Anisotropy of magnetic susceptibility data for a ferromagnetic granite (Godhra Granite, NW India) are presented and it is shown that the degree of magnetic anisotropy ($P$) is not controlled by the mean susceptibility ($K_m$). Analyses carried out across a high-strain zone lying between granite and adjacent gneiss show that $P$ values are highest in samples that lie close to the contact and decrease away from it. Based on these results it is concluded that if $P$ is not controlled by $K_m$, then the former can be used to gauge strain-intensity variations in ferromagnetic granites.

Keywords: anisotropy of magnetic susceptibility, strain, ferromagnetic minerals, granites.

Low field anisotropy of magnetic susceptibility (AMS) studies have been commonly used in the past to record the internal fabric in granitic rocks by Hrouda & Lanza (1989) and Bouchez (1997), and more recently by de Wall et al. (2001), Callahan & Markley (2003), Neves et al. (2003) and Henry et al. (2004). AMS is calculated as a second rank tensor based on measurements taken at different sample orientations (Tarling & Hrouda 1993). AMS measurements provide an important parameter that is referred to as the degree of magnetic anisotropy ($P$), which is the measure of the eccentricity of the magnetic susceptibility ellipsoid having three principal axes $K_1$, $K_2$ and $K_3$ ($K_1 > K_2 > K_3$). In the past, AMS data have been used as a measure of strain in rocks (e.g. Rathore 1979; Borradaille & Alford 1987; Borradaille 1988, 1991; Hrouda 1993; Tarling & Hrouda 1993; Borradaille & Henry 1997; Mukherji et al. 2004). Hrouda (1993) has mathematically investigated the relationship between $P$ and strain for different theoretical models (passive, line/plane, viscous and ductile) and has found that $P$ increases with the increase in strain for all the models. It is known that the diamagnetic, paramagnetic and ferromagnetic constituents of a rock are together responsible for its bulk susceptibility and, according to Hrouda, the above relationship between $P$ and strain holds true for paramagnetic minerals such as chlorite and biotite, as well as for ferromagnetic minerals such as magnetite. Borradaille & Alford (1987) carried out AMS studies on experimental materials (rocks) before and after deformation and inferred a linear relationship between change in the degree of magnetic anisotropy and bulk strain-ratio. However, in granitic rocks, the application of such a relationship between $P$ and strain has been a matter of debate.

According to Bouchez (1997), if granitic rocks have a mean susceptibility ($K_m$) value <500 μSI, then they are categorized as paramagnetic granites. Otherwise they are referred to as ferromagnetic granites. In the former, Fe-bearing silicates (e.g. biotite) are responsible for the $K_m$, whereas, in the latter, ferromagnetic minerals (e.g. magnetite) contribute to the susceptibility of the specimen. It has been found that in paramagnetic granites, the $P$ value generally does not exceed 1.1 (Archanjo et al. 1995; Bouchez 1997). In paramagnetic granites the magnetic fabric is defined by the shape fabric axis or shape preferred orientation of Fe-bearing silicates and this fabric is parallel to the magnetic fabric obtained by AMS measurements. Therefore $P$ values have been used as strain-intensity gauges in such paramagnetic granites (Archango et al. 1995). Contrary to this, it is believed that in ferromagnetic granites the magnetic fabric is not necessarily dependent on the fabric of Fe-bearing silicates because of the presence of magnetite, which has a high intrinsic susceptibility, thus making the paramagnetic contribution negligible. In such rocks the magnetic fabric is controlled by the shape anisotropy of magnetite grains (Tarling & Hrouda 1993). According to Archango et al. (1995), the intensity of this shape fabric in ferromagnetic granites is not on account of the intensity of strain. Moreover, in magnetite-bearing rocks, the $P$ values may be strongly dependent on the $K_m$ values (Rochette et al. 1992). Therefore it has been suggested by Archango et al. (1995) that the $P$ values in ferromagnetic granites cannot be used as strain intensity gauges (also see Bouchez 1997).

However, some recent AMS studies of ferromagnetic (magnetite-bearing) granites give results that are contrary to the above. Callahan & Markley (2003) have carried out an AMS investigation on porphyritic granites of the Mount Waldo Pluton (Maine, USA) and their AMS data (Callahan & Markley, 2003, table 2) reveal that a granite with $K_m$ as low as 4 μSI has a $P$ value of 3.943, whereas a granite with a very high $K_m$ of 20 490 μSI has a $P$ value of 1.087. This indicates that $P$ need not always be directly controlled by $K_m$. Henry et al. (2004) carried out AMS studies on Alous-En-Tides granite (Algeria), where they noted a good correlation between preferred orientations of magnetite grains and the magnetic fabric. $K_m$ v $P$ graphs for undeformed, less deformed and strongly deformed granite reveal that $P$ increases with $K_m$ in each case (Henry et al. 2004, fig. 9). However, $P$ values of strongly deformed granites are higher than those of less deformed or undeformed granites with similar $K_m$ values, which implies that strain can control $P$ in magnetite-bearing granites. Moreover, in the above study, the preferred orientation of magnetite was correlated with the regional compressional stress field during the late magmatic stages that resulted in strong deformation, thus supplementing the importance of strain in controlling magnetic fabric even in ferromagnetic granites.

Consequently, although there are some studies that do not advocate the use of $P$ values of ferromagnetic granites for gauging strain-intensity variations, there are other studies implying that the contrary may be possible. This study investigates this relationship between strain and $P$ in ferromagnetic granites through an AMS investigation of granites and associated gneiss samples from the southern part of the Aravalli Mountain Belt (NW India).
Geology of the study area. The Aravalli Mountain Belt is of Precambrian age. It lies in northwestern India and extends in a NE–SW direction for a distance of 600 km to the south of Delhi. The basement rocks are Archaean in age and are referred to as the Banded Gneissic Complex (Heron 1953). This Archaean basement is overlain by two main Proterozoic metasedimentary and meta-igneous sequences: the Aravalli and Delhi Supergroups (Gupta et al. 1992). The southern parts of the AMB comprise banded gneisses, metasedimentary rocks of the Aravalli Supergroup and 955 ± 20 Ma (Gopalan et al. 1979) acid igneous intrusive rocks referred to as the Godhra Granite, the last being the subject of the present investigation. This granite occurs as an elongated body with a NW–SE trend and occupies an area of about 5000 km². It is flanked by metasedimentary rocks (quartzites and metapelites) of the Lunavada and Champaner Groups belonging to the Aravalli Supergroup in the northern and southwestern parts; these are older than the granite. To its east and SE the granite is flanked by banded gneiss (Fig. 1). The Godhra Granite is dominantly coarse to porphyritic with fine-grained varieties occurring at a few places. It is generally biotite bearing and hornblende also occurs in many of these rocks. For the purpose of the present AMS investigation, samples from the Godhra Granite and associated gneiss were studied.

AMS analyses. AMS analyses of cylindrical specimens of granites and gneisses were carried out using a KLY-4S Kappabridge (AGICO, Czech Republic) at the Department of Geology & Geophysics, Indian Institute of Technology, Kharagpur. A total of 489 cylindrical specimens each of 25.4 mm diameter and 22 mm height from 202 sites in the granite were investigated. (Locations of sampling sites within granite are available online at http://www.geolsoc.org.uk/SUP18220. A hard copy can be obtained from the Society Library.) A total of 96 cylindrical gneiss specimens from 42 sites lying to the east of the granite were also analysed. Except for densely forested areas, sampling was carried out for almost all accessible parts of the granite to decipher the internal fabric of the entire granite. It was found that the $K_m$ in the granite varies between 22 and 46 000 $\mu$SI, with most of the samples having values $>500$ $\mu$SI. Therefore, the Godhra Granite is dominantly ferromagnetic in nature, where magnetite dominantly controls its susceptibility.

Figure 2a is a contoured magnetic susceptibility map that shows the variations in $K_m$ values throughout the granite. The $P'$ values vary between 1 and 2.053, and Figure 2b is the contoured $P'$ map of the granite. $K_m$ and $P'$ values in the gneiss vary in the range of 48–143 500 $\mu$SI and 1.01–1.81, respectively. Analyses of the orientations of $K_1$ (magnetic lineation) and $K_3$ (pole to magnetic foliation) using lower hemisphere equal area projections reveal that the magnetic foliation strikes generally in an east–west direction with gentle to moderate northerly dip, and the magnetic lineation has a gentle westerly plunge.

To the south of Janiyara (location in Fig. 1) in the southeastern parts of the granite, the contact between granite and gneiss is well exposed on outcrop scale. As seen in Figure 2, both $K_m$ and $P'$ values are high in this part of the granite. As the aim of the present study is to observe whether $P'$ can be used to determine strain-intensity variations in a ferromagnetic granite, this southeastern part was chosen for further detailed AMS investigation. The outcrop selected has an area of 300 m² and the contact between gneiss and granite has a trend of 115°. The gneiss at the contact shows evidence of shearing (see the supplementary publication online for a field photograph). The orientation of the highest strain zone is parallel to the contact between granite and gneiss. The granite is porphyritic with biotite and hornblende as important minerals and lies to the south of the contact; the gneiss lies to the north of the contact. AMS analyses reveal that the granite as well as gneiss in this outcrop have high susceptibilities.

![Fig. 1. Generalized lithostratigraphic map of the study area (modified after Gupta et al. 1992). Inset: AMB, Aravalli Mountain Belt; D, Delhi; arrow points to the study area.](image1)

![Fig. 2. Contoured $K_m$ (a) and $P'$ (b) maps of the Godhra Granite.](image2)
Discussion. Correlation between \( P' \) and strain intensity in ferromagnetic granites has been a matter of debate. To apply \( P' \) as a strain-intensity gauge in such rocks, it is important to demonstrate that \( P' \) is independent of \( K_m \). Also, the effect of clustering of magnetite crystals needs to be considered because in ferromagnetic granites this can lead to magnetic interactions between grains, which results in the absence of any consistent relationship between \( P' \) and shape ratios (SR) of magnetite crystals (see Archanjo et al. 1995, fig. 9).

A comparison of Figure 2a and b reveals that areas that have high \( K_m \) also have low \( P' \) (e.g. northwestern part of the granite). Thus, for the Godhra granite, there is no proportional relationship between \( P' \) and \( K_m \) on a regional scale. The same is true for the granite samples studied in the vicinity of the contact (Fig. 4). Thus the variation in \( P' \) with distance from the contact cannot be attributed to concentration of magnetite. Having established that in the present case \( P' \) is independent of \( K_m \), it is worth discussing the applicability of \( P' \) values for gauging strain-intensity variations in ferromagnetic granites. Microscopic investigation of the granites reveals that the opaque minerals generally lie adjacent to the phyllolites and are thus mimetic to this fabric, and do not show any significant clustering similar to that in the granites studied by Archanjo et al. (1995). This rules out the influence of magnetic interactions of clusters of magnetite crystals. Therefore, in the example presented, the systematic increase in \( P' \) values of the two lithologies towards the contact can be attributed to strain-intensity variations. As there is field evidence of accommodation of high strain at the contact, the systematic increase in \( P' \) of the two lithologies towards the contact is correlatable with increase in strain magnitude. This is despite the fact that both the granite and the gneiss have very high \( K_m \) values, indicating their ferromagnetic nature.

Conclusions. The relationship between \( P' \) and strain in ferromagnetic granites has been a matter of debate in earlier studies and there are two schools of thought. It has been concluded from some previous studies of ferromagnetic (magnetite-bearing) granites that \( P' \) increases with increase in \( K_m \) and in such granites \( P' \) values cannot be used as strain-intensity gauges. In contrast, a few other studies revealed that \( P' \) values are not always dependent on \( K_m \) and may be related to stress/strain. The present study on the Godhra Granite and adjacent gneiss has provided useful information about AMS studies of ferromagnetic granites, which are listed below.

1. \( P' \) values in ferromagnetic granites need not always be controlled by the \( k_{in} \) value. In the case of the Godhra Granite, this is clear on a regional scale from Figure 2, where it is noted that localities having high \( K_m \) (e.g. northwestern part of the granite) have low \( P' \) values. This is also demonstrated in the samples studied along the traverse across the gneiss–granite contact (Fig. 4).
2. \( P' \) can be used as a strain-intensity gauge at least on an outcrop scale, where (a) no direct relationship is observed between \( P' \) and \( K_m \) and (b) there is systematic variation in \( P' \) values from one part of the outcrop to the other. In the present study, this has been demonstrated by the systematic increase in \( P' \) values in the granite as well as the gneiss towards the contact between them.
3. As \( P' \) values in both the granite and the gneiss increase towards the contact, it can be concluded that emplacement of the Godhra Granite was syntectonic with deformation of the gneiss.

![Figure 3](image-url)  
Fig. 3. Plot showing the relation between \( P' \) values of granite and gneiss and distance \((L \text{ metres})\) of the sample from the contact (high-strain zone) between the two lithologies.

![Figure 4](image-url)  
Fig. 4. \( K_m \) v. \( P' \) plot of the granites collected along the traverse across the contact with gneiss.
From the above conclusions it is clear that the AMS data from the Godhra Granite favour strain as an important controlling factor for \( P' \). This calls for further investigations on ferromagnetic granites in different parts of the world to test the validity of the above conclusions and to determine how frequently \( P' \) and strain can be correlated.

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