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A review of anisotropy of magnetic susceptibility analysis of Indian dykes: Implications for magma emplacement

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Abstract

The analysis of Anisotropy of Magnetic Susceptibility (AMS) is a powerful and rapid technique to examine the preferred orientations of mineral (magnetic) fabrics and can indicate the nature of a magma transport (vertical or lateral). The relationship between magnetic fabric and geometry of a dyke swarm enables us to understand magma emplacement processes. Depending on the mutual relationship of magnetic fabric and individual dyke geometry, mode of magma transport is interpreted. The knowledge on the nature of magma transport combined with information on geometry, magmatic overpressure and geochemistry enable us to comment on dyke emplacement processes, the location of possible feeders, syn-emplacement and post-emplacement deformations and prevailing stress regime during emplacement. A number of dykes and dyke swarms have been emplaced into the Indian shield at different points in time. Their ages vary from the Mesoarchean to Tertiary. We present here a review of three case studies where AMS technique was applied to the samples collected from Indian dykes. Two case studies are on the Proterozoic dykes that intruded into the Dharwar craton and the third case study is on Mesozoic dykes that punctured the South Indian Granulite Terrain (SIGT). The dykes generally show "normal" anisotropy fabric to indicate vertical magma emplacement with few exceptions where lateral/inclined magma flow was suggested or the results were inconclusive. We present here a critical review on the interpretation of such "anomalous" fabrics and comment on further studies that can be carried out to extract more information from such results.

Keywords: *Anisotropy of Magnetic Susceptibility (AMS), Dyke, Fabric, Emplacement.*

1. Introduction

The study of dyke emplacement has been a significant area of interest in recent times amongst Volcanologists, Structural Geologists and Geochemists (Raposo and Ernesto 1995; Raposo and D'Agrella-Filho 2000; Aubourg et al. 2002; Raposo et al. 2007; Ray et al. 2007; Kissel et al. 2010; Airoldi et al. 2011; Pan et al. 2014). Due to their journey from a deeper chamber through the crust to the surface, dykes can be the source of valuable information on mantle composition, the interaction of magma with the crustal rocks (Pan et al. 2014). They provide indications of the prevailing stress regime during their emplacement (Curtis et al. 2008; Pan et al. 2014). The magma movement can be vertical from a deeper source directly to the surface or to a shallower chamber or the movement can be lateral from the source and spread over a large area (Pan et al. 2014). These movements could be related to larger mantle plumes (Ernst and Baragar 1992) or smaller localized sources (Archanjo et al. 2000). Depending on the type of movement and dyke geometry, injection type can be indicated; whether it is a product of passive injection (Pan et al. 2014) or injected under a radial stress field associated with a mantle plume (Curtis et al. 2008) or emplaced through existing faults and fractures or emplaced passively under strong anisotropic horizontal stresses (Ray et al. 2007).

Anisotropy of Magnetic Susceptibility (AMS) is a rather quick and less ambiguous method to delineate rock fabric which is related to magma emplacement (Khan 1962; Wing-Fatt and Stacey 1966; Symons 1975; Knight and Walker 1988; Curtis et al. 2008; Pan et al. 2014) or later deformation. The distinction between lateral and vertical lava flow allows us to distinguish the long-lived feeders from the rest which otherwise have similar geometrical characteristics like orientation, thickness, length, and width. This also helps us to determine if the source of the magma chamber was shallow or deep.

There are some recent examples where Anisotropy of Magnetic Susceptibility studies on dyke swarms was performed worldwide (Ernst and Baragar 1992; Curtis et al. 2008; Pan et al. 2014). Pan et al. (2014) have analyzed magma flow directions for 6 Cretaceous dyke swarms from the coastal SE China using AMS. The sub-vertical flow of magma was inferred from symmetrical imbrications of magnetic foliations against dyke walls. In another study by Curtis et al. (2008), AMS analysis was done on the Jurassic dykes in H.U. Sverdrupfijella, Dronning Maud Land, Antarctica. This study revealed vertical magma transport for Straumsvola area, whereas dykes from Jutulrora area show lateral transport. Ernst and Baragar (1992) tried to understand the geometry of the flow pattern of magma in the Mackenzie giant radiating dyke swarm by using the concept of magnetic fabric.

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Other than a study on dykes, AMS technique is being applied since earlier days in many instances where magnetic anisotropy could be associated with tectonic, magmatic or sedimentary fabrics (Hrouda 1982; Graham 1996). It has been studied extensively in deformed rocks where degree of anisotropy has been used as a proxy to finite strain and/or relationship of magnetic fabric with rock fabric has been used to differentiate between sedimentary and tectonic fabric (Borradaile and Tarling 1981; Hrouda 1991; Averbuch et al. 1992; Hrouda 1993; Tarling and Hrouda 1993; Aubourg et al. 1997; Borradaile and Henry 1997; Parés et al. 1999; Saint-Bezar et al. 2002; Borradaile and Jackson 2004; Maffione et al. 2015; Sheibi et al. 2016). AMS technique has been applied by Indian scientists in other geological contexts too. Few of the recent examples are as follows. Renjith et al. (2016) did fabric analysis of quartzite which has negative susceptibility using AMS technique. They found evidence of compressional tectonics from AMS and structural studies in the Mesoproterozoic Singhora basin of central India. Mamtani et al. (2013) analyzed the kinematics of deformed Granitoid using AMS. Tripathy et al. (2009) evaluated the regional strain gradient in mylonitic quartzites from the footwall of the Main Central Thrust Zone in Garhwal Himalaya. Mallik et al. (2009) described magnetic fabric variations along the fault-related anticlines in the Eastern Kachchh, Western India. Nagaraju et al. (2008) studied Transpressional tectonics during the emplacement of Pasupugallu Gabbro Pluton in the Western margin of Eastern Ghats Mobile Belt.

We present here three case studies where AMS technique has been used on Indian dykes.

1) Prasad et al. (1999) carried out a low-field AMS analysis on Proterozoic dykes and their basement rocks around Harohalli, South India. The study suggests "normal" magnetic fabrics for three dykes and other dykes from the area show either "inverse" or "anomalous" magnetic fabrics, indicating the single domain (SD) uniaxial magnetite grains were dominant and a complex mixture of SD and multi-domain (MD) grains respectively.

2) Pratheesh et al. (2011) studied Cretaceous mafic dykes in the Moyar Shear Zone (MSZ) area, north Kerala for their anisotropy of magnetic susceptibility. AMS data on these dykes suggests normal magnetic fabrics, hence vertical magma emplacement.

3) Kumar et al. (2015) analyzed the magnetic fabric of radiating dyke swarm in the Eastern Dharwar Craton, southern India and suggested vertical magma flow and proximal source.

2. The methodology of AMS sampling and measurement

Multiple cylindrical cores are generally drilled from each oriented dyke sample. Measurement of magnetic susceptibility and its anisotropy is carried out using Kappa Bridge. Orientation and magnitude of the three principal axes of the magnetic susceptibility fabric, viz. K_1, K_2, and K_3 are measured. Magnetic foliation (F), magnetic lineation (L), corrected degree of anisotropy (P′) and shape parameter (T) is 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 fabric and T gives the shape of the susceptibility fabric, i.e. prolate where T<1 or oblate where T>1 (Tarling and Hrouda, 1993). The following parameters are calculated using the following relationships:

Mean (bulk) Susceptibility $K_m = (K_1+ K_2+ K_3)/3$

The degree of magnetic anisotropy, $P' = \exp\{2[(\ln K_1 - \ln K_m)2+(\ln K_2-\ln K_m)2+(\ln K_3-\ln K_m)2]\}^{1/2}$

Shape parameter $T= (2 \ln K_2-\ln K_1-\ln K_3)/(\ln K_1-\ln K_3)$

Rochette (1988), Rochette et al. (1991) and Aubourg et al. (1999) describe three types of anisotropy fabric applicable to dykes. They describe "normal fabric" where K_3 is nearly perpendicular to the dyke wall (K_1 being parallel to the flow direction), "inverse fabric" where K_1 is nearly perpendicular to the dyke wall and intermediate fabric where K_2 is perpendicular to dyke wall. It is generally believed that only normal fabric is representative of magma flow (Wing-Fatt and Stacey 1966; Symons 1975; Knight and Walker 1988) but other scientists (Khan 1962; Tauxe et al. 1998) believe that inverse fabric might indicate magma flow too. Geoffroy et al. (2002) came up with an alternative method where imbrication of magnetic foliation with dyke wall is used to determine the direction of magma transport.

3. Spatial and temporal distribution of Indian dykes

Srivastava (1996) provides a comprehensive review of the dykes emplaced in the Indian craton through time (Fig 1). They pointed that dykes are less prominent in the Proterozoic basins of India and are polymetamorphosed in the mobile belts like the Eastern Ghats and Central Indian Tectonic Zone (CITZ). Proterozoic mafic dykes from Singhbhum craton are of doleritic composition and termed as 'Newer Dolerite dykes' which intrudes into the older granitic bedrock (Dunn 1929; Srivastava 2018). In the Southern Granulite Terrain (SGT), mafic dykes made of continental tholeiitic basalt intruded the Agali-Coimbatore and Tiruvannamalai crust during the Early-mid-Proterozoic and T-MORB or TOIB type tholeiitic late Phanerozoic dykes intruded in coastal Kerala (Sinha-Roy and Furnes 1981; Radhakrishna et al. 1990; Radhakrishna and Joseph 1993). Proterozoic mafic dyke swarms intruded in the Dharwar craton have significant deformation imprints (Halls and Zhang 1995; Srivastava er al. 2014). Bastar craton marks the presence of three distinct Precambrian mafic dyke swarms Meso-Neoarchaean (~3.0-2.7 Ga) sub-alkaline mafic dykes, Neoarchaean-Palaeoproterozoic (2.5-2.4 Ga) boniniticnorite dykes and Paleoproterozoic (~1.9 Ga) sub-alkaline mafic dykes (Crookshank 1963; Ramakrishnan 1990; Srivastava 1996; Srivastava and Singh 2003; Srivastava 2006; Rao et al. 2007; Srivastava 2008).

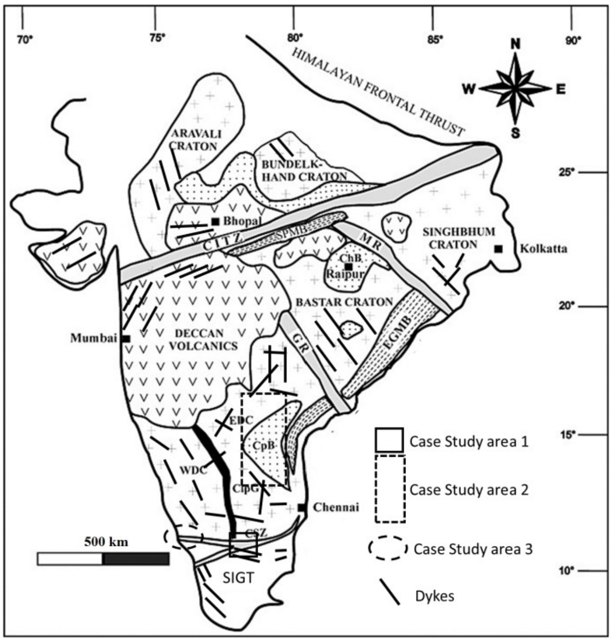

Fig 1. Simplified Geological and tectonic map of India, showing majors cratons, mobile belts and suture zones and dykes and dyke swarms in different Archean cratons, Deccan volcanics and other regions (modified after French et al. (2008); Srivastava (2006) and Yellappa et al. (2012). SPMB-Satpura Mobile Belt, GR-Govari Rift, MR-Mahanadi Rift, ChB-Chatttisgarh Basin, CITZ-Central Indian Tectonic Zone, EGMB-Eastern Ghats Mobile Belt, EDC-Eastern Dharwar Craton, WDC-Western Dharwar Craton, CpB-Cuddapah Basin, ClpG-Closepet Granite, CSZ-Cauvery Suture Zone, SIGT-South Indian Granulite Terrain.

The Aravali craton and the Bundelkhand craton are intruded by mafic dykes and dyke swarms which puncture the Banded Gneissic complex (BGC) and Banded Granite Gneissic complex (BGGC) respectively. They are vastly variable in their composition and they were emplaced during Archaean to Proterozoic (2.8 Ga to 1.4 Ga e.g. Gopalan et al. 1990; Sarkar 1997; Srivastava 2006). The dyke swarms related to Deccan volcanism are extensive and they largely spread over states like Gujrat, Maharashtra and Madhya Pradesh. Their orientation varies between NS, ENE-WSW and EW. Extensive palaeomagnetic studies around geomagnetic field reversal and continental drift have been carried out on Deccan volcanics including related dykes (Radhakrishna and Joseph 1993; Srivastava 2006). Doleritic dykes intrude the Lower Cambrian Krol and Tal Formations in the Nainital region of the Kumaun Lesser Himalaya (Valdiya 1988). In the central and NW Shillong plateau dykes of doleritic, basaltic and ultrabasic composition have intruded the basement rocks. Their general orientation varies from NW-SE, NE-SW and N-S direction (Rao 2002; Srivastava and Sinha 2004; Srivastava 2006). Genetically these dykes could be related to Kerguelen hotspot which formed Rajmahal trap (Srivastava 2006).

4. AMS on dykes of Dharwar craton

Case study 1:

Prasad et al. (1999) reported AMS analysis results of Proterozoic dykes from Dharwar craton around Harohalli, South India. Although dykes of different generations and petrographic characteristics are exposed in this area, they only focused on eight unmetamorphosed dolerite dykes. The orientation of the analyzed dykes varies from NW-SE to E-W (Fig 2) and they intrude both peninsular gneiss and Closepet granite. The foliation planes throughout this region dips towards East with N-S trends (Drury et al. 1984).

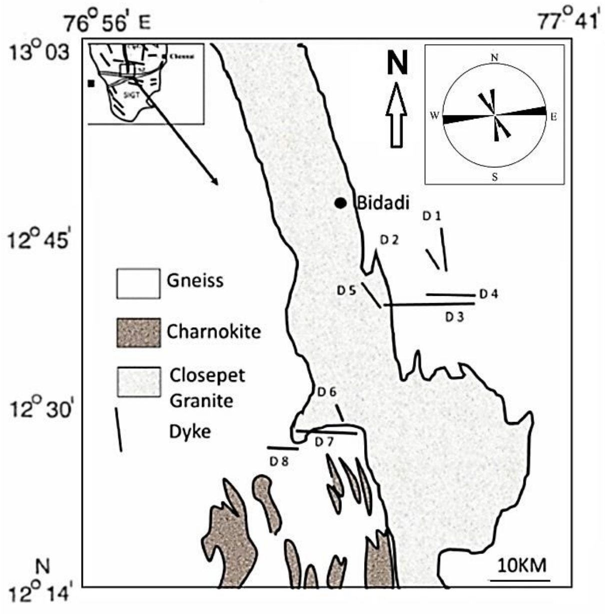

Fig 2. Simplified Geological map of Case study 1 area (modified after Prasad et al. (1999)) showing the disposition of dykes. Smaller map shows the position of the study area. Dyke trends are represented by the rose diagram in the inset.

The dominant magnetic minerals responsible for the bulk susceptibility reported from the dykes are titano-magnetite and magnetite. Forty oriented samples from these eight dolerite dykes were collected and analyzed. They reported the mean susceptibility measured from these dyke samples varying between 0.12 X 10-2 to 7 X 10-2SI. It seems that the bulk susceptibility for the analyzed samples is mostly contributed by the ferromagnetic minerals with some contributions from the paramagnetic and diamagnetic minerals. The degree of anisotropy (P′) for the majority of dykes is low (≤ 1.05) with exception shown by two dykes (D1 and D8,) with a somewhat higher degree of anisotropy (≤ 1.12).

Prasad et al. (1999) assigned the low degree of anisotropy with magma flow and a moderate degree of anisotropy with alterations in the magnetic grains. Three of the eight analyzed dykes (D1, D3 and D8) display "normal" magnetic fabric where K_3 is horizontal and perpendicular to the dyke wall and K_1-K_2 plane or the magnetic foliation is vertical. For D1 and D3 dykes K_1 axis is vertical and for D8, magnetic foliation is parallel to the strike of the dyke. These set of dykes indicate vertical magma flow. Another dyke (D6, Fig 3) shows "inverse" fabric characterized by K_3 being vertical, the K_1-K_2 plane being horizontal and K_2 axis being parallel to the dyke strike. This inverse fabric is attributed to the single domain (SD) effect as a consequence of the presence of very small uniaxial grains of magnetic minerals (Rochette et al. 1992) or due to hydrothermal alterations or due to lateral flow away from spreading center.

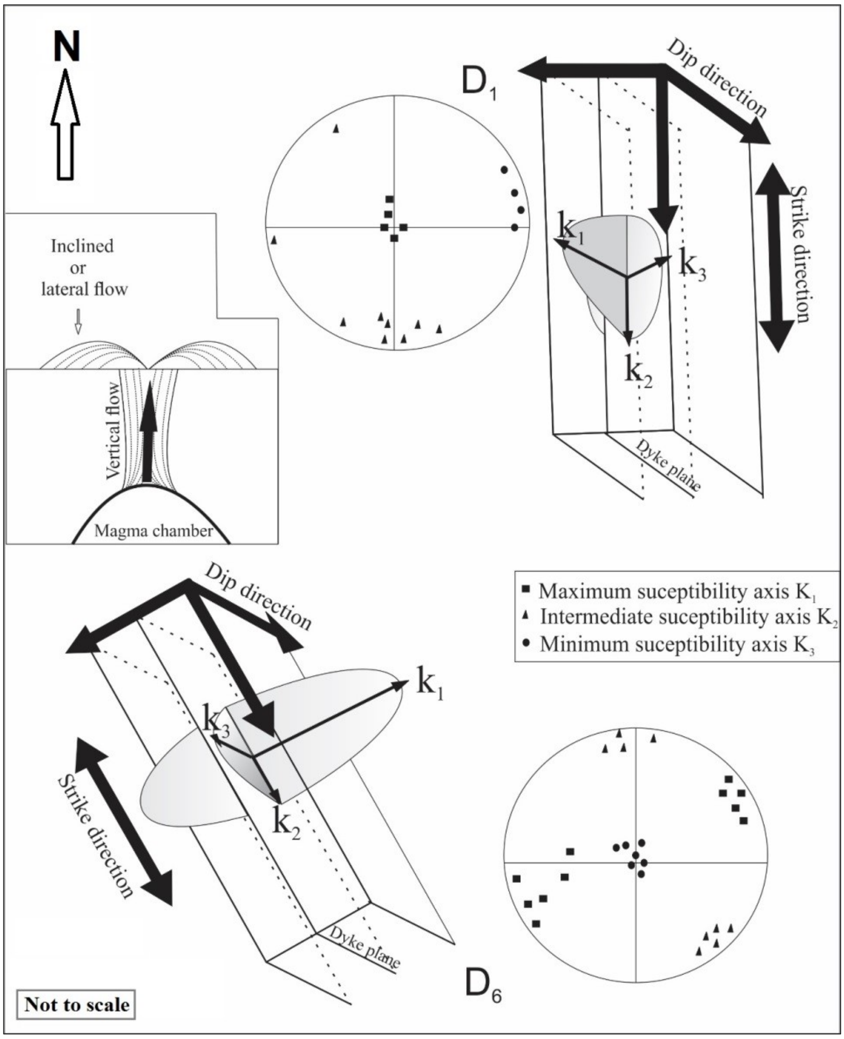

Fig 3. Hypothetical diagram showing susceptibility ellipsoid of dyke D6 and D1 depicting inverse fabric and normal fabric respectively. A hypothetical diagram in the inset shows vertical magma flow near magma chamber and inclined or horizontal flow away from it.

The stereographic projection of AMS data for dyke D1 and D8 is shown in figure 4a and 4b respectively. Another dyke (D2) shows anomalous fabric where K_1, K_2, K_3 do not exhibit any correspondence to the petro-fabric. Rochette et al. (1992) described such fabric due to the combined effect of both single domain (SD) and multi domain (MD) magnetic grains. The magnetic fabrics were randomly oriented for the rest of the dykes and any conclusion could not be drawn (Prasad et al. 1999). Apart from these dykes present in this area, AMS results for Peninsular Gneiss, Closepet granite and Charnockite were also studied by the authors. The close conformity between the N-S trending Regional foliations and the AMS fabric of this rock type hints to a common structural control syngenetic to charnockite formation, although the relationship between dyke's AMS fabric and the regional structure is not discussed in this terrain. AMS interpretation would be more feasible if the regional structural features are compared with the AMS result of the dykes, which is lacking in this case study.

Case study 2:

Kumar et al. (2015) present AMS analysis on the mafic dyke swarm that intrudes the Archean basement rocks in the Eastern Dharwar Craton. The dykes are exposed around the Cuddapah basin on its north, northwest and western flanks (Fig 5). The dyke swarm is of ~2082 Ma of age and forms a radiating dyke swarm converging towards a center beneath the Cuddapah basin (Kumar et al. 2015). The general trend of the dykes varies from N1340W to N280E depending on its position with respect to the Cuddapah basin. They reported that the individual dyke thickness varies between 30 m and 75 m along strike. They chose 11 sites both from Northern and Western part of the Cuddapah basin, where dykes were sampled (121 samples) for AMS analysis because of the constraints on the availability of in-situ outcrops. They considered AMS fabric in these dykes as primary as the sampled dykes were unmetamorphosed and petrography revealed that the opaque minerals were fairly fresh. The degree of anisotropy (P′) was low and varied between 1.019 and 1.128, in both the sectors which they considered as an indicator of primary magmatic fabric. The average bulk susceptibility was high ~ 3.06 X 10-2SI unit which indicates that most of the contribution comes from ferromagnetic minerals. AMS fabric data from most of the samples from the northern sector show "normal" AMS fabric with K_1 always is sub-vertical and K_3 being normal to the dyke wall (Fig 4c). This fabric was inferred to be the product of vertical magma flow. One sample from the northern sector showed "inverse" fabric where K_1 and K_2 are in the dyke plane and K_3 is perpendicular to it, but K_1 is close to horizontal and K_2 is vertical (Fig 4d).

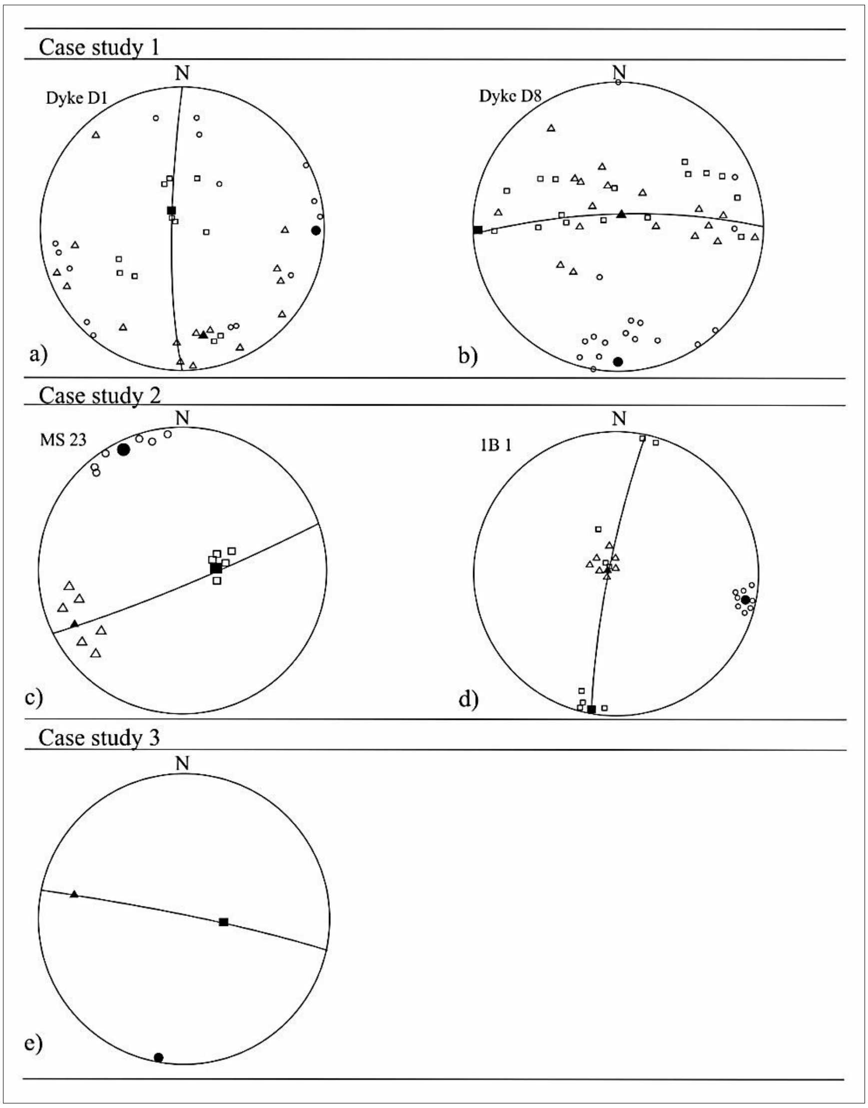

Fig 4. Equal area plots of principal susceptibility axes for the dykes. Mean susceptibility directions are represented by solid symbols. The great circle indicates average magnetic foliation.

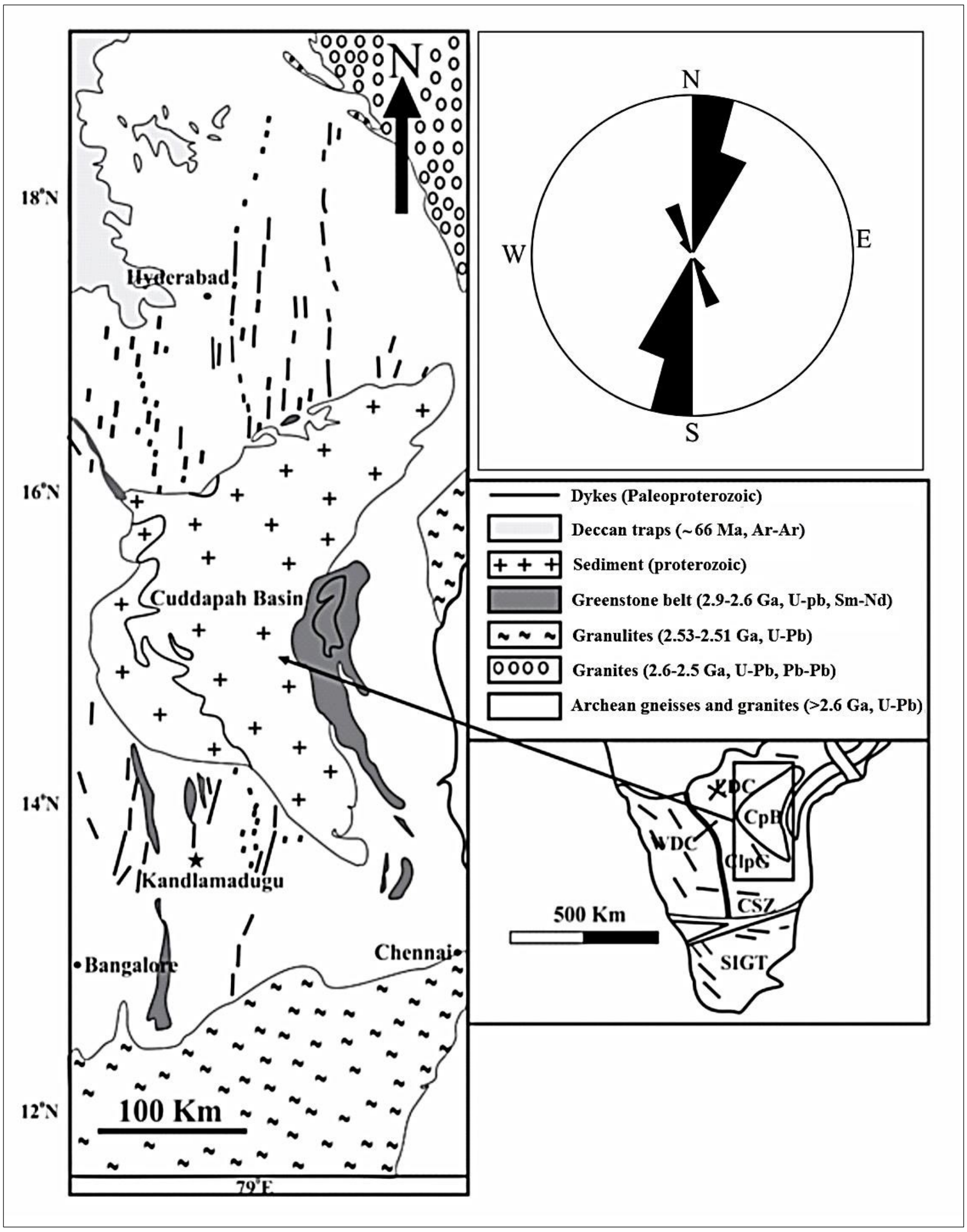

Fig 5. Simplified Geological map of Case study 2 area (modified after Kumar et al. (2015)) showing radiating dyke swarm around Cuddapah basin intruding into the Eastern DharwarCraton. Smaller map shows the position of the study area.Dyke trends are represented by the rose diagram in the inset.

This could be interpreted as being the product of lateral magma flow. An alternative interpretation is that this pattern is formed due to rolling effects on large grains (Cañón-Tapia 2004; Kumar et al. 2015). Another sample from the Northern sector show "abnormal" magnetic fabric (Kumar et al. 2015), where K_1 was sub-horizontal and perpendicular to the dyke wall and K_2 was sub-parallel and sub-vertical and K_3 was along the strike of the dyke. This type of magnetic fabric could form either due to the single domain effect (SD) (Stephenson 1994; Kumar et al. 2015) or due to the late growth of ferromagnetic minerals in a direction perpendicular to the dyke plane (Cañón-Tapia 2004; Kumar et al. 2015). The samples from the Western sector displayed "normal" fabric indicating vertical magma transport. Kumar et al. (2015) inferred that in general, the magma flow direction in the dykes was nearly vertical and upward. They also inferred the possibility of a proximal magma source (<500 km) (Ernst and Baragar 1992). Further, Kumar et al. (2015) concluded that the large aerial extent, radiating geometry and vertical magma flow of the dyke swarm indicate that the dyke emplacement occurred above a centrally located magma source. Finally, they preferred a thermal model (Haxby et al. 1976) to conclude the formation processes of Cudappah basin as a consequence of plume activity which leads to crustal thinning, subsidence and gravity faulting as a result of thermal relaxation.

5. AMS on dykes of South Indian Granulite Terrain (SIGT)

Case study 3:

Pratheesh et al. (2011) analyzed Cretaceous mafic dykes from the Moyar Shear Zone (MSZ) area, north Kerala with respect to their anisotropy in magnetic susceptibility. These dykes striking NE-SW, NW-SE, NNW-SSE and ENE-WSW (Fig 6) intrude the South Indian Granulite Terrain (SIGT) and are spread around MSZ. They are of olivine/quartz-normative tholeiitic composition and show a strong correlation with N-Type MORB (Pratheesh et al. 2011). This Cretaceous mafic magmatism is of great significance being a major constraint in understanding the evolution of Gondwanaland (Saha and Chakraborty 2003; Srivastava 2006). These dykes are 30cm to 5m wide with few dykes being wider than 10m. There are small dyke veins less than 30cm wide occurring in the major dykes. The contact of the dyke and the host rock is very sharp and do not really show any evidence of assimilation. For the wider dykes, margins are relatively fine-grained than the central part (Pratheesh et al. 2011). The bulk susceptibility of the dyke samples ranges from 0.08 X 10-2 SI to 10.6 X 10-2 SI. According to Pratheesh et al. (2011), the bulk susceptibility is mostly contributed from the ferromagnetic minerals (titanomagnetite and clinopyroxene). The dykes show “normal” magnetic fabrics nearly parallel to their trends, but the magnetic lineation (K_1) shows variation in its plunge (Pratheesh et al. 2011). They reported the average orientation of the magnetic foliation (K_1- K_2 plane) being WNW-ESE (Fig 4e). Whereas, the average orientation of the magnetic foliation for the mylonites from MSZ was found to be EW which is subparallel to the magnetic foliation of the dykes. Among the analyzed dykes, the one which is located at the center of the Maximum Concentration Cluster (MCC) of the dyke swarm shows vertical emplacement. In other locations, away from the MCC, shows inclined to horizontal (lateral) flow. The dominance of inclined flow in the dyke swarm is attributed to the fact that magma was possibly emplaced through the existing fracture system of the deformed metamorphic bedrock. The magnetic foliation and lineation trajectories in deformed metamorphic rocks and syenite pluton, influenced by the regional tectonic events, indicate a dextral sense of shear based on their similarities in orientation as that of the megascopic and microscopic structural fabrics. Pratheesh et al. (2011) described the magma flow into the post-tectonic dykes through a common conduit. They interpreted that the magma flow was vertical near the conduit and eventually became lateral/inclined away from it.

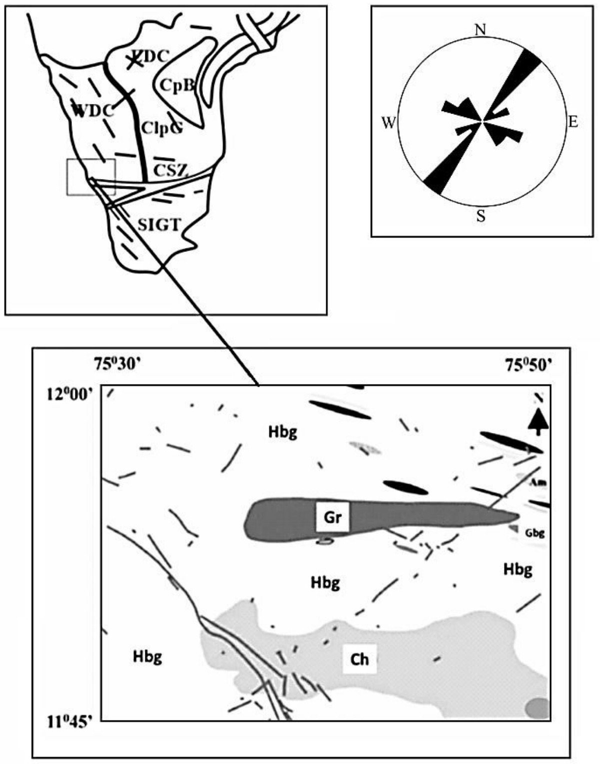

Fig 6. Simplified Geological map of Case study 3 area (modified after Pratheesh et al. (2011)) showing the disposition of dykes around Moyar Shear Zone puncturing the SIGT. Smaller map shows the position of the study area. Hbg-Hornblende biotite gneiss, Ch-Charnokite, Am-Amphibolite, Gbg-Garnetiferous Hornblende biotite gneiss.Dyke trends are represented by the rose diagram in the inset.

6. Discussion

The application of AMS on volcanic rocks dates back to 1960s. Khan (1962) first coined the possibility of a correlation between magnetic fabric and lava flow by coupling the concept of axial length and orientation of a single mineral grain with its principle susceptibility axes in such a way that the directional attributes of maximum and minimum susceptibility axes of a single elongated magnetic grain will correspond to the semi-major and semi-minor axes of the grain respectively. It is generally believed that Major 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). Khan (1962) set up a model on the basis of the implication of the movement of ellipsoidal particles submerged in the viscous fluid which depicts that the AMS of any rock is the result of the combined contribution of its constituent mineral phases. Khan’s theory suggested that in both lava flows and dykes, the intermediate susceptibility axes (K_2) would point along the flow direction. But Wing-Fatt and Stacey (1966) came up with a contradictory idea against Khan’s hypothetical model through their fact-finding studies that revealed the parallelism of maximum susceptibility axes (K_1) with the flow direction. Potter and Stephenson (1988) invoked the possibility of very small single domain (SD) magnetite crystals where "inverse fabric" (Major susceptibility axis K_1 being perpendicular to the magma flow direction) would be evident. According to them, for very small, single domain (SD) particles, the relationship between the susceptibility axes and the axial length of the grains might get reversed giving rise to the inverse fabric. The size threshold between Single Domain and Multi-Domain grains depends on geometry, chemical composition and state of stress (Butler and Banerjee 1975; Dunlop and Özdemir 2001; Cañón-Tapia 2004) which implies that there will always be some uncertainty regarding the effect of SD particles on the AMS of a rock. In spite of this fact, the SD effect gained huge attention in the interpretation of AMS results of dykes in absence of any other viable explanation. Initially, turbulent flow was marked as the responsible factor for the anomalous fabrics (Knight and Walker 1988). According to Park et al. (1988), the domain structure of the magnetic particles, that is responsible for the resulting AMS, gets subjected to the post-emplacement stresses which give rise to the anomalous fabric. Rochette et al. (1991) described an inverse fabric from Ophiolites in Oman and described them to be the result of hydrothermal alteration. It is clear from the above discussion that there could be more than one possibility which may cause anomalous fabric.

The contrasting mean susceptibility (Km) magnitude of different mineral species helps in the identification of governing phases that actually contribute to the measured AMS. It is important to understand the magnetic mineralogy of the samples to interpret AMS results properly. For example, it is important to establish that the AMS fabric is actually acting as a proxy to the shape fabric of the elongated grains. It is also important to understand if the result is affected by any SD (single domain) effect or any recrystallization that happened after magmatic emplacement (hydrothermal alteration, later tectonic deformation) or magnetic interaction effect (Stephenson 1994). The presence of anomalous fabric (any deviation from normal fabric) thus can be interpreted many ways viz. presence of single domain grain, hydrothermal alteration, later recrystallization of ferromagnetic minerals or simply lateral movement. The lateral movement could be attributed to flow from mantle plume or a flow away from the spreading center of the dykes. Even if the source is proximal and the flow is vertical at the spreading center, it can show inclined-lateral fabric away from it.

According to Hrouda (1991), very little proportion of ferromagnetic minerals (~1 vol%) can easily govern the magnetic attribute of a rock including its typical mean susceptibility. If the bulk susceptibility of the rock sample is more than 0.5 X 10^{-2}SI unit, (Cañón-Tapia 2004) it implies that the contribution to the bulk susceptibility is mostly from the ferromagnetic minerals (titanomagnetite), and the contribution from paramagnetic and diamagnetic minerals can be neglected. In such cases, the shape fabric of the ferromagnetic minerals could be represented by the AMS results which can be different from overall petro-fabric of the bulk rock. Similarly, if bulk susceptibility is <10^{-4}SI unit, the contribution of the ferromagnetic minerals can be neglected and the AMS fabric will be representative of the fabric shown by the paramagnetic minerals with some contributions from the diamagnetic minerals. It is, therefore, important to establish the relationship of the AMS fabric with the rock fabric before interpreting the AMS data as magma flow indicator.

The bulk susceptibilities of the dyke samples reported from all three case studies (Case study 1: 0.12 X 10-2 to 7 X 10-2, Case study 2: 3.06 X 10-2, Cas study 3: 0.08 X 10-2 SI to 10.6 X 10-2 SI) indicate that dominant contributors were ferromagnetic minerals like magnetite or titano-magnetite but contribution from the diamagnetic and paramagnetic minerals cannot be neglected for many samples. The possible range of mean susceptibility (Km) values for each case study is shown in figure 7 where Km values above the dotted line indicate a contribution from ferromagnetic particles. In all three case studies, no effort has been made to exclusively study the orientation of ferromagnetic grains. The degree of anisotropy in all three case studies is generally low with a few exceptions. The low degree of anisotropy indicates primary magnetic fabric resulting from magma flow rather than subsequent deformation. A few samples with a higher degree of anisotropy (in D1 and D8from case study 1; the sample of MSZ from case study 2) indicated the effect of deuteric alteration (Prasad et al. 1999) or destruction of magnetite grains or different composition of opaque minerals (Pratheesh et al. 2011).

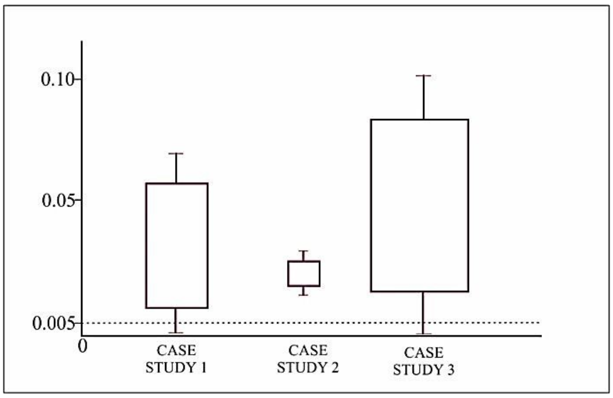

Fig 7. Mean susceptibility range for each case study represented by the box diagram. The data above the dotted line represent contribution from ferromagnetic minerals.

The presence of "inverse" magnetic fabric, as evident in all three case studies, is often inconclusive and can have more than one possible interpretations such as the presence of single domain grains, hydrothermal alteration, later recrystallization of ferromagnetic minerals or simply lateral movement. In the first case study done by Prasad et al. (1999), the inverse fabric evident from some sample with vertical K_3 axis and horizontal K_2 axis on the dyke plane and K_1 axis normal to the dyke plane was thought to be the result of rolling effect (Khan 1962). It can either indicate that the flow was inclined or lateral, or it can indicate the presence of very small magnetite/ titanomagnetite grains (SD effect) in the flow (Canon-tapia 2004) or it can be produced due to later hydrothermal alterations (Rochette et al. 1991). Although magnetic granulometry test operated on dykes with inverse fabric did not actually reassure the SD effect hypothesis. Besides the size limit for SD and MD grains are uncertain to some extent. According to Pratheesh et al. (2011), K_1 axis was vertical at the junction point of the dykes which gradually attained an inclined to sub-horizontal orientation away from this point indicating an emplacement from a common conduit through the deformed metamorphic rocks and fractures associated with shearing. Kumar et al. (2015) explained the inverse fabric as the result of SD effect or due to the late stage growth of ferromagnetic minerals perpendicular to the dyke plane of a vertical flow although it may be the result of lateral movement away from spreading center. But no clear evidence was produced to point out any clear interpretation. Besides, all the discussed case studies lack any proper evidence depicting the interrelationship between silicate fabric and magnetic fabrics. In general, the silicate fabric corresponds to flow dynamics which can coincide with the magnetic fabric indicating the distribution of anisotropy of magnetic minerals. According to Wiegand et al. (2017), the distribution and preferred orientation of silicate fabric can be recorded by studying 3 sections of an oriented sample: horizontal section, along strike vertical section and across strike vertical section (Fig 8). This type of microscopic analysis is recommended while interpreting the AMS results in all these three discussed case studies.

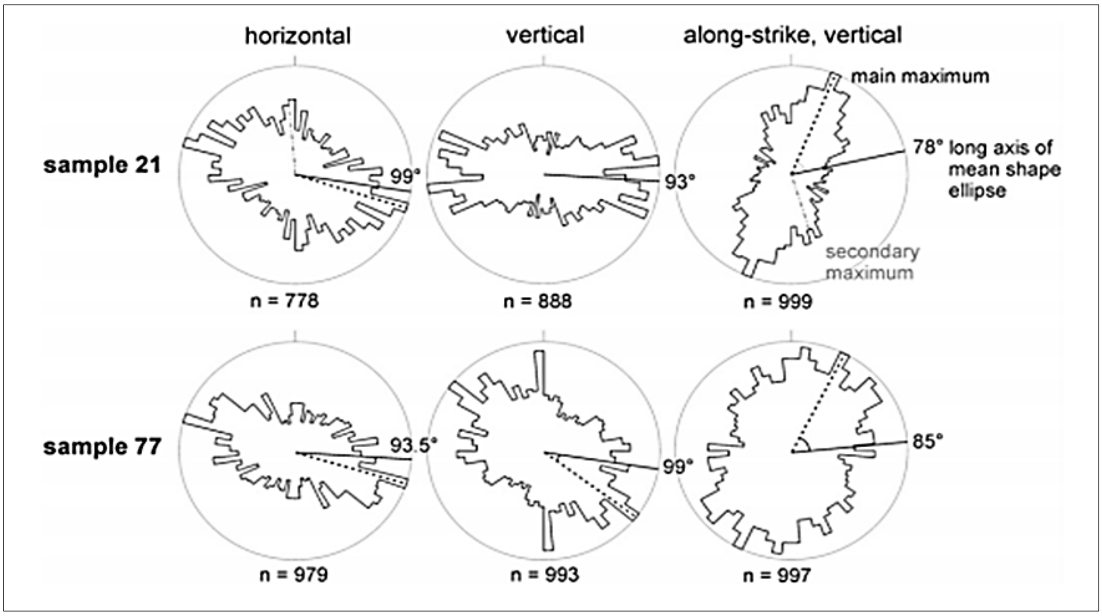

Fig 8. Orientation distribution of silicate fabric (plagioclase and pyroxene phenocrysts) in 2 samples from the dyke walls, obtained with the software program ImageJ (Rasband 2012). The long axes of silicate mean shape ellipse is shown by a black line and the AMS maxima is shown by the dotted line (modified after Wiegand et al. (2017))

All these works were done by following the deterministic approach for a large number of samples. The uncertainty of this easy perspective in building up a neat and clean interpretation for the exceptional results makes it a restrictive approach. Hence in all three case studies, the interpretation of inverse fabric is left inconclusive and further investigation to find out the actual case was not done. It is, therefore, recommended to interpret magnetic fabric for individual samples (more so for the samples showing "inverse" and "anomalous" fabric) in the light of its petro-fabric, magnetic mineralogy and geochemistry for extracting more information than that can possibly be extracted by simply analyzing and reporting bulk results by concentrating on sample to sample detailed analysis (Cañón-Tapia 2004).

6. Conclusions

- We review here three case studies from India where AMS technique was used to understand the mode of magma transport applicable for dyke swarm emplacement. Two of them are on Proterozoic dykes intruded into the Dharwar craton and the third one is on Cretaceous dyke swarm intruded into the SIGT.

- In all the case studies, the studied dykes are mafic in composition mostly consisting of plagioclase feldspar and clinopyroxene along with some other minerals including Fe-Ti oxides. Most of the bulk susceptibility (Km) values are plotted above the threshold value of 0.5 X 10-2 SI unit which according to Cañón-Tapia (2004) is considered from ferromagnetic mineral contribution (Fig 7).
- The major magnetic fabrics observed in all three case studies are dominantly "normal" with few exceptions of "inverse" and "anomalous" fabrics. Prasad et al. (1999) concluded the dominance of Multi-Domain (MD) magnetite in a large number of dyke samples from the AMS results with few exceptions (dyke D6) where Single Domain (SD)magnetic grains could be present. As the interpretation of the AMS result can be vastly different depending on whether MD or SD is dominant (Cañón-Tapia 2004), therefore, we recommend a thorough magnetic mineralogical analysis (example: Scanning electron microscopy and Temperature-dependent susceptibility test)before any AMS interpretation is done.
- Prasad et al. (1999) conclusively indicated the vertical mode of magma transport for three Proterozoic dykes that intruded the Dharwar craton in the Harohalli area out of eight analyzed. For the rest interpretation was not conclusive.
- Kumar et al. (2015) inferred that in general, the magma flow direction in the dykes that intruded the Archean basement rocks in the Eastern Dharwar Craton around Cuddapah basin was nearly vertical and upward. They also inferred the possibility of a proximal magma source (<500 km). Further, they concluded that the large aerial extent, radiating geometry and vertical magma flow of this dyke swarm indicate that the dyke emplacement occurred above a centrally located magma source.
- The Cretaceous dyke swarm intruding the SIGT near MSZ, show dominantly lateral magma transport away from the Maximum Concentration Cluster (MCC) of the dykes. Whereas, the dykes near the MCC show vertical magma transport. Pratheesh et al. (2011) concluded that the dominance of inclined/lateral flow in the dyke swarm is attributed to the fact that magma was possibly emplaced through the existing fracture system of the deformed metamorphic bedrock. They described the magma flow through a common conduit. They also interpreted that the magma flow was vertical near the conduit and eventually became lateral/inclined away from it.
- Hence, we recommend a detailed microscopic study to document the magnetic mineralogy and the preferred orientation of plagioclase feldspar laths to understand the controllable factors of distribution anisotropy of AMS fabric (Fig 8, Wiegand et al. 2017).

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