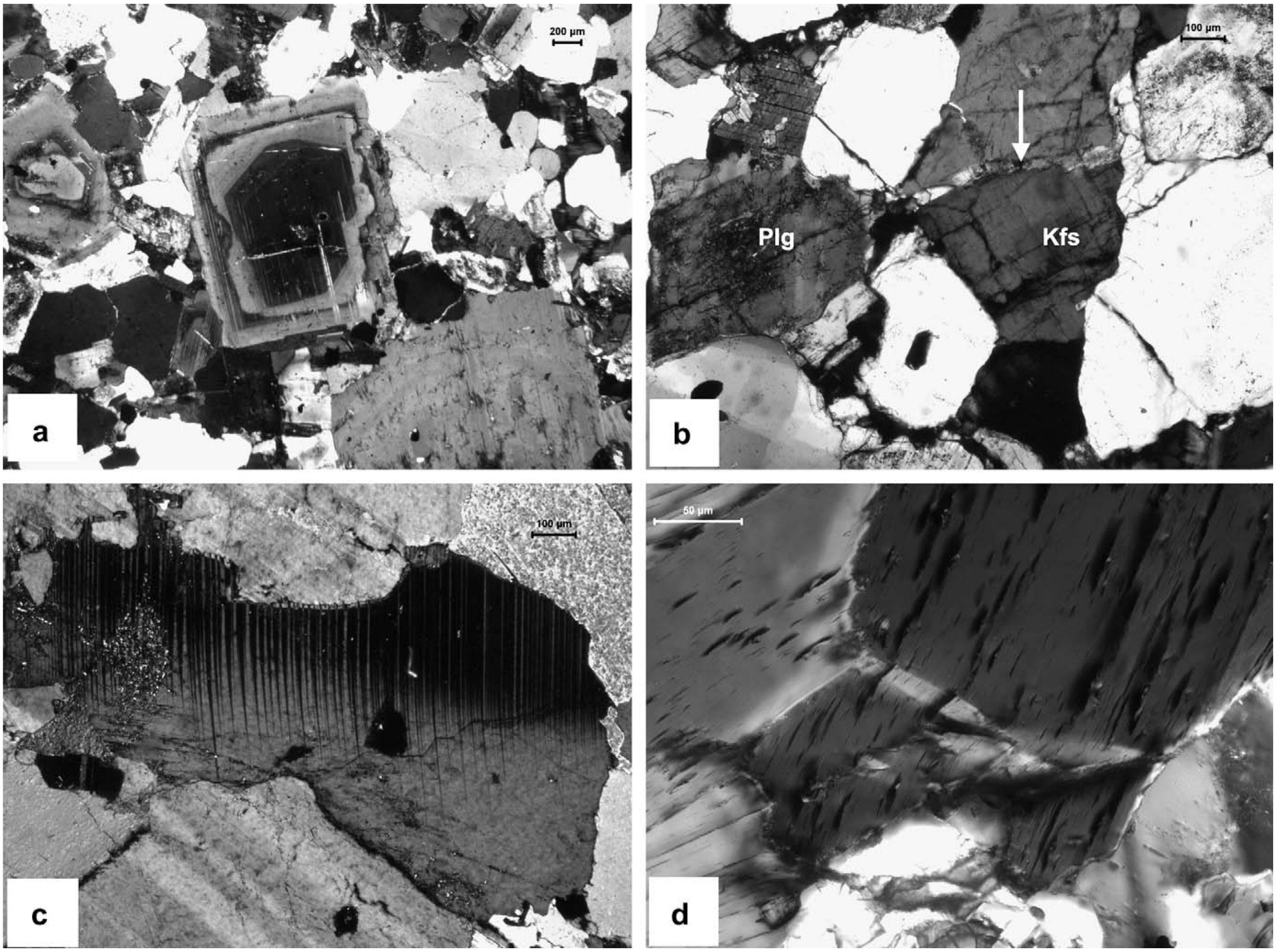

Fig. 3. Photomicrographs of microstructures noted in Godhra Granite. (a) Oscillatory zoning in plagioclase. (b) Fractured K-feldspar healed by plagioclase (arrow) indicating melt present deformation. (c) Deformation twins in plagioclase. (d) Kinked biotite. (a), (b) are from north of Godhra, and (c) and (d) are from vicinity of Chhota Udepur.

compiled for Bi and F. θ for Bi and F were determined and these were used to calculate κ_{bi} and κ_f. These define the degree of SPO of Bi and F respectively. Note that >70 crystals of Bi and >50 of F have been considered in most thin sections, largely above the critical number (30) necessary to get a reliable κ value (Piazolo and Passchier, 2002). In order to evaluate the relationship between intensity of magnetic data with the intensity of digitally calculated statistical SPO data (κ) the following plots were prepared: strength of magnetic lineation (L) vs. κ, degree of magnetic anisotropy (P') vs. κ and mode of aspect ratio (R) vs. κ. Separate plots were prepared for data from Bi and F and the results are presented in the following section.

4. Results

4.1. Magnetic data

AMS study of 248 granite samples reveals that the K_m varies between 12 and 46,000 μSI. A major part of the granite has $K_m > 500$ μSI and, following the classification of Bouchez (1997), the granites are largely classified as ferromagnetic in character. Multidomain magnetite is indeed present in these granites (Mamtani and Greiling, 2005). The strength of magnetic lineation (L) for the whole granite varies between 1.001 and 1.266. In the contoured L map (Fig. 4) it is observed that L tends to be higher in the south than in the north. A similar trend was also noted from the contoured P' diagram of Godhra Granite (Fig. 2b of Sen et al., 2005); P' in the granite ranges between 1.000–1.643. *Supplementary Data-3* contains the tabulated AMS data for all the Godhra Granite samples analysed from 248 sites.

4.2. SPO data from the thin sections and comparison with magnetic data

It is noted from AMS measurements that the intensity of magnetic fabric (L and P') is stronger in the southern parts of the granite. It was also shown earlier that the northern part of the granite has a dominance of magmatic structures whilst low-T solid-state deformation fabric is abundant in the southern part. Therefore, for determination of κ, samples were selected from across the entire Godhra Granite with the

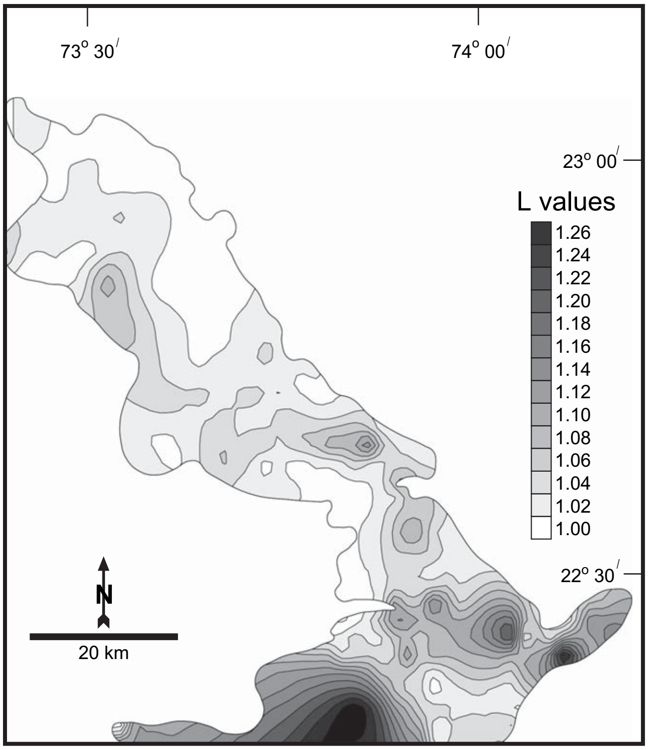

Fig. 4. Contoured magnetic lineation strength (L) map of the Godhra Granite. It maybe noted that the strength of the magnetic lineation is higher in the southern parts of the granite as compared to the northern parts.

aim of identifying differences in the degree of SPO. The region to the south of Devgadh Bariya is referred to as the southern sector (11 oriented thin sections were studied from this part; see filled squares in Fig. 1b) and the region to the NW of Devgadh Bariya is referred to as the northern sector (9 oriented thin sections; open triangles in Fig. 1b).

The entire SPO database concerning the 20 samples and the magnetic data are given in Table 1. θ was the primary SPO data that was determined from each thin section. Using this data κ_{bi} and κ_f were calculated (see Section 3.2). κ_{bi} for the northern granites varies between 0.063 and 0.783 with the mode $\kappa_{bi} = 0.35$ and median $\kappa_{bi} = 0.288$. κ_{bi} for the southern granites lies between 0.063 and 0.873 with the mode $\kappa_{bi} = 0.53$ and median $\kappa_{bi} = 0.478$. κ_f for the northern granites lies between 0.028 and 0.71 (mode $\kappa_f = 0.15$ and median $\kappa_f = 0.18$) while for the southern granites it is between 0.068 and 0.858 (mode $\kappa_f = 0.50$ and median $\kappa_f = 0.575$). Thus, κ_{bi} and κ_f are both higher in the south than in the north. Piazolo and Passchier (2002) concluded that if a rock has $\kappa > 0.2$, then it has a geologically significant preferred orientation. It is noted that only 2 samples, one each from the north and south have $\kappa_{bi} < 0.2$. Five samples from the north and 2 from the south have $\kappa_f < 0.2$. This implies that in the Godhra Granite, the SPO is better defined by Bi. Moreover, there is only one sample (no. 527) that has both κ_{bi} as well as $\kappa_f < 0.2$. With many number of samples showing a significant SPO, especially κ_{bi} (>0.2), it is worth comparing this database with the magnetic data and to evaluate SPO development in the granite.

The contours of Fig. 4 reveal that the southern part of the Godhra Granite has stronger L values than in the northern part. For the 20 samples of this study it is also observed that $L_{(north)} < L_{(south)}$ (Table 1). Moreover, the modes and the median values of κ_{bi} and κ_f are also higher in the southern granites. This indicates that the degree of SPO is stronger in the southern sector of the Godhra Granite than in the northern one. Fig. 5 shows plots that evaluate the relationship between intensity of magnetic fabric and κ (for Bi as well as F). Both graphs of L vs. κ_{bi} (Fig. 5a) and L vs. κ_f (Fig. 5b) reveal a positive correlation between κ and L.

It is known that P' is a useful gauge of magnetic fabric intensity. Figs. 5c,d document the relationship between P' vs. κ_{bi} and P' vs. κ_f respectively. Out of the 11 samples from the south, 8 have $\kappa_{bi} > 0.4$ and 6 have $\kappa_f > 0.4$. Only 3 samples have κ_{bi} as well as $\kappa_f > 0.4$ out of the 9 northern granites. It is noted that the granites from the north have lower P' than the south. While P' values for the northern granites range between 1.024 and 1.066 (mode $P' = 1.013$), they range between 1.106 and 1.578 for the southern samples (mode $P' = 1.350$). Thus, the P' as well as κ (for both Bi and F) are higher for the southern granites. This implies a positive correlation between P' and κ. The R_{bi} vs. κ_{bi} and R_f vs. κ_f plots (Figs. 5e,f) show that samples with longer minerals tend to have a higher κ value. It is also important to note that mode and median $R_{bi} \approx 2$ from both the north and the south while mode and median $R_f < 1.8$ for the whole granite. Implications of these R values are discussed in the Section 5.

In order to statistically evaluate the data, the authors have determined the correlation coefficient (r). It may be noted that r (which is also referred to as the Pearson product-moment correlation coefficient) is basically applied to evaluate linear relationships. Since, the present data from a natural situation need not necessarily be linear, the authors have also used the Spearman's rank correlation coefficient (ρ), which allows determination of the strength of the relationship between two sets of data (the reader is referred to the URL http://en.wikipedia.org/wiki/Spearman's_rank for further statistical details). Table 2 shows the values of r and ρ determined for L vs. κ, P' vs. κ and R vs. κ for Bi and F. All the correlations except ρ for R_f vs. κ_f are positive; the latter shows almost no correlation with a value of -0.043. ρ for P' vs. κ_{bi} is also low with the value being 0.208. Apart from this all the other plots have a relatively high ρ value. The probability of each correlation (ρ) not being on account of chance is also tabulated as % in Table 2. It is clear that except P' vs. κ_{bi} and R_f vs. κ_f, all the correlations have a probability of $\approx$90% or more. A significance graph (ρ vs. degree of freedom) has also been drawn to graphically represent the significance level of these correlations (Fig. 6). Since L vs. κ_f, P' vs. κ_f and R_{bi} vs. κ_{bi} have $\approx$95% probability, these values fall close to the 5% significance level curve implying that the likelihood of these correlations being positive on account of chance is as low as $\approx$5%. L vs. κ_{bi} correlation has $\approx$90% probability and this value plots at some distance from the 5% significance level curve in Fig. 6. Nevertheless, this correlation is $\approx$90% reliable. It is inferred that the correlations for L vs. κ (Bi and

Table 1
SPO data from oriented thin sections of the Godhra Granite, southern parts of Aravalli Mountain Belt (India)

Sample No.	K_m (μSI)	n_{bi}	n_f	P'	L	κ_{bi}	R_{bi}	κ_f	R_f
Samples from the northern part of the Godhra Granite									
441	5313	81	53	1.03	1.013	0.605	2.094	0.462	1.641
442	3884	94	63	1.024	1.014	0.288	2.042	0.17	1.713
452	5023	107	67	1.056	1.041	0.362	1.987	0.18	1.78
468	4249	76	37	1.053	1.001	0.244	1.912	0.028	1.648
471	6190	85	56	1.049	1.007	0.215	1.792	0.359	1.554
489	4671.3	76	58	1.061	1.042	0.708	1.935	0.415	1.552
527	1113.6	76	52	1.049	1.027	0.063	1.938	0.082	1.837
532	1530.4	88	63	1.047	1.017	0.277	1.769	0.132	1.761
536	2094.75	81	64	1.066	1.032	0.783	2.203	0.71	1.943
Median				*1.049*	*1.017*	*0.288*	*1.938*	*0.18*	*1.713*
Mode				*1.013*	*1.017*	*0.35*	*1.98*	*0.15*	*1.68*
Samples from the southern part of the Godhra Granite									
99	16153.9	91	53	1.409	1.207	0.565	2.075	0.797	1.631
144	4653.1	63	45	1.248	1.076	0.588	2.114	0.419	1.566
155	4597.75	97	63	1.578	1.113	0.33	2.139	0.068	1.608
217	10098.64	86	61	1.268	1.074	0.063	1.903	0.575	1.613
218	3090.87	77	31	1.228	1.058	0.631	2.109	1.16	1.758
285	2298.3	87	76	1.106	1.013	0.454	1.885	0.313	1.628
323	39970	76	62	1.153	1.08	0.478	1.877	0.388	1.636
325X	14970	84	34	1.377	1.05	0.444	2.116	0.858	1.6
376	951.06	85	47	1.236	1.264	0.873	2.052	0.655	1.689
387	2111.3	88	68	1.16	1.109	0.512	1.7	0.719	1.755
401	6310	95	51	1.391	1.17	0.333	2.05	0.344	1.39
Median				*1.248*	*1.08*	*0.478*	*2.052*	*0.575*	*1.628*
Mode				*1.350*	*1.10*	*0.53*	*2.13*	*0.50*	*1.68*

Intensity of magnetic fabric as determined from AMS analyses is also given for the same samples. K_m = Mean magnetic susceptibility; P' = Degree of magnetic anisotropy; L = strength of magnetic lineation: n_{bi} and n_f are number of crystals of biotite (Bi) and feldspar (F) that were used to determine the strength of lineation (concentration parameter) given by κ_{bi} and κ_f respectively; R_{bi} and R_f are the modes of aspect ratio for Bi and F respectively.

F), P' vs. κ_f and R_{bi} vs. κ_{bi} are all statistically significant and that the correlations would further improve with a larger sample size. In contrast to the above, ρ as well as its probability for P' vs. κ_{bi} and R_f vs. κ_f are found to be quite low and their statistical significance cannot be demonstrated from the present data and sample size.

5. Discussion

5.1. SPO, aspect ratio and magnetic data

The database presented above provides a unique opportunity to evaluate the relationship between SPO, aspect ratio and magnetic fabric data in granitic rocks. Because most κ_{bi} are >0.2 (the limit for a significant SPO as given by Piazolo and Passchier, 2002) and mode κ_{bi} > mode κ_f for both the northern and the southern sectors, it is inferred that in the Godhra Granite, biotite has a stronger SPO and thus best defines the lineation. Ildefonse et al. (1990, 1992a) and Launeau and Cruden (1998) have revealed that elongated minerals tend to have a stronger SPO. Piazolo et al. (2002) carried out experiments to investigate the roles of aspect ratio (R), matrix rheology and vorticity on SPO development of population of rigid objects during progressive deformation. Their investigation revealed that experiments with $R = 3$ had a strong SPO ($\kappa > 1$). By contrast, experiments with $R = 2$ had κ between 0.3 to 1. A similar conclusion was made by Pennacchioni et al. (2001) on naturally deformed rocks (Mont Mary mylonite, Italian western Alps), where they found that the fabric intensity (SPO) was higher in rocks with aspect ratio $R > 3$ and less for those with $R = 2.5-3$. Cañón-Tapia and Chávez-Álvarez (2004) numerically investigated the influence of aspect ratio and amount of deformation on SPO development and found that elongated particles achieve a stable orientation with very little amount of deformation. They also concluded that a stable orientation can be reached at moderate deformation ($\gamma = \sim 5$) if the aspect ratio is between 4 and 1.8. Recent investigations by Mandal et al. (2005) on the influence of aspect ratio on rotation of multiple inclusions have also revealed that inclusions with larger aspect ratios rotate less than those with lower aspect ratios. This implies that inclusions with higher aspect ratios have a more stable orientation and a higher SPO degree.

The present study supports the results obtained in the above experiments. As documented above (Table 1), mode R_{bi} > mode R_f and most of the $\kappa_{bi} > 0.2$, the limit mentioned by Piazolo and Passchier (2002) to reach a significant SPO. Also, κ_{bi} vs. R_{bi} has a positive correlation ($\rho = 0.440$). Moreover, it is found that the northern as well as southern granites have $R_{bi} \approx 2$ and mode κ_{bi} values are 0.35 and 0.53 respectively. These results fit well with the findings of Piazolo et al. (2002) that if $R = 2$, then κ lies between 0.3 and 1. The $\kappa < 0.2$ values in the Godhra Granite can be attributed to the fact that these naturally occurring rocks have a wider range of aspect ratios. This situation is in contrast to the experimental setup of Piazolo et al. (2002) where all the objects in

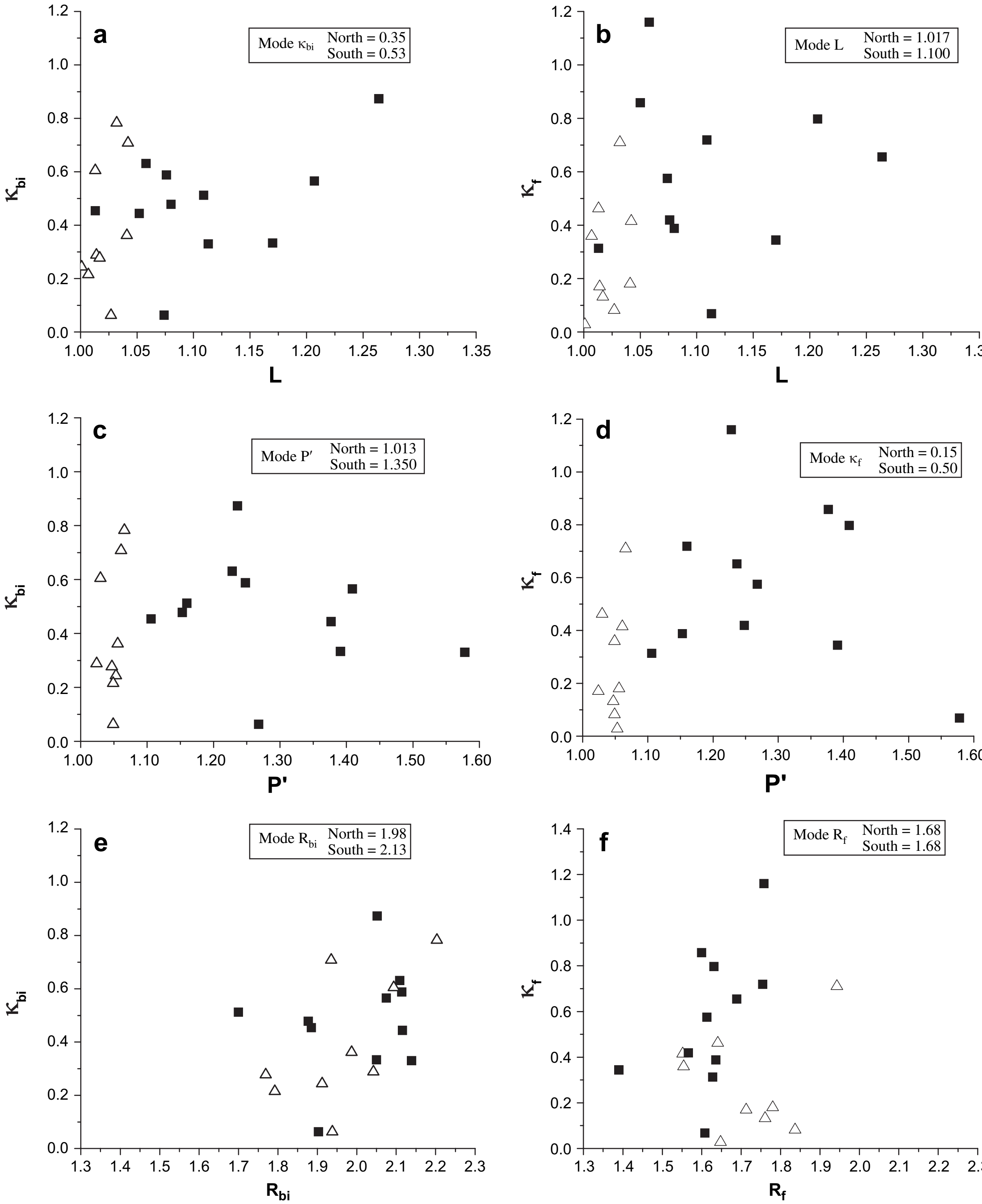

Fig. 5. Plots comparing the strength of mineral lineation (κ) with intensity of magnetic fabric. (a) and (b) are L vs. κ plots for biotite (Bi) and feldspar (F) respectively. (c) and (d) are P' vs. κ plots for Bi and F respectively. (e) and (f) are the aspect ratio (R) vs. κ plots for Bi and F respectively. Open triangles in each plot are for the samples from the northern sector of the Godhra Granite while the filled squares are for samples from the southern sector.

an experiment had the same R-values. On basis of the present investigation it is predicted that if a similar experiment was done with objects having different R-values, but $R_{mode} \sim 2$, a situation similar to the one in the Godhra Granite, then lower κ values would be obtained ($\kappa \leq 0.3$). In addition to the above, the present study also reveals a positive correlation between κ and the strength of the magnetic lineation L. Since all the 20 samples analysed are ferromagnetic ($K_m > 500$ μSI), this implies that magnetic data are a good measure of degree of SPO even in magnetite-bearing granites.

Table 2
Statistical evaluation of correlation of data plotted in Fig. 5

Parameters	r	ρ	% Probability of ρ
L vs. κ_{bi}	0.3930	0.366	89.04
L vs. κ_f	0.3480	0.431	94.12
P' vs. κ_{bi}	0.0493	0.208	63.72
P' vs. κ_f	0.2760	0.419	93.42
R_{bi} vs. κ_{bi}	0.4250	0.440	94.52
R_f vs. κ_f	0.0950	−0.043	15.86

r is the correlation coefficient, which was calculated using Microsoft Excel. ρ represents the Spearman's rank correlation coefficient, which was calculated using Wessa, P. (2006) Free Statistics Software, Office for Research Development and Education, version 1.1.18 (URL http://www.wessa.net/). The probability of ρ obtained from the calculation is tabulated as %.

5.2. Relation between regional strain and SPO in the Godhra Granite

Since the southern part of the Godhra Granite has a stronger SPO than the northern part, it is worth discussing the possible role of strain. Although strain is an important parameter that controls the degree of SPO, it is not the only parameter (Piazolo and Passchier, 2002). Aspect ratio of rigid objects, type of flow, rheological properties of the matrix material, rigid body rotation, dynamic recrystallisation and metamorphic reactions are some of the other factors that also control degree of SPO (Pennacchioni et al., 2001; Piazolo et al., 2002; Piazolo and Passchier, 2002; Cañón-Tapia and Chávez-Álvarez, 2004). Arbaret et al. (1997) carried out analogue 3D experiments under simple shear to understand evolution of biotite fabrics in magmatic rocks and concluded that the fabric strength parameter is insensitive to the strain magnitude undergone by the magma. A comparison of results obtained in the present study with those from experiments and mathematical modeling (e.g., Treagus and Treagus, 2001; Piazolo et al., 2002) allows a better evaluation of the role of strain in controlling degree of SPO. In the present case, regional strain can be inferred as an important parameter that controlled the degree of SPO provided two aspects can be established: (a) the role of rheology was insignificant; this is important because from field and petrographic studies it is known that the northern part of the granite was subjected to more magmatic state deformation while the southern part suffered more solid-state deformation; and (b) strain resulting from difference in aspect ratios of minerals (Bi and F in the present case) did not play an important role in the variation of degree of SPO in different parts of the granite. The remaining part of this section thus concentrates on the above two aspects.

5.2.1. Influence of rheology on SPO

Piazolo et al. (2002) investigated the influence of matrix rheology on the degree of SPO during progressive deformation of a population of rigid objects. They found that in experiments with populations of rigid objects having aspect ratio, $R = 2$, the rheology of the matrix materials does not have any systematic influence on the degree of SPO. On the contrary, for experiments with $R = 3$, the degree of SPO is higher if matrix material is non-Newtonian, power law type as compared to a Newtonian matrix. In the present study of the Godhra Granite, it is found that R_{bi} and $R_f \ll 3$. In fact, the highest $R_{bi} = 2.203$ and highest $R_f = 1.943$. Median and mode $R_{bi} \approx 2$ while median and mode $R_f < 1.8$ for both the northern and southern granites. Despite this, the strength of mineral lineation for Bi and F is stronger for the southern granites. In light of the work of Piazolo et al. (2002) it is therefore safe to infer that the higher SPO in the south of the Godhra Granite cannot be attributed to rheological differences between the northern and southern parts of the granite.

5.2.2. Aspect ratio and strain

Treagus and Treagus (2001) investigated the relationship between aspect ratio and strain and found that competent elliptical objects with aspect ratio ≥3 undergo more strain than circular objects with the same viscosity. They also concluded that this relation between aspect ratio and strain is insignificant for objects having lower aspect ratios (<2). As shown above, in the Godhra Granite median and mode $R_{bi} \approx 2$ whereas median and mode $R_f < 1.8$. Therefore, if the whole Godhra Granite were subjected to a particular magnitude of strain, the differences in R-values in the north and south would not significantly influence the measurement of strain in different parts of the granite. Thus, it is argued that differences in aspect ratios of Bi (as well as F) do not substantially control the differences in degree of SPO in different parts of the Godhra Granite.

Having ruled out the influence of aspect ratio and rheology in controlling the differences in SPO degree, regional strain remains the dominant candidate, especially in light of the fact that the southern Godhra Granite is close to the CITZ and that its emplacement was synchronous with tectonic rejuvenation along the CITZ (Mamtani and Greiling, 2005). Therefore, the higher SPO degree in the south of the granite implies that it underwent higher strain than in the north, and this is attributed to the activity of the CITZ.

P' values have been used earlier to gauge strain (e.g. Borradaile and Alford, 1987; Hrouda, 1993). In ferromagnetic granites the use of P' as a measure of magnitude of strain hasbeen cautioned in earlier studies because of the possible influence of size, shape and distribution of magnetite on the magnetic data (Archanjo et al., 1995; Hargraves et al., 1991; Cañón-Tapia, 1996, 2001; Grégoire et al., 1995, 1998). Rochette et al. (1992) showed that in magnetite bearing rocks, P' maybe controlled by K_m. However, there are studies on magnetite-bearing granites where such a one-to-one correlation between P' and K_m does not exist (e.g., Callahan and Markley, 2003). Moreover, Henry et al. (2004) noted a good correlation between P' and intensity of deformation of magnetite-bearing granites (Alous-en-Tides granite, Algeria). For the Godhra Granite, P' has been found to be independent of K_m and it has been advocated as a useful strain intensity gauge (Sen et al., 2005). In the present study, it was found that the intensity of magnetic fabric (L and P') as well as κ (Bi and F) are higher for the southern granites than the northern granites. The authors infer this as an indication of a higher SPO in the

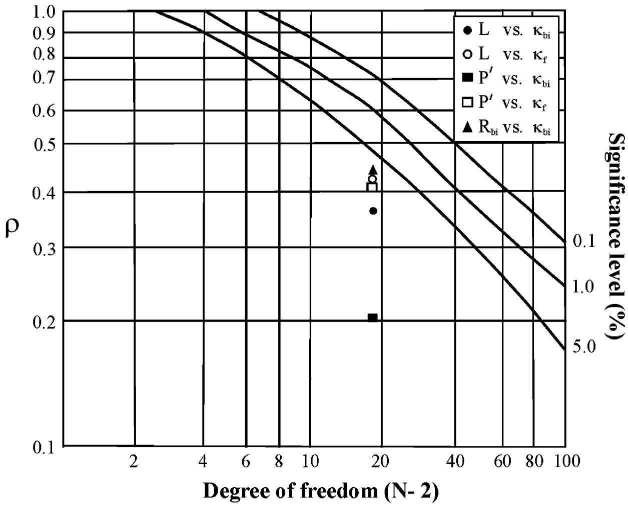

Fig. 6. Significance graph for Spearman's rank correlation coefficient (ρ). N represents the number of pairs of items in sample, which is 20 in the present case thus making the degree of freedom (N-2) as 18. R_f vs. κ_f had a ρ value of -0.043, which has not been plotted. The basic significance graph on which the present data are plotted was downloaded from the URL (http://www.geographyfieldwork.com/SpearmansRank.htm).

southern part. The Spearman's rank correlation coefficient (ρ) for L vs. κ (for Bi and F) and P' vs. κ_f are not only positive, but also statistically significant with a $\geq$90% probability. However, the correlation for P' vs. κ_{bi} for the 20 samples analysed is weak and could not be demonstrated to be statistically significant. According to the authors, this implies that in the present study, L is a better measure of the degree of SPO as compared to P'. Further, the authors would like to mention that although P' and κ_{bi} do not have a statistically significant level of correlation, mode P' and mode κ_{bi} are higher for the south than the north. The authors therefore, infer this as an indication of higher degree of SPO in the southern granites. It is envisaged that the statistical correlation between the magnetic and non-magnetic parameters is likely to improve with the increase in sample size. On the whole, the present data indicates that samples with a tendency to have strong magnetic fabric also tend to have a strong mineral fabric. And as shown above, regional strain is the dominant candidate in the present study that controls the strength of the mineral fabric (SPO degree). Therefore, it is concluded that in the Godhra Granite the variation in the intensity of magnetic fabric is an indicator of degree of SPO and is dominantly a manifestation of the variation in strain on the regional scale.

5.3. General applicability of the method to granites and other magmatic rocks

As shown above a positive correlation between κ and intensity of magnetic fabric is noted. In a massive rock like granite that often develops no prominent mesoscopic foliation, the magnetic foliation derived from AMS measurements is the fastest and probably the best technique at present to identify a foliation in such rocks. The technique to determine κ explained by Piazolo and Passchier (2002) requires that the measurements be made in the foliation plane. Therefore, the methodology of determining κ in the K_1K_2 (magnetic foliation) plane of the granite (or any other magmatic rock) satisfies this basic condition. AMS and shape fabric data have been compared earlier only in a limited number of investigations (e.g. Archanjo et al., 1995, 2002, 2006; Pignotta and Benn, 1999; Bolle et al., 2000; Diot et al., 2003). All these studies have used the intercept method developed by Launeau and co-workers (1990, 1996, 1998), which requires analyses of three perpendicular thin sections prepared through the principal planes of the magnetic susceptibility ellipsoid i.e., K_1K_2, K_1K_3 and K_2K_3 planes. These three sections are equivalent to the XY, XZ and YZ planes respectively of the strain ellipsoid. However, determination of κ, as proposed by Masuda et al. (1999), used by Piazolo and Passchier (2002) as well as Piazolo et al. (2002) and applied in the present investigation requires only the K_1K_2 section. As noted from the results of this study, the intensity of κ relates well with the intensity of magnetic lineation, thus proving the usefulness of the technique. The degree of magnetic anisotropy P', which quantifies the eccentricity of the magnetic susceptibility ellipsoid and is based on 3D data, also tends to be higher in samples with high κ; the later is a 2D concentration parameter. From the present data of 20 samples, this correlation between P' and κ is statistically significant for F but not for Bi. Despite this, mode values of P' as well as κ (both for Bi as well as F) are higher for the southern granites than the northern granites. Also, mode $L_{south} > L_{north}$. The authors infer this difference in L, P' and κ values to be a useful indicator of regional scale variation in the degree of SPO and thus a gauge of regional strain-intensity variations. It is therefore suggested that if a study requires comparison of SPO and magnetic fabric magnitudes, it is not necessary to study three perpendicular sections prepared along the principal planes of the magnetic susceptibility ellipsoid. Determination of κ in the K_1K_2 plane would suffice.

5.4. The problem of subfabrics

An important point that must be mentioned is the role of subfabrics arising from different SPO's related to different mineral species in a rock. In the present study Bi and Hb data were treated together for determination of κ_{bi}. As stated in Section 3.2, out of the 20 samples investigated, only 4 contained hornblendes along with biotites and only a small percentage of the former comprise the flaky minerals. Therefore, in the case of the Godhra Granite, the influence of incorporating Hb with Bi for the calculation of degree of SPO (κ_{bi}) is considered insignificant. Conversely, presence of equal proportions of two elongated/flaky minerals belonging to different species (e.g., Bi and Hb) could result in a significant error of κ if the calculation treats the two minerals together. In such a case it would be necessary to treat data from the two mineral species separately and determine respective κ values to identify SPO's related to different subfabrics. Therefore, it is cautioned that the merging of orientation data (θ values) of two mineral species (as done in the case of Bi + Hb in the present study) should be applied only if a single flaky mineral species dominates. Otherwise, κ values of individual mineral species should be considered before making regional scale interpretations.

With regards to ferromagnetic granites, there can be another problem related to size, proportion and nature of the distribution of magnetite grains within the rock (Hargraves et al., 1991; Stephenson, 1994; Archanjo et al., 1995; Grégoire et al., 1995, 1998; Cañón-Tapia, 1996, 2001; Borradaile and Jackson, 2004). However, for such rocks it has been demonstrated in some earlier studies that magnetite mimics the biotite fabric (e.g., Archanjo et al., 1995). Launeau and Cruden (1998) also found a parallelism between magnetite orientation and overall petrofabric of the Archean Lebel syenite (Canada). These inferences from previous studies are important and indicate that the role of magnetite in the present study is not critical because: (a) in the Godhra Granite also magnetite is observed to mimic biotite fabric in many samples; and (b) the objective of the present study is primarily to evaluate the relationship between degree of SPO using magnetic data and a non-magnetic parameter (κ in this case). As demonstrated above, a good correlation is found between these two parameters determined from two independent techniques. However, magnetite subfabrics need to be evaluated carefully if: (a) magnetite does not mimic the flaky mineral fabric; and (b) the study is aimed at comparing orientations of magnetic fabric and SPO.

6. Conclusions

The present study provides a useful method that can be applied to analyse the degree of SPO in granitic and other magmatic rocks in order to understand the relationship between intensity of magnetic fabric, degree of SPO and regional strain. First, the intensity of magnetic fabric (L and P') is determined with the help of AMS measurements. Using the AMS data, a thin section parallel to the magnetic foliation plane is prepared to determine the degree of SPO using the concentration parameter (κ). This is done on images captured with a digital camera attached to a microscope with the determination of mineral orientation (θ) with respect to a given reference line of the microscope (or computer screen). θ can be determined automatically with a digital image analysis software after binarizing the image; alternatively, it can be done by making measurements manually on photomicrograph prints. Subsequently, the θ value of different crystals of a particular mineral is entered into the excel worksheet given by Piazolo and Passchier (2002) and the κ value for the mineral under consideration is calculated. κ gives a measure of the SPO degree for the mineral. The intensity of magnetic fabric can then be evaluated in light of the κ value. Such a technique applied to a large number of spatially distributed samples can be found useful to identify strain gradients. With regards to the present study of the Godhra Granite, insight into the relationship between its emplacement and regional tectonics has been obtained:

1. The intensity of magnetic fabric can be a reliable indicator of degree of SPO in naturally deformed rocks, especially granites that develop barely visible foliations and lineations. The positive correlation between intensity of magnetic fabric and concentration parameter (κ) in the Godhra Granite demonstrates this.
2. There can be instances where the degree of SPO in a granite (or any other magmatic rock) is attributable to regional strain. However, it is necessary to establish first that the influence of rheology and mineral aspect ratio on strain magnitude is negligible. This is the case for the Godhra Granite, where the $R_{bi} \approx 2$ and $R_f < 2$. The degree of mineral SPOs with such low R values is not influenced by rheology, nor related to variation in degree of strain related to differing R-values (Treagus and Treagus, 2001; Piazolo et al., 2002). Despite the low R-values, the southern part of the granite has a higher SPO degree (κ_{bi} as well as κ_f) than the northern part. Since the granite is synchronous with the tectonic rejuvenations along the CITZ that lies to the south of the granite, this difference is inferred to be a consequence of the proximity of the southern part to the CITZ. Therefore, the variations in the degree of SPO between the northern and southern parts of the granite can be attributed to the positive strain gradient towards the south.
3. Whilst variation in the magnetic fabric intensity can help identify regions that have a stronger degree of SPO, caution needs to be exercised to readily attribute strain gradients on the basis of magnetic data solely. An alternative and independent method must be used to determine the degree of SPO. If a positive correlation can be established between the results from these techniques, then the variation in the magnetic fabric magnitude can be used for further regional scale interpretations. In this aspect, the Godhra Granite can be considered as a good example. Its southern part has a stronger magnetic fabric, both in linear aspects (Fig. 4) and in total (Fig. 2b of Sen et al., 2005). Moreover, since κ_{bi} as well as κ_f are higher in samples from the southern parts of the granite, the variations in L and P' do point to variations in SPO intensities, which the authors have correlated with regional strain. In conclusion, in light of the present study, L and P' appear as useful parameters to select samples that are devoid of easily recognizable strain markers for SPO analyses by using an alternative technique.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.jsg.2006.07.005.

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