Establishment of correlation between anisotropy of magnetic susceptibility and magma flow fabric: an insight from Nandurbar–Dhule dyke swarm of Deccan Volcanic Province

There are rising concerns about the robustness of interpretation from Anisotropy of Magnetic Susceptibility (AMS) studies, because often correlation between AMS and geological fabric is not properly established before a wide regional-scale interpretation is made. Here, we document case studies on two dykes from the Nandurbar–Dhule dyke swarm (western India) of Deccan Volcanic Province (Figure 1 *a*), where we have tested if shape-preferred orientation of the elongated mineral grains (flow fabric) is actually represented by AMS fabric. In one of the dykes, we observed that AMS fabric is coplanar with the fabric of major constituent silicate minerals; hence it represents magma flow fabric. In the other dyke, AMS fabric largely represents the shape fabric of the opaque minerals which were deposited in the interstitial spaces of the mineral grains after the dyke was emplaced; hence it does not correspond to the primary magma flow fabric. These findings reinforce the need for detailed understanding of rock fabric in order to make robust interpretation of AMS data.

Elongated mineral grains in magmatic rocks are aligned in the direction of magma flow. Extermination of magmatic fabric formed during the early phase of evolution of magma, weak development of primary magmatic fabric, and preservation of late-stage superimposed fabric impose some logical restrictions in deciphering the flow pattern from conventional rock-fabric analysis[1–7]. AMS analysis usually helps overcome such constraints and provides us with a less ambiguous and quick technique by which magmatic fabrics can be easily analysed. Thus, magma flow pattern can be inferred once a correlation is established between AMS and shape-preferred orientation of the primary elongated mineral grains.

AMS data are visualized in the form of a susceptibility ellipsoid with three principal susceptibility axes[8]. One of these three axes can be colinear with the flow direction, if the major axes of the elongated grains are oriented by magma flow.

The Nandurbar–Dhule dyke swarm consists of approximately 210 mafic dykes of tholeiitic composition. They penetrate the Deccan flood basalts and are largely oriented along ENE–WSW strike. They also form linear ridges along the strike. The dyke swarm is spread over an area of 14,500 km^2 in Maharashtra, western India[9] (Figure 1 *a*). Ray *et al.*[9] argued in favour of a shallow magma chamber feeding the dykes vertically above it and laterally away from it.

Three oriented samples were collected from the margin of dyke no. 47 and two samples from dyke no. 41. Oriented cores were drilled out from the samples (Figure 1). A total of ten and eight specimen cores were successfully extracted from dyke nos 47 and 41 respectively. They were then analysed for AMS at the Geomagnetic Laboratory, Indian Institute of Technology, Kharagpur, using KLY-4s spinner kappa-bridge[10].

The primary output result contains orientation and susceptibility values along three mutually perpendicular axes of the susceptibility ellipsoid, viz. K_1 (maximum), K_2 (intermediate) and K_3 (minimum). The $K_1 - K_2$ plane is generally referred to as magnetic foliation and K_1 axis is referred to as magnetic lineation.

Cañón-Tapia[11] documented that K_1 is generally parallel to the magma flow direction and magnetic foliation is parallel to the dyke wall, if susceptibility is vastly contributed by multi-domain (MD) magnetic grains (normal fabric), and K_3 will represent the magma flow direction if there is significant contribution from single-domain (SD) grains.

It is to be noted that bulk susceptibility of samples collected by us is generally very high (>10–2 SI units), which indicates that major contribution to susceptibility is from ferromagnetic grains-magnetite, titano-magnetite, that appear opaque under transmitted light. Contributions from diamagnetic and paramagnetic minerals (silicates) can be neglected.

Explanation for shape-preferred orientation (SPO) of each mineral phase from thin-section analysis can provide insights into the development of magnetic minerals in comparison with the other phases. During magma/lava emplacement, a well-developed silicate fabric is formed which generally comprises of the magmatic fabric that may reflect the flow direction. This magmatic fabric, in our case, is governed by the orientation of elongated plagioclase laths (Figure 1 *b*). By comparing this silicate fabric with the AMS fabric, we can verify whether the latter is representative of silicate template and hence magma flow[12,13].

For dyke nos 47 and 41, SPOs of plagioclase laths (Silicate Fabric Template (SFT)) and ferromagnetic opaque mineral grains (i.e. Fe–Ti oxides; Opaque Mineral Fabric Template (OMFT)) were determined in three mutually perpendicular sections: across dyke-strike vertical, horizontal and along dyke-strike vertical (Figure 1 *c*). We prepared thin sections from one of the cores used for AMS measurement, so that any discrepancy between the two sub-fabrics due to lateral variation could be ruled out. Finally, SFT and OMFT were obtained using the intercept method and compared with the AMS fabric[14]. Using this method, the orientations of the plagioclase laths and opaque minerals were digitally recorded from three mutually orthogonal photomicrographs (Figure 1 *c*) and then combined to reconstruct the three-dimensional angular distribution of SFT and OMFT respectively. The whole crystal shape anisotropy of a sample can be detected by this method.

Dyke no. 47 shows very well constrained OMFT in three mutually perpendicular sections, while SFT is relatively poorly constrained (Figure 2 *a*). Although less-pronounced secondary maxima occur in SFT, the primary maxima largely coincide with the OMFT maxima and AMS fabric. On the other hand, dyke no. 41 shows similarities in the OMFT maxima and AMS fabric, but is at a high angle with the SFT maxima (Figure 2 *b*). For dyke no. 47, although SFT and AMS fabric are subparallel to each other, they are not exactly coplanar. Such small deviation could be due to polymodal distribution of the plagioclase laths (based on ~25 plagioclase grains analysed from

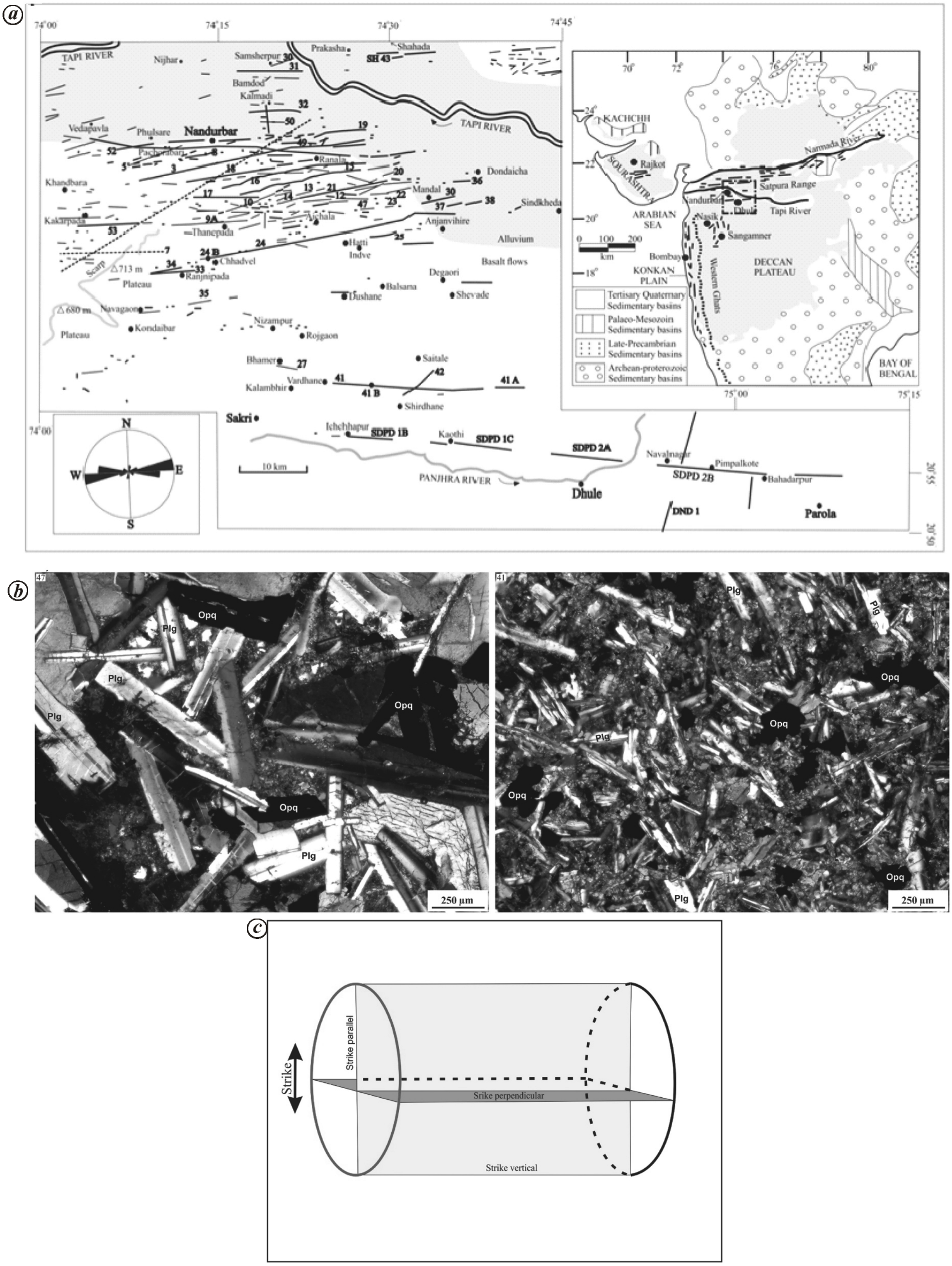

Figure 1. ***a***, Map of the Nandurbar–Dhule dyke swarm showing the major physiographic and geological features, dykes, and sampling locations (modified after Ray *et al*.[9]). ***b***, Transmitted light photomicrographs showing mutual occurrence of plagioclase (Plag), clinopyroxene (Cpx) and opaque (Titanomagnetite). Section from dyke no. 47 shows relatively coarser grain size with respect to dyke no. 41. In case of dyke no. 47, most of the magnetic grains (opaque) are roughly parallel to the plagioclase grains, unlike dyke no. 41. In case of dyke no. 41, the opaque minerals show random orientation with irregular shape. ***c***, Orientation of the thin sections prepared from Anisotropy of Magnetic Susceptibility (AMS) core to determine the Silicate Fabric Template and Opaque Mineral Fabric Template.

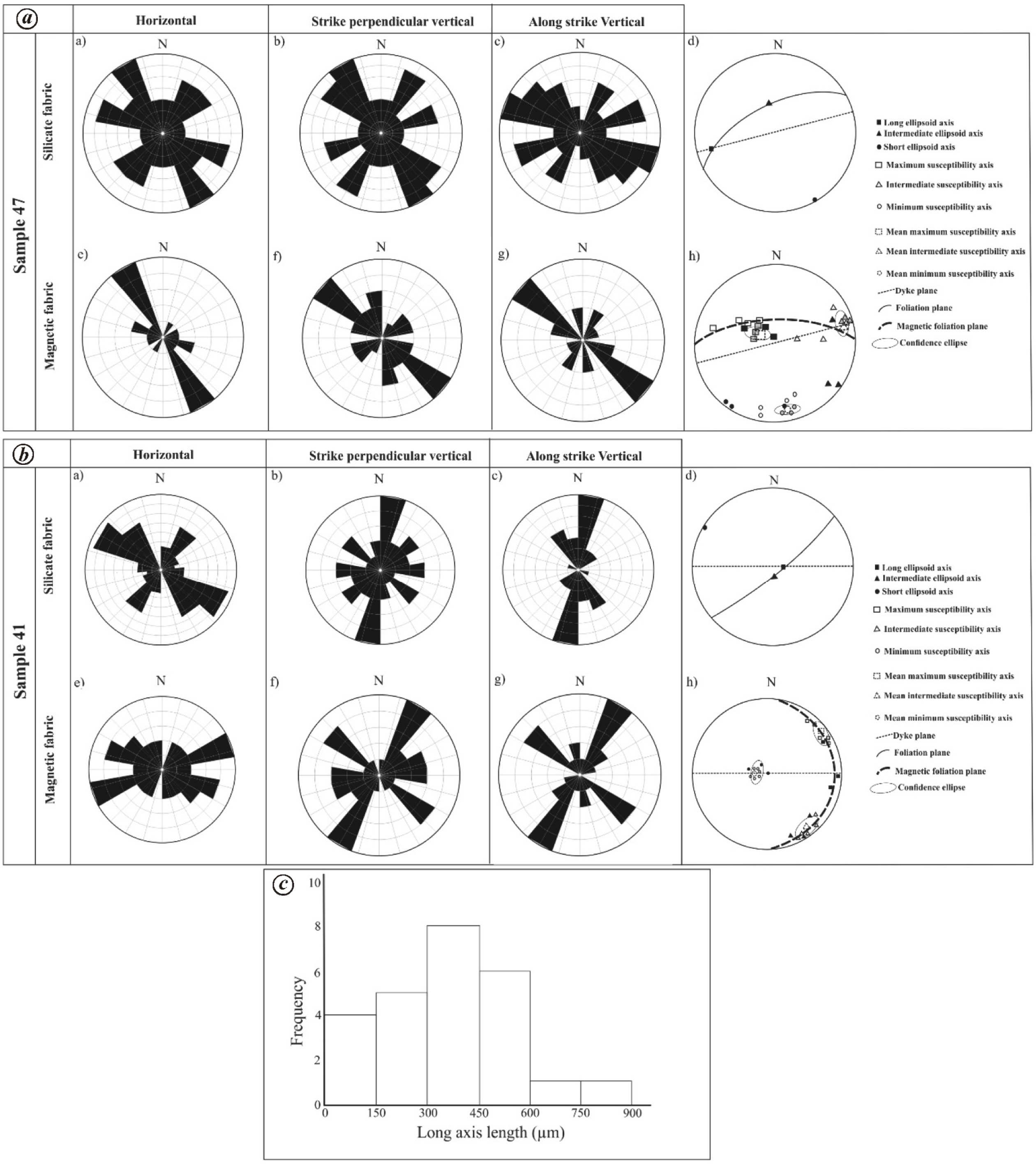

Figure **2.** ***a***, Dyke no. 47: Distribution of long-axis trend of plagioclase (a–c) and magnetic minerals (e–g) from dyke no. 47 in three mutually perpendicular planes. Note the similarity in trend between silicate and magnetic minerals. (d) Stereonet plot of silicate fabric with gently plunging long axis trending towards WSW. (h) Stereonet plot of AMS fabric. ***b***, Dyke no. 41: Distribution of long-axis trend of plagioclase (a–c) and magnetic minerals (e–g) from dyke no. 41 in three mutually perpendicular planes. Note the dissimilarity in trend between silicate and magnetic minerals. (d) Stereonet plot of silicate fabric with gently plunging long axis trending towards WSW. (h) Stereonet plot of AMS fabric. Different colours in the stereonet imply specimens from different samples of the respective dyke. ***c***, Histogram showing polymodal distribution of plagioclase laths in sample collected from dyke no. 47.

each thin section) in the dyke sample[15] (Figure 2 *c*). Dyke no. 41 is possibly representing 'anomalous' fabric, where K_1 axis and ($K_1 - K_2$) plane are perpendicular to the dyke plane[13,15] (Figure 2 *a*).

Hargraves *et al.*[13] suggested that a template created by early crystallizing plagioclase laths may control the distribution of ferromagnetic mineral particles. This seems to be the case for dyke no. 47 and hence, AMS largely mimics the silicate fabric, although AMS fabric is controlled by the ferromagnetic opaque minerals. Hence AMS can be used here as a proxy for the determination of magma flow direction. Although there are other factors that can affect the AMS results, such as dominance of SD particles, late-stage crystallization, metamorphism, hydrothermal activity, deformation, etc. there are no evidences of such factors, and hence the magnetic fabric is considered to be primary 'normal'. Hence we can assume that the direction of K_1 will be parallel to the direction of magma flow. Figure 2 *a*(h) shows that K_1 is inclined, indicating an oblique/lateral magma flow during dyke emplacement.

In case of dyke no. 41, OMFT does not match with SFT (Figure 2 *b*). As OMFT primarily guides the AMS fabric and SFT is formed due to magma flow, AMS cannot be used as a flow fabric indicator. We have documented here examples where primary fabric and AMS fabric are associated. Similar methodologies can be adopted while correlating AMS with deformation fabrics. In such cases, it will be of prime importance to precisely analyse which deformation phase is represented by AMS. Special care should be given while associating the 'degree of anisotropy' of the susceptibility ellipsoid with relative strain suffered by the rocks, especially sedimentary rocks, where the value of absolute susceptibility is itself very low. Demarcating directional anisotropy in such rocks could be rather ambitious and the calculated anisotropy could fall well below the measurement error limit. We suggest that AMS is a good technique for fabric analysis because of its simplicity and rapidness, but must be complemented with prior work that establishes its relation with the corresponding fabric.

1. Das, A., Mallik, J., Bandyopadhyay, K. and Alam, R., *Iran. J. Earth Sci.*, 2018, **11**(1).
2. Hutton, D., *Earth Environ. Sci. Trans. R. Soc. Edinburgh*, 1992, **83**, 377–382.
3. Bouchez, J. L., In *Granite: From Segregation of Melt to Emplacement Fabrics*, Springer, Dordrecht, The Netherlands, 1997, pp. 95–112.
4. Vigneresse, J. L. and Clemens, J. D., *Geol. Soc. London, Spec. Publ.*, 2000, **174**(1), 1–19.
5. Ferre, E., Bordarier, C. and Marsh, J. S., *Tectonophysics*, 2002, **354**(1–2), 1–23.
6. Majumder, S. and Mamtani, M. A., *Phys. Earth Planet. Inter.*, 2009, **172**(3–4), 310–323.
7. Renjith, A. R., Mamtani, M. A. and Urai, J. L., *J. Struct. Geol.*, 2016, **82**, 48–59.
8. Tarling, D. H. and Hrouda, F., *The Magnetic Anisotropy of Rocks*, Chapman and Hall, London, 1993.
9. Ray, R., Sheth, H. C. and Mallik, J., *Bull. Volcanol.*, 2007, **69**, 537–551.
10. Jelinek, V., *Tectonophysics*, 1981, **79**, T63–T67.
11. Cañón-Tapia, E., *J. Geol. Soc. London*, 2004, **238**, 205–225.
12. Hrouda, F., Chlupáčová, M. and Rejl, L., *Earth Planet. Sci. Lett.*, 1971, **11**(1–5), 381–384.
13. Hargraves, R. B., Johnson, D. and Chan, C. Y., *Geophys. Res. Lett.*, 1991, **18**(12), 2193–2196.
14. Ildefonse, B., Launeau, P., Bouchez, J. L. and Fernandez, A., *J. Struct. Geol.*, 1992, **14**(1), 73–83.
15. Wiegand, M., Trumbull, R. B., Kontny, A. and Greiling, R. O., *Tectonophysics*, 2017, **716**, 149–167.

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