



# Applicability of AMS technique as a flow fabric indicator in dykes: insight from Nandurbar–Dhule Deccan dyke swarm

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## Abstract

Determination of the nature of magma flow (vertical or lateral) from rock fabrics in a dyke swarm holds significant importance in deciphering its emplacement mechanism, depth of magma chamber and its association with mantle plumes. Nandurbar–Dhule dyke swarm from Western India consists of ~210 mappable, tholeiitic, large, linear dykes intruding the country rocks of Deccan basalt. We discuss here the development of flow-controlled rock fabrics in these dykes as a function of their thicknesses. Magnetic fabric obtained from anisotropy of magnetic susceptibility (AMS) analysis of the samples collected from these dykes was used as a proxy for rock (flow) fabric. Samples from the central parts of the thicker dykes (strike perpendicular thickness > 10 m) show random and inconsistent development of magnetic fabrics than their marginal counterparts. Petrography suggests the development of relatively clear shape-preferred orientations of the elongated mineral grains only at the margin of a thick dyke. Thinner dykes (strike perpendicular thickness < 10 m) show both consistent magnetic fabrics and clear shape-preferred orientations. We propose that the center of a thick dyke fails to provide (due to high flow velocity, slower cooling rate, lack of friction-induced shearing, and draining back of magma) a favorable condition where (a) flow fabric can efficiently develop and (b) magnetic fabric can effectively mimic the flow fabric. Thinner dykes and the margins of the thicker dykes are, hence, better candidates for observing flow fabrics represented by magnetic fabrics. This work is also motivated by the reservations expressed by earlier researchers in using the AMS technique for magma flow characterization, especially for giant dyke swarms. We have critically evaluated their reservations in light of our results and commented on the applicability of the AMS technique on such studies.

**Keywords** Dyke · AMS · Fabric · Deccan traps · Magma flow

## Introduction

Dykes are the narrow aisles through which magma had flown from its underground source (directly from the mantle or from a subcrustal magma pond) towards the surface and, in turn, could have ended up feeding large volcanic provinces. Magma emplacement mechanism in a dyke is a fairly complex phenomenon and is generally controlled by regional tectonic condition, network of planar discontinuities forming potential conduits, available magma volume, available heat budget, etc. (Airoldi et al. 2011; Aubourg et al. 2002; Kissel et al. 2010; Pan et al. 2014; Raposo and D’Agrella-Filho

2000; Raposo and Ernesto 1995; Raposo et al. 2007; Ray et al. 2007). Knowledge about magma transportation within a dyke provides valuable insights about the magma plumbing system operating within an apparently discordant conduit which may or may not be joined with other such conduits at depth (Pan et al. 2014).

Previously, several thermo-mechanical models were proposed as possible explanations for the physical and spatial distribution of the mineral phases in dykes (Correa-Gomes et al. 2001; Féménias et al. 2004; Nkono et al. 2006). These models were largely based on some petrographic evidences as the resultant magma fabrics are primarily defined by the physical disposition of different mineral phases and their distribution under the influence of prevalent magma flow. The elongated grains (mineral phases) respond more to the magma flow by aligning themselves along the flow direction compared to the euhedral shaped grains. Therefore, the study of Shape-Preferred Orientations (SPO) of an elongated

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mineral phase, for example, Plagioclase Feldspar laths in mafic volcanic rocks, should provide information about causative magma flow direction.

Conventional methods like the study of dyke segmentation, gas bubbles, vesicles, mineral lineation, and petrography (Coward 1980; Philpotts and Philpotts 2007; Ohashi et al. 2018; etc.) can be extremely time-consuming yet ambiguous for understanding flow directions. Hence, the methods are not effective for flow geometry characterization of large ( $K_m$  scale) dyke swarm. Khan (1962) first coined the possibility of a correlation between magnetic fabric and lava flow. He established that the Anisotropy of Magnetic Susceptibility (AMS) of a group of elongated grains of magnetite will be similar to their orientations (Canon-Tapia 2004). It is generally believed that the maximum susceptibility axis ( $k_1$ ) will be parallel/sub-parallel (normal fabric) to the magma flow direction (Wing-Fatt and Stacey 1966; Symons 1975; Knight and Walker 1988; Canon-Tapia 2004). Potter and Stephenson (1988) invoked the possibility of very small single-domain (SD) magnetite crystals where “inverse fabric” (maximum susceptibility axis  $k_1$  being perpendicular to the magma flow direction) would be evident. Rochette et al. (1991) reported inverse fabric from Ophiolites in Oman and described them to be the result of hydrothermal alteration. There are some recent examples where AMS studies on dyke swarms were performed (Curtis et al. 2008; Ernst and Baragar 1992; Nagaraju and Parashuramulu 2019; Pan et al. 2014; Weigand et al. 2017; Yan et al. 2017; Hrouda et al. 2019). Pan et al. (2014) have analyzed magma flow directions for six Cretaceous dyke swarms from the coastal SE China using AMS. They inferred sub-vertical flow of magma from symmetrical imbrications of magnetic foliations against dyke walls as predicted by simulating the combination of magnetic sub-fabrics related to magma flow in dykes (Callot and Guichet 2003). In another study by Curtis et al. (2008), AMS analysis was carried out on the Jurassic dykes in H.U. Sverdrupfjella, Dronning Maud Land, Antarctica. This study revealed vertical magma transport in the Straumsvola area; whereas, dykes from Jutulrora area show lateral transport. Ernst and Baragar (1992) used magnetic fabric to determine the flow pattern of magma in the Mackenzie giant radiating dyke swarm. Although inconclusively, Nagaraju and Parashuramulu (2019) discerned the evidence of a sub-horizontal flow at deep mid-crustal levels and explained in lights of the localized magma chamber/mantle plume, flow dynamics and prevailing stress condition. Weigand et al. (2017) also suggested a sub-vertical or steep magma flow in Etendeka Province, Namibia and discussed the consistency of their AMS results with field observation (dyke segmentation, topography, etc.). Similarly, Yan et al. (2017) analyzed several dykes from different regions of North China Craton and came up with variable flow directions in different regions. Based on the imbrication

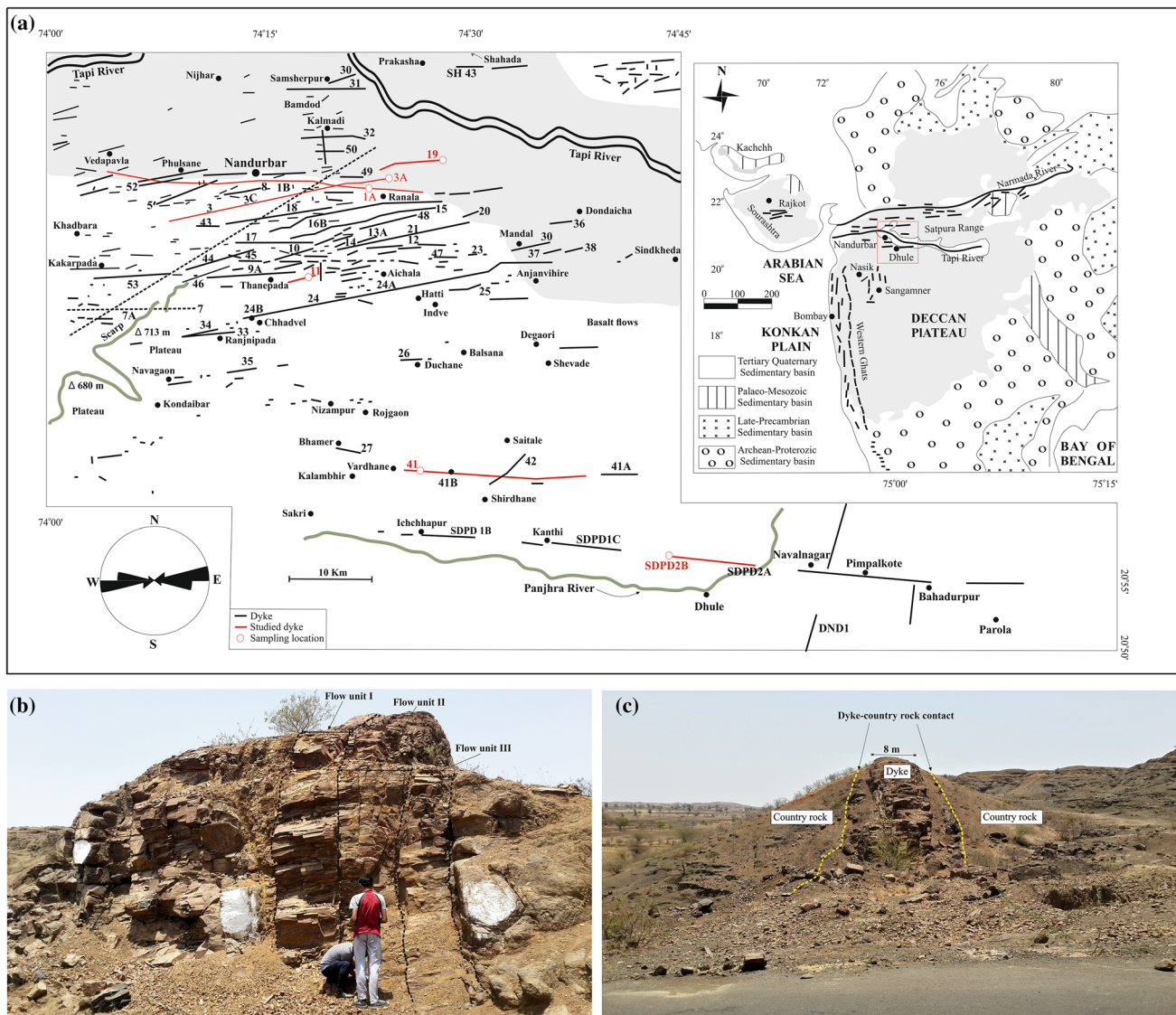
pattern of the AMS fabric along dyke margin, they determined absolute flow direction to be Northwards and South Westward. They suggested a post-collisional extension to be responsible for the emplacement of this dyke swarm. Hrouda et al. (2019) have studied a composite lamprophyre dyke from Central Bohemian dyke swarm of Czech Republic and detected magma-free flow and forcefully driven flow. They characterized these two types of flow based on the dominance of normal fabric in case of magma-free flow and intermediate or inverse fabric in case of forcefully driven flow. According to them, two types of different magma pulses with different viscosity parameters are responsible for this type of flow pattern.

Nevertheless, it is important to mention that, there are some concerns about the robustness of the interpretations from AMS studies because often correlation between AMS and the geological fabric is not properly established before a wide regional scale interpretation is made. McHone et al. (2005) further expressed their strong reservations against using AMS as flow fabric indicators for giant dyke swarms especially for interpreting lateral flow. They argue that AMS is mainly contributed by magnetite grains in basalt, which crystallize when the magma is relatively cold probably after magma flow has stopped. Ray et al. (2007) have also raised similar doubts mentioning the possibility of late-stage crystallization of ferromagnetic grains around plagioclase laths making the AMS results being completely unrelated to the magma flow direction.

In this paper, we have carefully studied samples from margins and central parts of thick ( $> 10$  m wide) and thin ( $< 10$  m wide) dykes to find out the correspondence of plagioclase network and ferromagnetic grains and then compared the results with obtained AMS fabrics. The orientation of the magnetic foliation ( $k_1$ – $k_2$  plane) with respect to the dyke wall across dyke length is used to test the consistency or randomness of magnetic fabric development. The aim of such analysis is threefold, (a) to understand how magma flow dynamics controls the development of mineral fabric, (b) to test our results against the concerns raised by earlier researchers and then to find out if a recipe can be prescribed which takes into account of such concerns and still can provide meaningful AMS results deciphering magma flow direction, and (c) to check the importance of sampling locations (the center or from the margin of a dyke) on AMS results.

## Geological background

Topographically Nandurbar–Dhule area in Western India is a flat region situated at an altitude of  $\sim 200$  m with respect to the mean sea level. The dykes show more or less consistent East–West trend (Fig. 1a). Nandurbar–Dhule dyke swarm ( $\sim 210$  dykes) intrudes the highly weathered Deccan



**Fig. 1** **a** Geological map of Nandurbar–Dhule dyke Swarm showing spatial distribution of dykes (modified after Ray et al. 2007). Top right inset shows the extent of Deccan Flood Basalt (shaded) in the Western part of India. Bottom left inset shows the angular distribu-

tion of dyke trends (mostly E–W). **b** and **c** Are field photographs of one of the N–D dykes. Different flow units demarcated by black dotted line are shown in **b**. **c** Shows the contact of dyke with the country rock

flood basalt (Fig. 1b and c). Relatively fresh and unweathered dykes form linear, often-prominent ridges that run for many kilometers. Some of the dykes show multiple sets of columnar joints (Fig. 1b) possibly indicating distinct cooling fronts. These dykes are composed of evolved tholeiitic basalt and basaltic andesite (Mellusso et al. 1999). Sethna et al. (1999) distinguished older and younger sets of dykes based on the paleomagnetic data and found normal magnetisation direction for the older sets of dykes. The younger set showed reverse magnetisation just like the preceding Deccan lava pile. Based on gravity modeling, Bhattacharji et al. (2004) suggested the presence of shallow magma chambers (depth 7–8 km) feeding the dykes in the past. Ray et al. (2007)

also argued in favor of a shallow magma chamber and calculated magmatic overpressure (1.93–77.5 MPa) responsible for emplacement. They found no systematic correlation between along strike length and across strike thickness of the dykes. They described this observation as a manifestation of thermal erosion. Sheth et al. (2019) obtained  $^{40}\text{Ar}/^{39}\text{Ar}$  ages for three dykes (Dyke 3 ~  $63.43 \pm 0.48$  Ma, dyke 5 ~  $67.49 \pm 0.89$  Ma and dyke SDPD1 ~  $67.06 \pm 0.60$  Ma; Fig. 1a) from this dyke swarm. They have correlated geochemically some of the dykes with younger flow units disposed elsewhere and identified them to be feeders to the flows. Dykes are more abundant in the Nandurbar area and gets scarcer away from it (Fig. 1), making Nandurbar region

being possible “cluster-center” for these dykes and possibly lying immediately above the source.

## Methodology

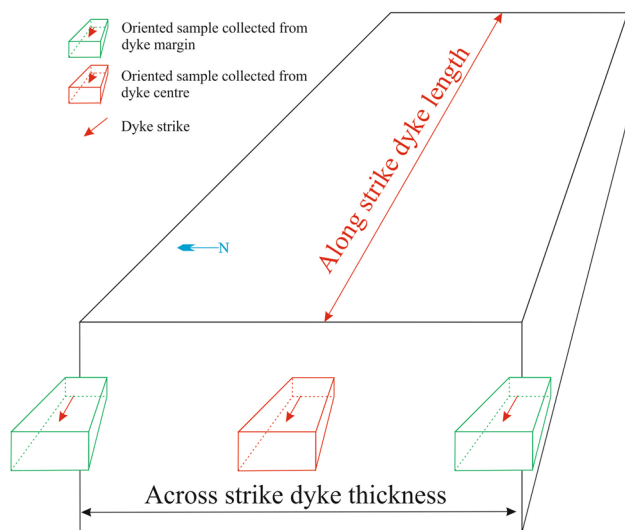
Multiple geographically oriented samples were collected from the marginal and central part of six dykes (Fig. 2) of different thicknesses (SDPD 2B ~ 5 m, 41 ~ 8 m, 1B ~ 6 m, 19 ~ 22 m, 11 ~ 36 m, 3A ~ 40 m). Thin sections, parallel to the horizontal plane (Perpendicular to the dyke plane as the dykes are mostly vertical) with its long axis being parallel to the axis of the dyke, were prepared from these samples to study the Shape-Preferred Orientation (SPO) of the plagioclase laths and ferromagnetic grains which appears opaque under the transmitted light microscope. Their distributions in orientation were then plotted in rose diagrams (Figs. 3 and 4). Energy-Dispersive Spectroscopic (EDS) analysis of the opaque minerals was done with the help of a Scanning Electron Microscope (SEM) to understand the magnetic mineralogy. The EDS data show the elemental concentration of the studied opaque ferromagnetic minerals (Fig. 5). Multiple cylindrical cores of 22 mm in height and 25.4 mm in diameter were drilled out from each oriented sample. Anisotropy of Magnetic Susceptibility for each core was measured using KLY-4s spinner kappa-bridge housed at the geomagnetic laboratory of Indian Institute of Technology, Kharagpur, India. Orientation and magnitude of the three principal axes of the magnetic susceptibility fabric, viz.  $k_1$ ,  $k_2$ , and  $k_3$  were measured. Magnetic foliation (F), magnetic lineation (L), corrected degree of anisotropy ( $P'$ ) and shape parameter (T) were calculated from the measurements. The magnetic foliation

(F) corresponds to the  $k_1$ – $k_2$  plane; whereas, the magnetic lineation (L) corresponds to the direction of  $k_1$ .  $P'$  represents the eccentricity of the magnetic susceptibility ellipsoid and  $T$  gives the shape of the susceptibility fabric, i.e., prolate where  $T < 1$  or oblate where  $T > 1$  (Tarling and Hrouda 1993). Then, the following parameters were calculated using the following relationships: (a) mean susceptibility  $k_m = (k_1 + k_2 + k_3)/3$ ; (b) degree of magnetic anisotropy,  $P' = \exp \{2[(\ln k_1 - \ln k_m)^2 + (\ln k_2 - \ln k_m)^2 + (\ln k_3 - \ln k_m)^2]\}^{1/2}$ , (c) shape parameter  $T = \{[2\ln(k_2/k_3)]/\ln(k_1/k_3)\} - 1$  (Jelinek 1981).

## Results

### Petrography

Petrography reveals the basic mineralogy of the dykes which are primarily composed of plagioclase laths and clinopyroxene with a good amount of opaque ferromagnetic grains (Figs. 3a, b, 4a and 5a). We do not observe significant grain size variation in silicates from the center to the margin of a thick dyke. However, the size and shape of opaque ferromagnetic grains notably change. In the center (Fig. 3a), the opaque minerals are almost euhedral and do not conform to any Shape-Preferred orientation (Fig. 3d). Plagioclase laths are also randomly oriented (Fig. 3c). In the margin of a thick dyke, however, both plagioclase and opaque minerals show relatively strong shape-preferred orientation and they are collinear with each other (Fig. 3e and f). The opaque minerals are significantly smaller in size. Above observations possibly hint to the phenomena of relatively rapid cooling at the margin allowing the silicate flow fabric to be preserved or the Bagnold's effect (Bagnold 1954) responsible of a classical crystal segregation (Platten 1995) in the core zone and an aphyric texture (typical chilled margins) on the rims of the dyke inducing a mineral differentiation towards the core. The silicate fabric is also being imitated by the opaque minerals as they crystallize almost simultaneously with the silicate grains in the margin. The same is not true at the center. Due to slow cooling, SPOs are either not developed in silicates or have been destroyed by later gravity-driven processes like backflow. The opaque minerals might be crystallized much later in the cooling process and occupied the interstitial spaces as almost euhedral grains. Slow cooling does not allow magnetite grains which crystallize in cubic system to form shape anisotropy as the grains form in euhedral shape. A thin dyke does not show significant deviation between silicate and magnetic mineral orientation as observed under microscope (Fig. 4a). There is no considerable distinction in fabric development from its margin to the center as evident from the rose diagram obtained from thin dyke samples (Fig. 4b). Corresponding silicate SPO shows the restricted distribution and the opaque minerals follow the same. This



**Fig. 2** Schematic diagram showing geometrical parameters of dykes viz. along dyke strike length and across dyke strike thickness. It also shows sampling pattern from a dyke

could be due to the alignment of the elongated grains followed by the traction resulting from the shear between the magma and the dyke wall. Rapid cooling enables to form elongated magnetite grains which in turn align themselves parallel to the plagioclase laths due to magma flow thereby acquiring strong shape anisotropy giving rise to AMS fabric.

## Magnetic mineralogy

Energy-Dispersive Spectroscopic (EDS) analysis by SEM shows (Fig. 5a) a good disparity between bright white-colored Titano-Magnetite with variable Ti content (Fig. 5b) and dark-colored silicate matrix. It confirms the observations made by Sethna et al. (1999).

## Anisotropy of magnetic susceptibility

Table 1 lists the results obtained from the AMS analysis. All the samples show mean susceptibility ( $k_m$ ) values well above  $10^{-2}$  SI units implying major contribution of susceptibility from ferromagnetic grains (Titano-Magnetite).

For thin dykes, the magnetic foliation ( $k_1$ – $k_2$ ) planes seem to be quite consistent in terms of their attitude (dip/strike) along the width of the dyke (Fig. 6). Also, the maximum susceptibility ( $k_1$ ) axes are sub-horizontal to gently plunging. On the contrary, magnetic foliation planes are not consistent in thick dykes along their width. Magnetic foliation planes are randomly oriented in the center among different samples (Fig. 7) implying weak development of magnetic fabric at the dyke center. The susceptibility axes do not form any significant cluster in case of central part of thick dykes unlike thin dykes (Fig. 7). In the margin of the dykes, however, magnetic foliation planes are consistent among different samples and show definite clustering of the susceptibility axes compared to the central part. The results imply quick chilling in the margin of thick and thin dykes facilitating the development and preservation of consistent magnetic fabric.

## Discussion

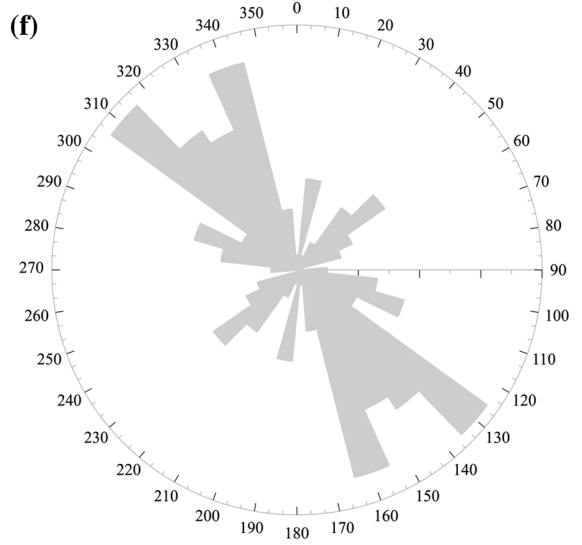
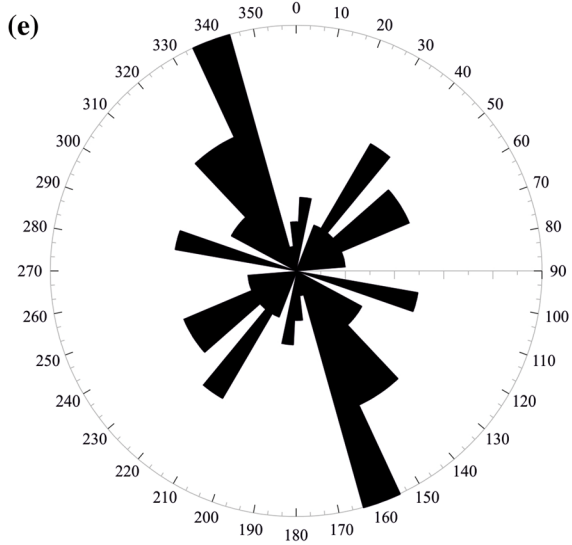
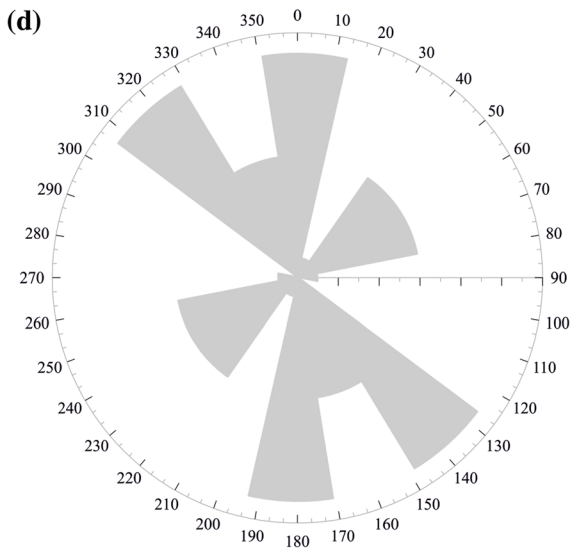
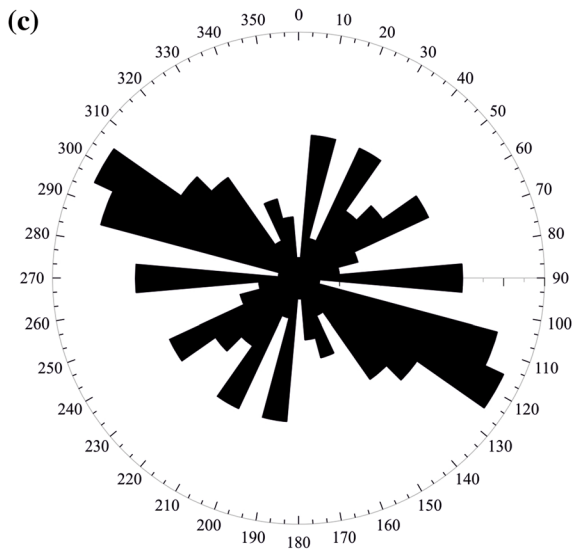
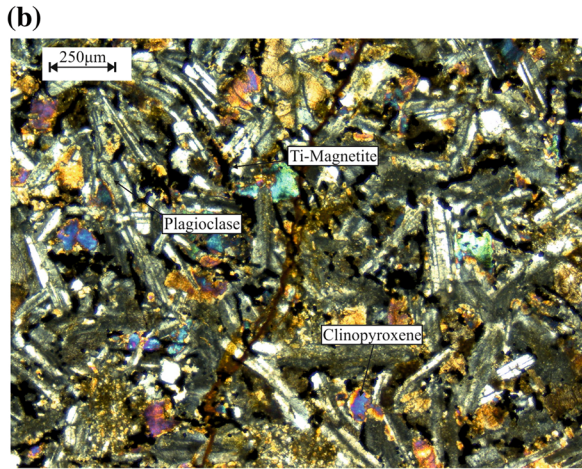
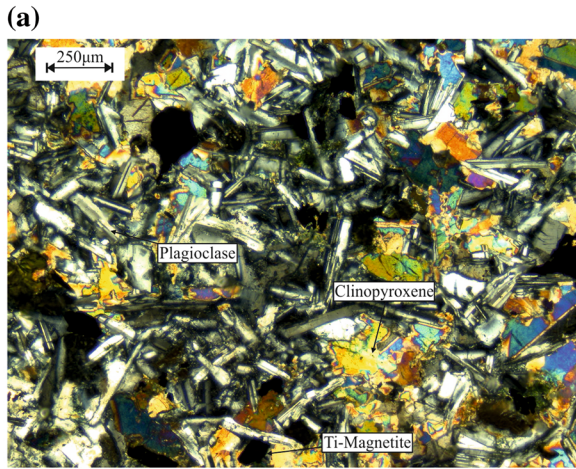
Nandurbar–Dhule dyke swarm consists of dykes of different lengths and widths (length: few meters–80 km and width: 0.5 m–65 m). For smaller dykes, where strike length is smaller than its width, vertical injection is a common assumption. In contrast, magmas in giant dykes are believed to flow laterally away from plume centers for hundreds or thousands of kilometers (McHone et al. 2005). Ray et al. (2007) have argued mostly vertical flow for smaller dykes in Nandurbar–Dhule dyke swarm and lateral flow for larger dykes, comparing its similarities with the dyke swarm in Iceland (as proposed by Gudmundsson 1990, 1995a,b). As mentioned earlier, Sheth et al. (2019) has further established

some of the dykes being feeders to distantly placed flood basalt flows which in a way also indicated the lateral flow of the magma in the dyke swarm. Hence, there is a scientific need to establish flow geometry for this giant dyke swarm, to prove or disprove its potential of being the feeder to the mighty Deccan flood basalt. This would add value to the ongoing debate about the origin of Deccan volcanism to be arising from a central edifice or from fissure eruption.

Flow geometry in a dyke swarm with hundreds of dykes can be rapidly constrained by AMS analysis. In our latest publication (Das et al. 2019a), we have documented that one must establish a correspondence between the 3D SPOs of primary elongated mineral constituent phases and that of the magnetic mineral phases (contributing to the AMS result) before any meaningful correlation is drawn between AMS fabric and the flow fabric. In the present paper (result section), we have further proved that such correspondence of SPOs between the ferromagnetic grains and silicates is best developed in the margin of a thick dyke and in a thin dyke.

Major criticism against using AMS as a flow fabric proxy comes regarding the late settling crystallization of ferromagnetic grains in the interstitial spaces of major silicate framework after the actual flow has stopped. McHone et al. (2005) argued that as the magma flow fabric should be strongly controlled by plagioclase laths, “around which the magnetite grains collect in layers along the planar feldspar faces”, flow fabric should be independent of the magnetic fabric. Also, a 3D plagioclase network (Philpotts & Dickson 2000) “collapses and flattens if the magma body is large enough (sills and large dikes)”. They also argued that the back-flow after diminishing of the fluid pressure could re-orient both feldspar phenocrysts and surrounding magnetite grains. So, it is important to correlate SPO and AMS results before proceeding with the interpretation of AMS data (Das et al. 2019a, and the present work).

We would like to draw the reader’s attention to the flow parallel-oriented photomicrographs from the center and the margin of a thick dyke (Fig. 3a and b). In the center, we observe the presence of almost euhedral ferromagnetic opaque minerals having no correspondence in alignment with the silicate grains like plagioclase laths. This point is further emphasized in the rose diagrams where the orientation of the plagioclase laths and opaque minerals is plotted (Fig. 3c and d). It is quite clear that neither the plagioclase grains nor the ferromagnetic opaque minerals show any preferred orientation. This could be due to the collapse and flattening of the silicate framework (McHone et al. 2005; Philpotts and Dickson 2000) due to its own weight in case of large dykes where cooling rate is very slow at the center. The ferromagnetic grains could be crystallized later than the actual flow stopped. The other explanation could be the presence of backflow where magma moves back through the dyke fractures destroying the rock fabric. Hence, the



**Fig. 3** **a** and **b** Photomicrographs of the thin sections of samples collected from a thick dyke's ( $\geq 10$  m) center and margin, respectively. **c** and **d** Show rose diagrams for angular distribution of the long-axis orientation of plagioclase and opaque minerals at the central part of the dyke. **e** and **f** Show rose diagrams for angular distribution of the long-axis orientation plagioclase and opaque minerals at the marginal part of the dyke

resultant AMS fabric should not represent the flow fabric rather than it will show the haphazard orientation of the magnetite grains crystallized in the interstitial space. The same is reflected in the stereograms where magnetic susceptibility axes are plotted. They show no coherence in magnetic fabric among different samples.

On the contrary, photomicrographs from the margins of the thick dykes (Fig. 3b) exhibit parallelism between plagioclase laths and magnetite grains. Due to a very fast cooling rate, possibly the silicate and magnetite grains got crystallized almost at the same time. Both plagioclase and magnetite grains show very distinct orientation preference and they are oriented in the same direction (Fig. 3e and f). In summary, the SPO of the silicate template is more or less copied by the ferromagnetic grains. Their preferred orientation indicates that the flow fabric must have been frozen due to rapid cooling and the correspondence of the silicate framework with the magnetite grains, gives us confidence about the usability of AMS technique as flow fabric indicator. The same is reflected in the stereograms where magnetic susceptibility axes are plotted (Figs. 6 and 7). It shows remarkable coherence among different samples.

In thin dykes ( $< 10$  m thickness), we see coherence in AMS fabric between samples from the center and from the margin indicating very rapid cooling of the whole dyke that froze the magnetic fabric (Fig. 6). We discussed this observations in light of the hypothetical 'Magma plumbing system model' (Fig. 8). During the magma movement along a fissure, it experiences frictional resistance along the host rock wall. The resultant frictional force creates a shear along the dyke margin. It starts to wane down towards the central part of the dyke (Bhattacharji 1967). The same friction also affects the velocity of magma across the dyke in the exact opposite way. Magma flow is fastest at the center and towards the margin, it becomes sluggish. Besides, conductive heat loss to the neighboring Deccan flow and along with strike advective heat transfer during magma migration through dyke (Gonnermann and Taisne 2015) affects the cooling mechanism. The advective heat transport is directly or indirectly a function of flow velocity. The solidification of magma depends on the balance between advective heat transfer and the conductive heat diffusion (Bruce and

Huppert 1989). Conductive heat diffusion across dyke dominates at its contact with the country rock. Hence, the magma will quickly get solidified at the dyke margin; whereas, it needs prolong cooling window at the center. Due to this long-lasting cooling window at the central part, phenocryst could be developed very well, but it is unlikely for these phenocrysts to show flow fabric as explained before.

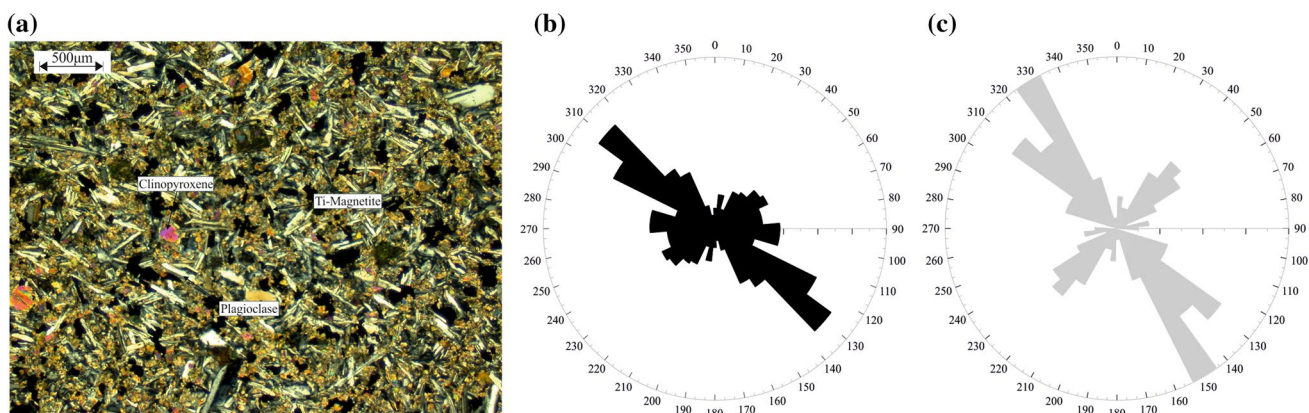
Therefore, we can conclude that the criticism raised by other researchers (McHone et al. 2005; Ray et al. 2007) is true but should be applied where magma cooling is a relatively slow process like at the center of the dykes. Although, the marginal part of the thicker dykes is susceptible to deuteric alterations which can alter magnetite into haematite, no evidences of such alterations have been found. For thinner dykes and for the samples collected from the margins of thicker dykes, AMS fabric can still be used as flow fabric proxy.

The actual interpretation of the flow fabric for these dykes will require further investigations in terms of the domain structures of the magnetite grains as discussed above. Comprehensive documentation of the flow fabric including a large number of dykes will be communicated in a future publication.

## Conclusion

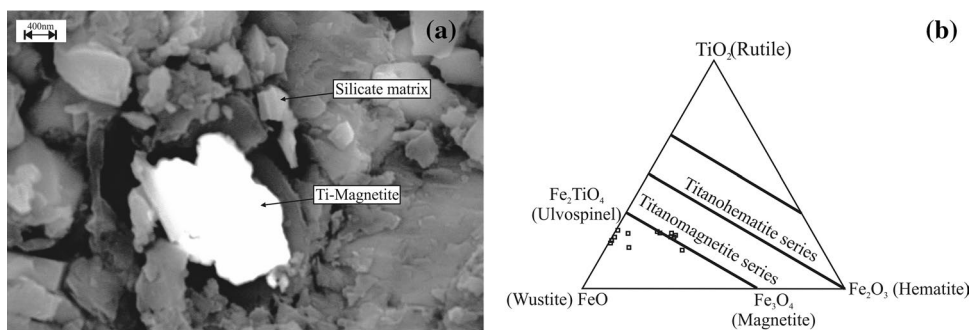
This article documents the influence of dyke thickness on magnetic fabric development. It also carefully reviews the reservations raised by previous researchers about the applicability of AMS in the determination of the direction of magma flow. It concludes:

1. Due to rapid cooling, magnetic fabric is preserved in the margin of a thick dyke or in a thin dyke and can very well be used for flow fabric determination once a good correspondence between silicate framework and magnetic grains is established.
2. The reservations raised by earlier researchers are mostly applied in the central part of a thick dyke, where slow cooling prevails. Gravity-driven processes like its own weight and backflow often hinder the development of a proper flow fabric.
3. We recommend sampling from the margins of a reasonably thick dyke for meaningful AMS results which can provide valuable information in determining the initial magma flow direction.



**Fig. 4** **a** Photomicrographs of sample from a thin ( $\leq 10$  m) dyke shows fine-grained silicate minerals and magnetic grains occupying the interstices. **b** Rose diagrams showing angular distribution of the long-axis orientation plagioclase. **c** Rose diagrams showing angular

distribution of the long-axis orientation opaque minerals. It is evident that both silicate and magnetic minerals are following the similar pattern



**Fig. 5** **a** Scanning Electron Microphotograph of dyke sample. Titanomagnetites are represented by bright grains enclosed in a dull silicate matrix. **b** Triangular plot showing elemental concentration of iron

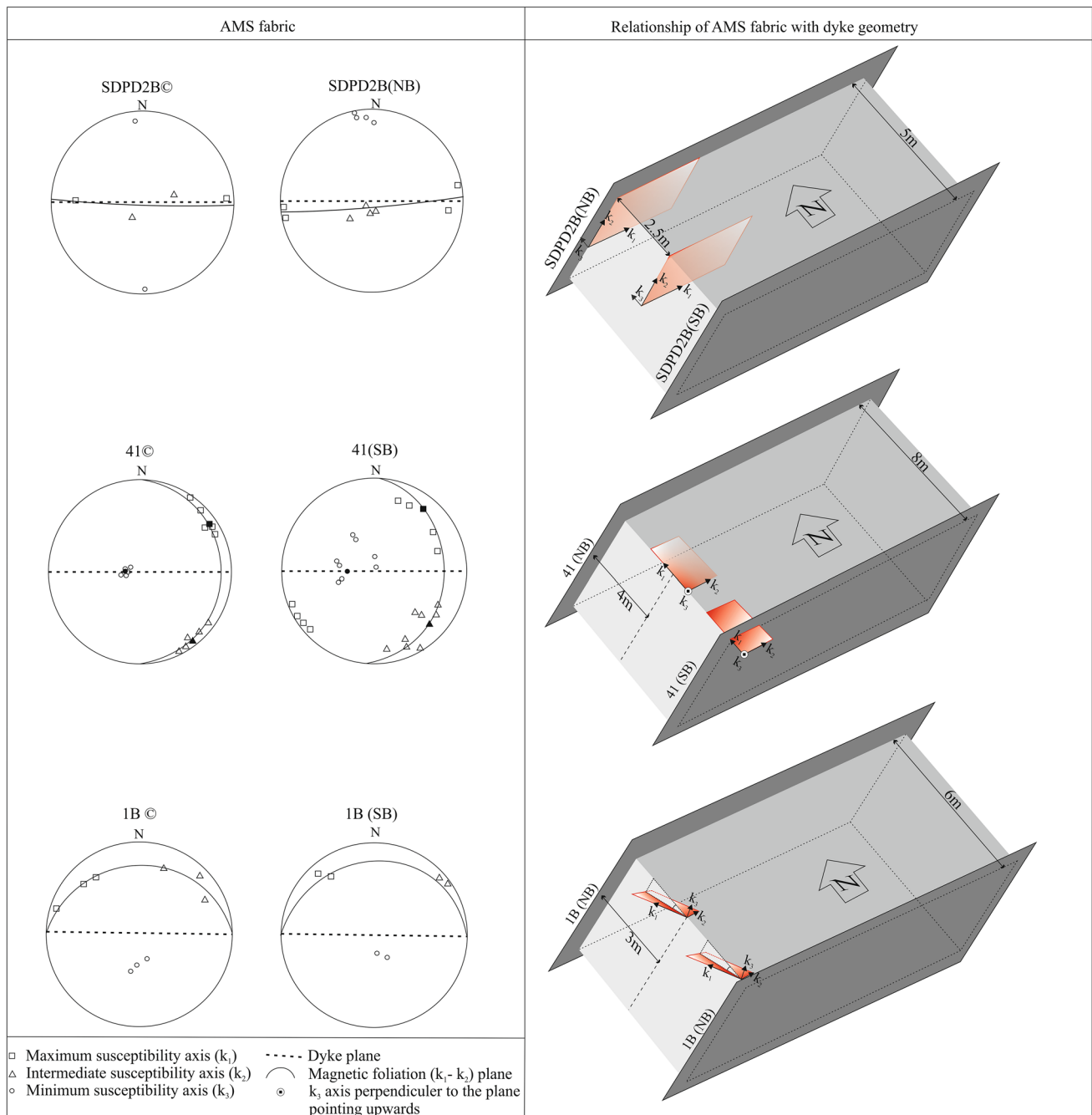
oxides with variable Ti content in the triangular diagram of  $\text{FeO}-\text{Fe}_2\text{O}_3-\text{TiO}_2$ . The hollow squares represent the composition of the ferromagnetic minerals in the study area

**Table 1** Anisotropy of magnetic susceptibility (AMS) data from different dyke’s center and margin

Sample no	Dyke trend	Dyke thickness (m)	$k_m$ (SI)	$T$	$P_j$	$k_1$ (D/I)	$k_2$ (D/I)	$k_3$ (D/I)
SDPD2B©	E–W	5	7.67E–02	0.214	1.026	270/2	114.2/79.5	354.5/2.2
SDPD2B(NB)	E–W	5	7.14E–02	–0.194	1.035	91/2	212/76.5	357.9/5.8
41©	E–W	8	6.86E–02	0.792	1.170	51.4/10.6	143/8.6	10.6/10
41(SB)	E–W	8	5.83E–02	0.461	1.029	59.3/0.4	149.3/10.3	326.8/79.7
1B©	E–W	6	4.83E–02	0.531	1.026	301.4/19.8	39.2/27.3	179/62
1B(SB)	E–W	6	7.89E–02	–0.161	1.014	320.5/18	51.4/3.3	156/71.1
3A©	N75E	40	4.70E–02	0.403	1.046	65.9/16.2	334.1/6.1	224.2/72.6
3A(SB)	N75E	40	3.79E–02	–0.072	1.013	216/83.5	99/7.2	2.4/2.6
11©	N73E	36	2.95E–02	0.262	1.024	237.8/59.2	197.1/21	346/34.3
11(SB)	N73E	36	3.89E–02	0.136	1.028	105.3/25	204.7/19.4	328.2/57.5
19©	N95	22	2.19E–02	–0.363	1.010	283/37.3	192.7/17.9	36.3/69.8
19(NB)	N95	22	4.08E–02	0.008	1.009	169.8/42.3	48.9/29.4	296.9/33.5

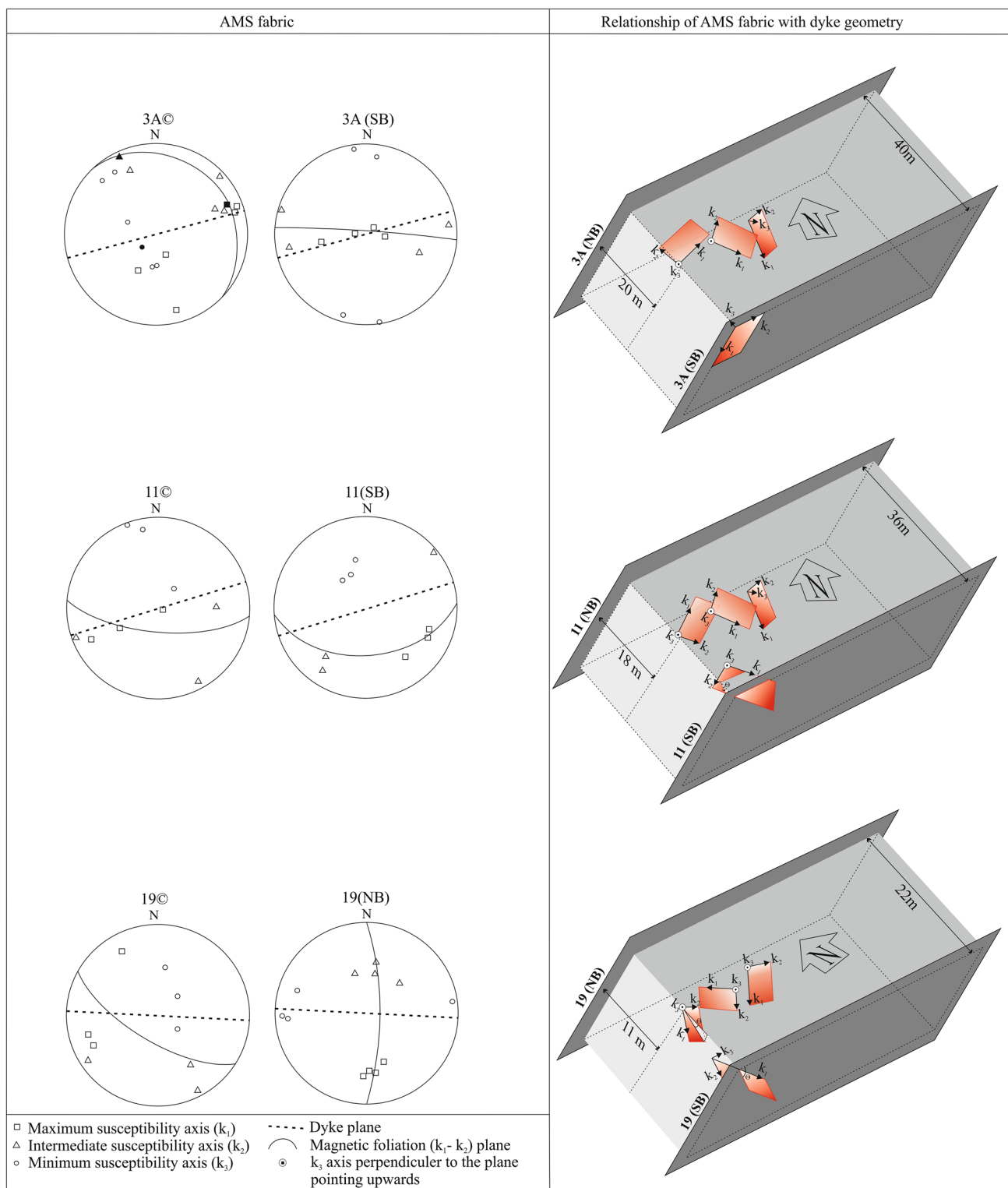
‘©’ represents samples from dyke center and ‘NB/SB’ means sample from norther/southern boundary, respectively. ‘D/I’ means declination/inclination





**Fig. 6** The distributions of AMS fabric across dyke are represented by the Stereonets and schematic diagram for different thin ( $\leq 10$  m) dykes. Samples from the central part of dyke are represented by ‘©’

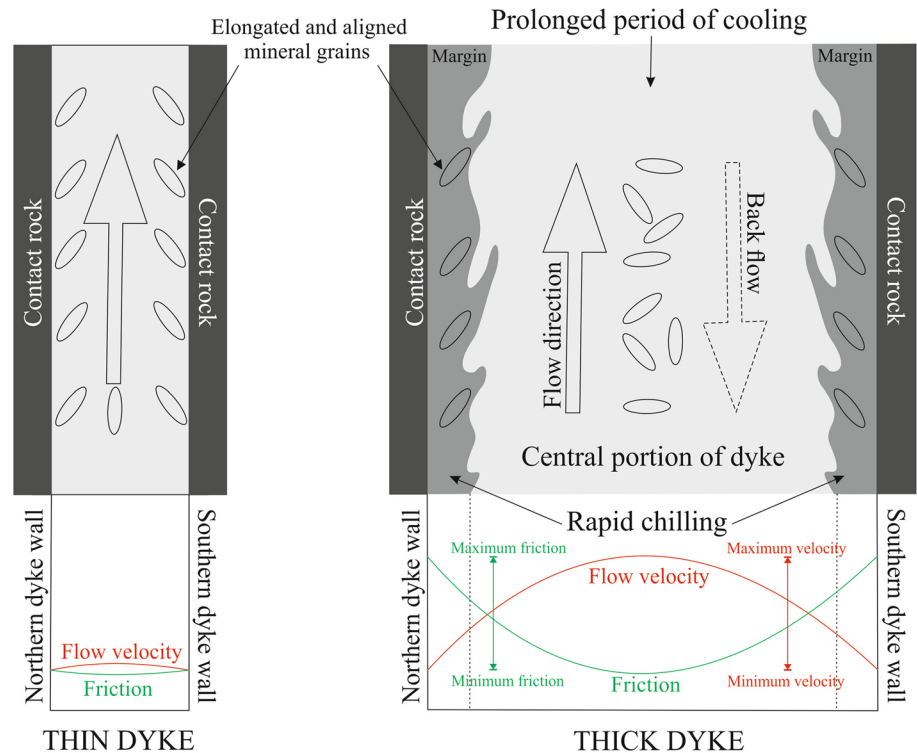
and from marginal part of dykes are represented by ‘SB’, i.e., southern boundary or ‘NB’, i.e., northern boundary



**Fig. 7** The distributions of AMS fabric across dyke are represented by the Stereonets and schematic diagram for different thick ( $\geq 10$  m) dykes. Samples from the central part of dyke are represented by ‘©’

and from marginal part of dykes are represented by ‘SB’, i.e., southern boundary or ‘NB’, i.e., northern boundary

**Fig. 8** Conceptual ‘Magma Plumbing System’ model diagram explaining the variation of rock fabric depending upon parameters like friction, flow velocity, duration of cooling, etc. as a function of thickness of the dyke



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