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Research Paper

AMS studies on a 450 km long 2216 Ma dyke from Dharwar craton, India: Implications to magma flow

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ABSTRACT

Anisotropy of magnetic susceptibility (AMS) studies were carried out on a precisely dated (2216.0 ± 0.9 Ma), 450 km long N–S striking dyke in the Dharwar Craton, to determine the magma flow direction along the dyke length. In order to use the imbrication of the magnetic foliation, forty eight samples were collected from 13 locations along the length of the dyke. Magnetogranulometry studies show that AMS fabric is dominated by medium grained interstitial Ti-poor multidomain magnetite. The corrected anisotropy degree (P_j) of the samples was found to be low to moderate, between 1.007 and 1.072, which indicates primary magnetic fabric. The magnetic ellipsoid is either triaxial, prolate or oblate and clearly defines normal, intermediate and inverse magnetic fabrics related to magma flow during the dyke emplacement. The maximum susceptibility axes (K_{max}) of the AMS tensor of the dyke is predominantly inclined at low angles (<30°), with no systematic variation in depth along the N–S profile, indicating sub-horizontal flow even at mid crustal levels which could probably be governed by location of the focal region of the magma source (mantle plume?), flow dynamics together with the compressive stresses exerted by the overlying crust.

1. Introduction

The mafic dyke swarms are expressions of deeply eroded Large Igneous Provinces (LIPs) and are therefore the main channels for magma transport from deep mantle sources. The pattern of magma propagation through fissures in the crust has been a topic of considerable interest. These studies have been often based on anisotropy of magnetic susceptibility (AMS) data, as it is an excellent proxy for inferring the petrofabric (preferred alignment of minerals) in rocks. AMS is controlled by the orientation of magnetic minerals during the emplacement of rocks, and especially in dykes mineral orientation is significantly influenced by the flow direction (Ellwood, 1982; Knight and Walker, 1988; Rochette et al., 1992; Tarling and Hrouda, 1993; Tauxe et al., 1998; Callot and Guichet, 2003; Canon-Tapia and Herrero-Bervera, 2009).

Dharwar craton of south India exposes a tilted Archaean crustal cross section of about 2°, exposing rocks of increasing metamorphic grade in greenschist, amphibolite to granulite facies from northern to southern region. Recently, the occurrence of a 450 km long N–S striking Paleoproterozoic dyke (2216.0 ± 0.9 Ma) was reported in this region straddling across the different isograds (Kumar et al., 2012b; Nagaraju et al., 2018a). This dyke is named as Andhra Karnataka Long Dyke (AKLD) as its existence occurs in Andhrapradesh and Karnataka states (Kumar et al., 2012b). The two Pb-Pb TE-TIMS baddeleyite ages (2215.9 ± 0.3 Ma, Kumar et al., 2014 and 2216.6 ± 0.7 Ma, Nagaraju et al., 2018a) and the U-Pb ID-TIMS baddeleyite age (2215.2 ± 2 Ma; Srivastava et al., 2011) on this dyke are identical within errors suggested its emplacement along its entire strike length to be within a geologically short time span of less than ∼1 Ma. This dyke is extending vertically down and exposed at different depth levels, therefore, offers a unique opportunity to study the pattern of magma flow at different crustal depths.

This paper mainly focuses on AMS studies of the AKLD along its entire strike length, to understand the magma flow pattern and suggest the possible location of the magma source for the emplacement of the dyke.

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2. Regional geology and sampling

Dharwar craton of southern India is the largest and one of the most extensively studied Archaean cratons of the Indian Peninsular shield. It consists of the southern granulite, Eastern Ghats granulite terrains and the low-grade northern block, which is further classified into two parts viz. Western Dharwar Craton (WDC) and Eastern Dharwar Craton (EDC) on the basis of divergent geological and tectonic characteristics (Swami Nath and Ramakrishnan, 1981; Naqvi and Rogers, 1987; Chardon et al., 2008). An accurate N–S trending shear zone that forms the eastern boundary of the Chitradurga greenstone belt is considered to separate western and eastern parts of the Dharwar craton which have distinct characteristics (Chadwick et al., 1992, 2000). Amalgamation of the western and eastern Dharwar cratonic blocks is interpreted to have taken place at ∼2.5 Ga (Chadwick et al., 1997).

Based on the progression in metamorphic grade from granulite-facies in the south to greenschist-facies in the northern part, it has been shown that the Dharwar craton exposes a natural crustal cross section of Neoarchean crust (e.g. Rollinson et al., 1981; Harris and Jayaram, 1982; Moyen et al., 2003). *P-T* estimates on the Peninsular Gneisses (Janardhan et al., 1982; Hansen et al., 1984; Gopalakrishna et al., 1986; Stähle et al., 1987; Sen and Bhattacharya, 1990), metapelites (Srinivasan and Tareen, 1972; Rollinson et al., 1981; Harris and Jayaram, 1982) and/or mafic rocks (Raase et al., 1986) of the greenstone belts, show *P-T* conditions vary from nearly 8 kbar and 800 °C (granulite facies) at 12°N, to 3.5 kbar and 500 °C (greenschist facies) at 15°N (Fig. 1). The present horizontal distance between the deepest and shallowest levels of the crust is about 450 km. The dip of the present erosion surface relative to the Neoarchean paleo-depth is about 2° (equivalent to a vertical distance of 10–13 km).

As in many Archaean blocks, dyke swarms are widespread in the Dharwar craton and have been described in detail earlier (e.g. Halls, 1982; Murthy et al., 1987; Halls et al., 2007, French and Heaman, 2010). These dykes range in age from Paleoproterozoic (French and Heaman, 2010; Demirer, 2012; Kumar et al., 2012a, b; Kumar et al., 2014, 2015; Nagaraju et al., 2018a, b) to Late Cretaceous (Kumar et al., 2001). Of these, the most dominant is the E–W to ENE–WSW trending giant radiating dyke swarm emplaced at

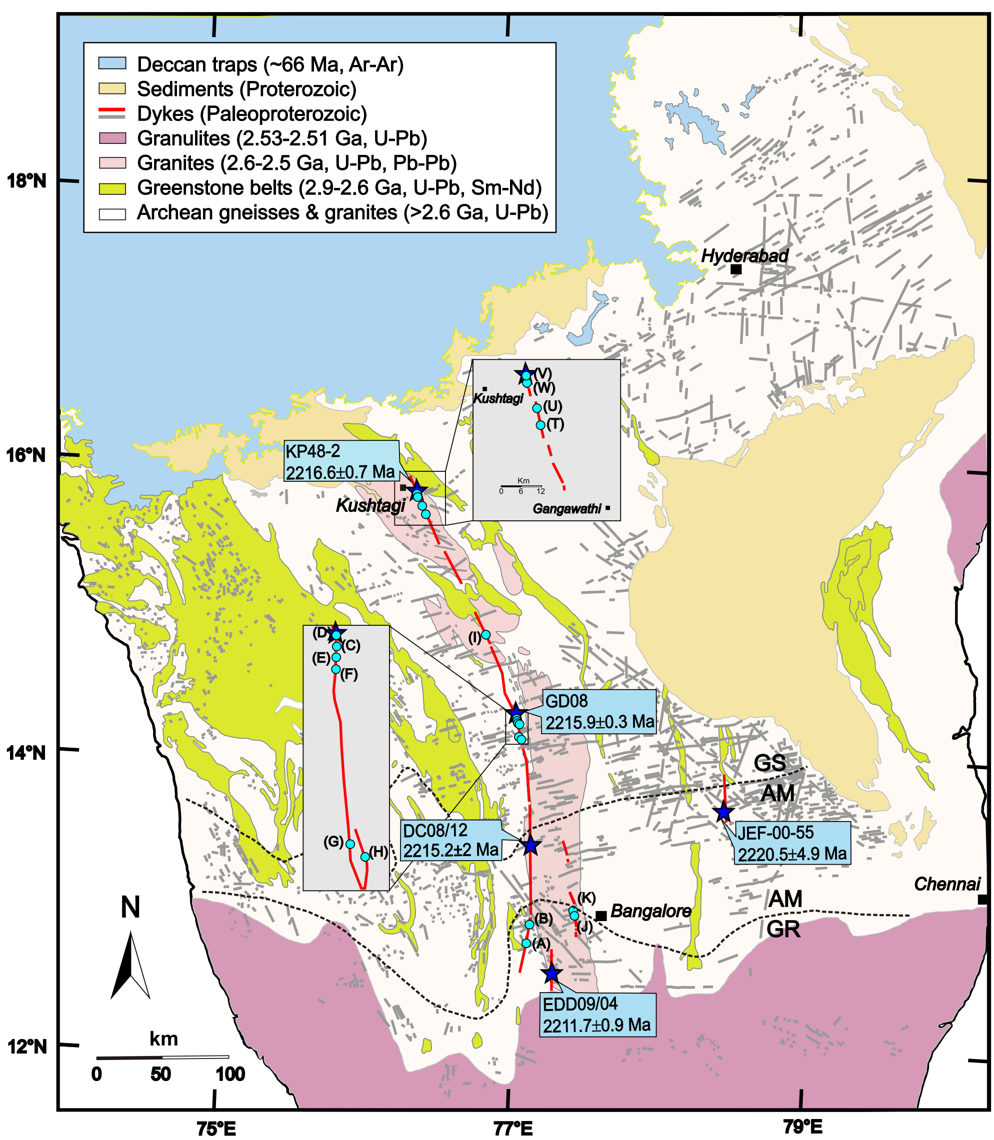

Figure 1. Simplified Geological map of Dharwar craton showing the distribution of mafic dykes (grey and red color lines). Cyan blue solid filled circles display the locations of sampling sites for present study. Blue filled stars represent reported precise U-Pb/Pb-Pb ages. GR: Granulite facies, AM: Amphibolite facies, GS: Green schist facies. Black dashed line demarcates the boundary of different metamorphic zones (taken from Nagaraju et al., 2018).

~2367 Ma with an aerial extent of nearly the entire eastern Dharwar craton (Halls et al., 2007; French and Heaman, 2010; Demirer, 2012; Kumar et al., 2012a; Babu et al., 2018). Other dyke swarms include a N–S oriented swarm at 2220.5 ± 4.9 Ma (this could be part of the AKLD swarm), a NW–SE to E–W striking swarm at ~2207 Ma (Nagaraju et al., 2018b), a radial WNW–ESE to NW–SE swarm at 2180.8 ± 0.9 Ma to 2176.5 ± 3.7 Ma (French and Heaman, 2010) and a radiating dyke swarm at 2081.8 ± 1.1 Ma (Kumar et al., 2015).

The AKLD sampled in this study is one of the largest single dykes in the Dharwar craton reported so far, it runs nearly parallel to the eastern margin of the Chitradurga schist belt to its east, along the western edge of the eastern Dharwar craton. It can be followed well for over 450 km in N–S orientation. In its southern most part, east of the Kunigal schist belt, the dyke intrudes mid-Archaean amphibolite grade gneisses, while along its middle and northern exposure, it cuts late-Archaean K-rich granites, low-grade gneisses and schists such as the Sandur schist belt (Fig. 1). The strike of the dyke is generally NNE in the southern and N–S in the middle parts, but swings ~25° NNW in its northern half, thus broadly following the regional structural grain. The thickness of the dyke varies between 40 m and 130 m and preserves a vertical dip along the entire strike length sampled. The dyke is medium to coarse grained and has sharp contacts with the country rock.

For AMS studies a total of 48 block samples were collected at 13 sites (between 5 and 9 oriented block samples from each site) along the strike of the AKLD. Samples were precisely oriented using Brunton magnetic compass. Sampling locations are given in Fig. 1. Sampling could not be done evenly all along the dyke length due to the paucity of in-situ outcrops. The contact between dyke margins and country rocks is poorly constrained at most of the sampling locations. In order to obtain imbrication of magnetic foliation, we sampled the dyke margins more intensively as against the dyke centres. Though our sampling was confined mostly to fresh outcrops at road cuts and in quarries, sampling across the width of the dyke from chilled margin to chilled margin was not possible in all sites due to the paucity of continuous in-situ out crops. Sampling from both the dyke margins was possible only at two sites (F and Q). Samples are medium to coarse grained towards the centre of the dyke and relatively finer towards the margin.

Sites A and B are located on the southern most exposure and are in the granulite facies country rocks, sites C, D, E, F, G, H and I, N, O, P, Q are located in the central and northern most regions of the dyke exposure respectively, but are all in the green schist facies rocks. Petrographic description and geochemical characterization of the AKLD was reported earlier by Kumar et al. (2012b) and Srivastava et al. (2014). The major mineral constituents of this dyke include plagioclase, augite and occasionally hypersthene, with minor amounts of magnetic minerals (modal abundance 4%–5%). Most samples exhibit poikilitic texture, though in a few sections porphyritic texture was also observed. Though the degree of metamorphism in the country rock increases from north to south, the extent of alteration or clouding in feldspar does not vary along strike. This dyke is basaltic tholeiite in composition with minor variation along strike (Kumar et al., 2012b).

3. Experimental procedures and AMS method

A total number of 190 oriented specimens representing 48 samples (of standard size 2.54 cm in diameter and 2.20 cm in length) were subjected to AMS measurements. Preliminary anisotropy of low-field magnetic susceptibility measurements were performed using a Kappabridge KLY-4 magnetic anisotropy susceptometer (AGICO Co. Ltd., Czech Republic) in a magnetic field of 200 A/m and a frequency of 976 Hz at Indian Institute of Geomagnetism (IIG), Allahabad and later all other measurements were done at National Geophysical Research Institute (NGRI), Hyderabad (India). Analysis of the data was done using Anisoft 4.2 software (Chadima and Jelinek, 2009). The mean normalized tensors were calculated following the statistical procedures of Jelinek (1978). The statistical precisions were calculated with bimodal statistics (Bingham, 1964). Sample susceptibility variations with temperatures (thermomagnetic analysis) were measured on Bartington Instrument model MS-2.

The anisotropy of magnetic susceptibility (AMS) of a rock sample is a second rank tensor (K) and can be represented by an ellipsoid of magnetic susceptibility (Tarling and Hrouda, 1993; Dunlop and Ozdemir, 1997). K is defined by three different eigenvectors, along three orthogonal axes of the ellipsoid and are designated as maximum, intermediate, and minimum susceptibilities, K_{max}, K_{int}, and K_{min} respectively. The shape of the AMS ellipsoid can be strongly flattened (oblate shape) to strongly elongated (prolate shape) or intermediate between them (triaxial shape) (Tarling and Hrouda, 1993). These principal susceptibilities K_{max}, K_{int}, K_{min} were also used to determine alternative combinations of magnitude parameters, such as the bulk susceptibility $K_m = (K_{max} + K_{int} + K_{min})/3$, the degree of magnetic lineation $L = (K_{max} - K_{int})/K_m$ (Khan, 1962), the degree of magnetic foliation $F = (K_{int} - K_{min})/K_m$ (Khan, 1962). The total anisotropy parameter ($H = L + F$) is a measure of the strength of the magnetic fabric (Owens, 1974). The shape anisotropy parameter 'T' is defined as $T = \frac{(2\eta_1-\eta_2-\eta_3)}{(\eta_1-\eta_3)}$ where $\eta_1 = \ln(K_{max})$, $\eta_2 = \ln(K_{int})$ and $\eta_3 = \ln(K_{min})$. This parameter ranges from a planar fabric ($0 < T < 1$; corresponds to oblate) to linear fabric ($-1 < T < 0$; corresponds to prolate). The corrected degree of anisotropy $P_j = \exp\left\{\sqrt{2[(\eta_1-\eta_m)^2+(\eta_2-\eta_m)^2+(\eta_3-\eta_m)^2]}\right\}$ with $\eta_m = \sqrt[3]{\eta_1\eta_2\eta_3}$ (Jelinek, 1981) is used to offer the strain information of the rocks. P_j is used to describe the amount of magnetic anisotropy. The additional parameter μ [$\tan\mu = (K_{max} - K_{int})/(K_{int} - K_{min})$] is the angle of the line from the horizontal (F-axis), ranging from 0° for purely oblate to 90° for purely prolate.

4. Results

4.1. Petrography and thermomagnetic analysis

Petrographic studies have been carried out on at least one sample from one site. Representative photomicrographs are given in Fig. 2. Plagioclase and augite are major mineral constituents with minor amounts of opaque minerals. Medium grained multi-domain (~50 μm) Ti-poor magnetite occurs more ubiquitously (4%–5%) as interstitial grains in these samples. All the samples show poikilitic texture with minor alteration.

Magnetic mineralogy as determined from thermomagnetic curves of low field susceptibility displaying a Curie temperature close to 580 °C indicates that the dominant magnetic carrier is Ti-poor magnetite (Fig. 3). During heating, all the thermomagnetic curves show a sharp drop at ~580 °C and occurring of the Hopkinson Peak before unblocking suggests SD (Single Domain) magnetite converting to super-paramagnetic state. The absence of decay in thermomagnetic curves between room temperature and ~300 °C show that paramagnetic susceptibility is negligible.

4.2. Anisotropy of magnetic susceptibility

In this study, we define a normal magnetic fabric when shape anisotropy with the geometric long axis is parallel to the easy axis

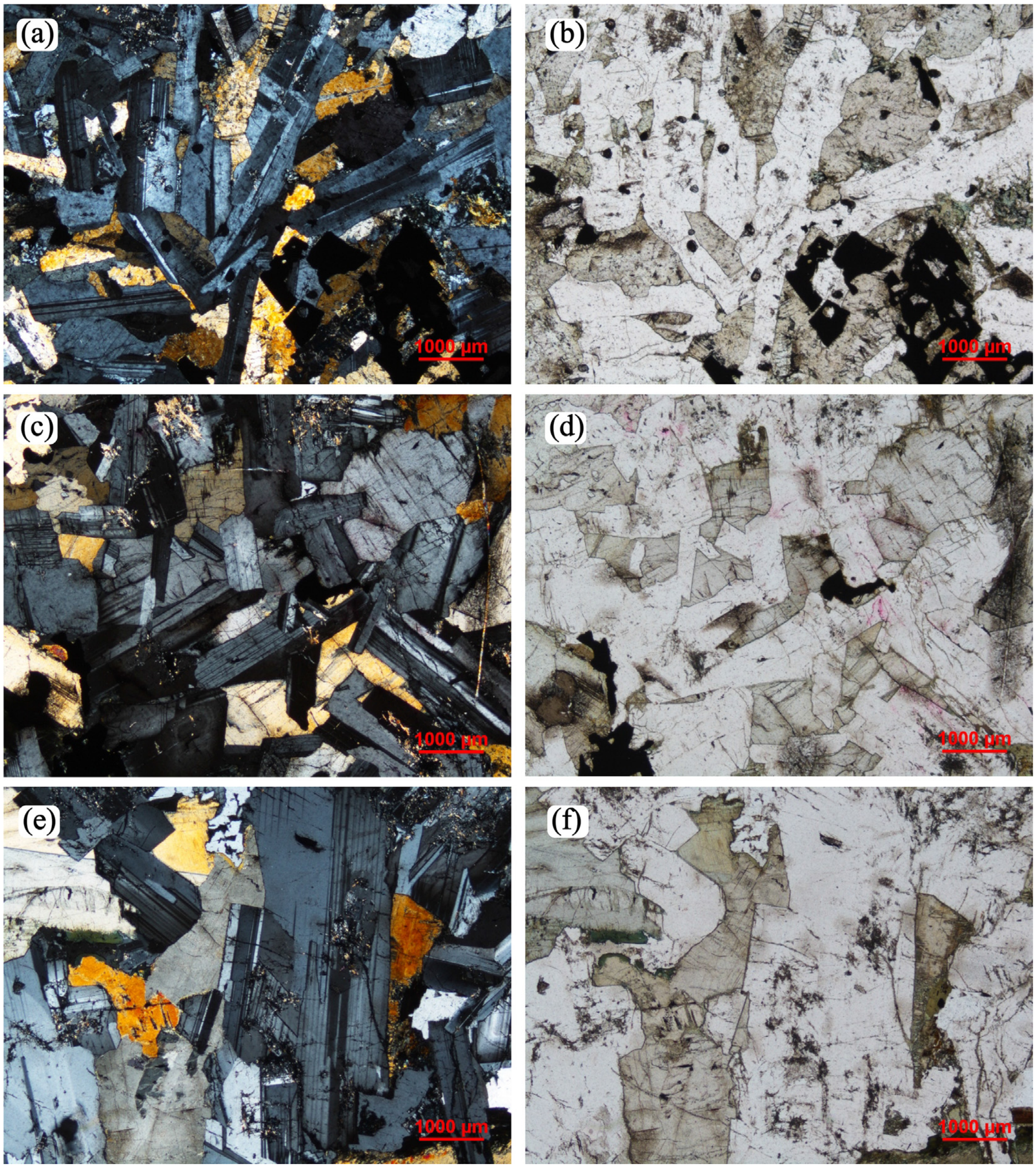

Figure 2. Representative photo micrographs of AKLD samples from north to southern region (a) and (b) are from the site V (c) and (d) are from site C, (e) and (f) are from site A.

of magnetization (K_{max}), magnetic foliation is close to dyke plane, at an angle lower than $\sim 40^{\circ}$ and K_{min} is perpendicular to the magnetic foliation. Conversely, the inverse magnetic fabric is characterised by geometric short axis is parallel to the easy axis of magnetization (K_{max}), K_{max} axes is perpendicular to the dyke margin and K_{min} is sub-vertical in the dyke plane. In the same way, an intermediate magnetic fabric is defined by the occurrence of K_{int} axes perpendicular to the dyke plane.

Magnetic fabric data is summarised in Table 1 and illustrated in Fig. 4. The mean magnetic susceptibility values of all the investigated samples are generally high but similar within an order of magnitude ranging from 2×10^{-2} to 5.6×10^{-2} SI units (Table 1). However, two samples (KP 47 and KP 48) from site O display lower magnetic susceptibilities. The high magnitude of mean susceptibility values larger than 10^{-3} SI units suggests that ferrimagnetic grains are the principal magnetic carriers. Therefore, the contribution of diamagnetic (feldspar) and paramagnetic grains (pyroxene) to the total anisotropy is negligible. In this dyke, the corrected anisotropy degree (P_j) of these samples were found to be fairly uniform and low to moderate between 1.01 and 1.09 with an average of 1.018, whilst most of them are lower than 1.05 (Fig. 5). The P_j values less than 1.05 indicating relatively weak anisotropic magnetic fabrics, typical of magmatic rocks (Tarling and Hrouda, 1993; Raposo and Ernesto, 1995). The ratio of oblate to prolate is 77/58 indicating that oblate grains predominate.

Meaningful statistical results were recovered from 12 sites, including six sites with normal magnetic fabric, four sites with inverse magnetic fabric and two sites with intermediate magnetic fabrics. In the case of site E, magnetic fabric is scattered. Sites (F, G, H, I, N and P) showing normal magnetic fabric displays the foliations defined by K_{max} and K_{int} axes, which are mostly parallel or sub-parallel to the dyke walls. In the sites with intermediate type of magnetic fabric (A and D), the foliation is sub-horizontal and K_{min} axes are clustered vertically. Whereas, in sites (B, C, O and Q) with inverse magnetic fabric shows the K_{min} axes being parallel or sub-parallel and magnetic foliation is perpendicular to the dyke walls.

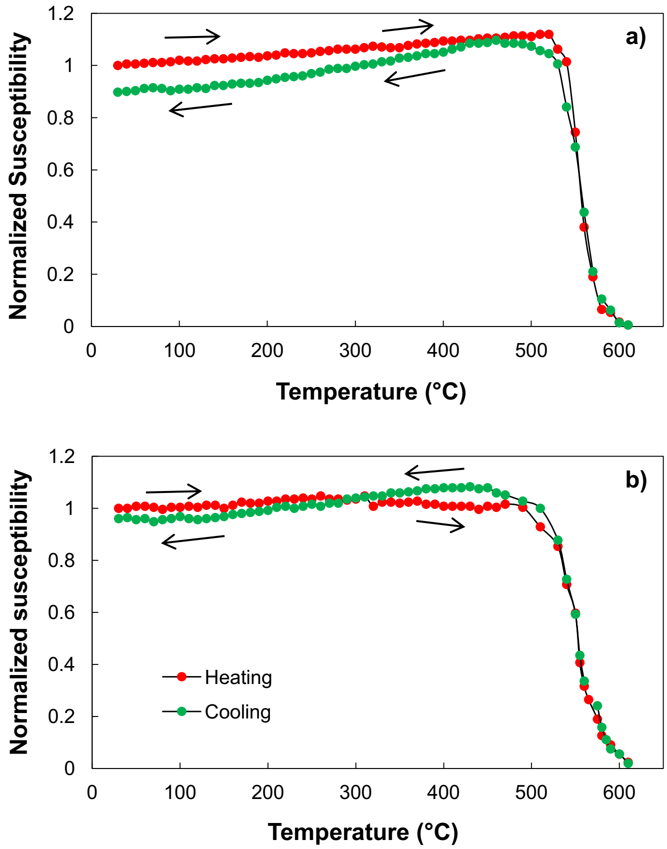

Figure 3. Typical examples of magnetic susceptibility vs. temperature dependencies (taken from Nagaraju et al., 2018a).

Remarkably, the inclinations of K_{max} axes in all sites representing normal, intermediate and inverse fabric are horizontal to sub-horizontal. Interestingly, the samples from the margins (within the chilled zone) preserved normal fabric except at site Q and the remaining samples which are collected away from the margins displayed intermediate and inverse fabric. The magnetic foliations are imbricated with respect to the dyke walls from both the eastern as well as the western margin of the dyke from site F. Though a similar imbrication pattern is observed in site Q, the magnetic foliations from eastern and western margins are perpendicular to the dyke wall. The shape parameter of the AMS ellipsoid ($\mu = 0°$ to 25° for oblate, 25° to 65° for triaxial and 65° to 90° for prolate, described in the preceding section) indicating that these are of triaxial shape with principal susceptibilities $K_{max} > K_{int} > K_{min}$. The dominance of triaxial shaped magnetic ellipsoid is consistent with the petrographic and rock magnetic evidence that the magnetic carrier in this dyke is predominantly the interstitially formed Ti-poor magnetite grains.

The maximum axis (K_{max}) of the AMS ellipsoid for the normal fabric samples are invariably along the dyke plane (N—S), dipping at relatively low angles (~25°) regardless of their site location on the dyke, either in the centrally located (F, G and H) or in the northern most sites (N and P). We found none of the normal fabric samples from the south, this is probably due to lack of samples from the chilled zone. However, since $K_{max} \approx K_{int}$ in the case of oblate shaped ellipsoids, inverse fabric samples with their K_{int} susceptibility axis parallel to the dyke plane are also assumed to represent flow alignment. As shown in Fig. 6, these eigenvectors have an identical orientation as that of the maximum axis of normal fabric samples, that is a shallow inclination and near N—S declination.

5. Discussion

The three types of AMS ellipsoids exhibit a relatively weak degree of anisotropic magnetic fabrics for all the sites, indicating insignificant tectonic effects on the primary flow related fabrics. Without exception, samples from all the sites are dominated by Ti-poor magnetite. The observed variation in AMS fabrics could reflect the arrangement of the ferromagnetic grains in the samples. Magma flow direction into the fractures during the emplacement of dyke controls the orientation of the magnetic mineral grains between the two walls. For ferromagnetic minerals like magnetite, the origin of the AMS is mainly due to shape-preferred-orientation-controlled (SPO) i.e. multi-domain (MD) grains predominate the formation of normal magnetic fabrics, while single-domain (SD) grains are responsible for inverse fabric and the coexistence of MD and SD magnetic grains correspond to intermediate magnetic fabrics (Stephenson et al., 1986; Rochette, 1988; Borradaile and Puumala, 1989; Jackson, 1991; Rochette et al., 1992, 1999; Ferré, 2002).

Knight and Walker (1988) demonstrated that the absolute magma flow direction in dykes using the elongated magnetic grains (K_{max} axes) imbricated against the chilled margins. A similar

Table 1
AMS directions of the Paleoproterozoic 2216 Ma N—S long dyke.

Site Name	Site Lat. (°N)	Site Long. (°E)	Strike	K_m	F	L	P_j	T	K_{max}		K_{int}		K_{min}	
									D (°)	I (°)	D (°)	I (°)	D (°)	I (°)
A	12.767	77.056	N14E	28,667	1.023	1.004	1.029	0.677	179	13	298	64	83	22
B	12.851	77.069	N357E	19,321	1.019	1.019	1.038	−0.003	187	6	278	4	38	83
C	14.216	76.977	N1E	23,154	1.041	1.009	1.054	0.621	127	8	219	12	6	76
D	14.218	76.977	N359E	31,062	1.018	1.022	1.040	−0.104	259	5	168	20	3	69
E	14.209	76.977	N357E	39,329	1.030	1.015	1.047	0.330	186	3	276	2	40	86
F West	14.204	76.977	N358E	24,556	1.010	1.005	1.015	0.327	111	12	202	6	321	77
F East	14.204	76.977	N358E	23,786	1.029	1.012	1.043	0.411	175	15	323	73	83	9
G	14.117	76.985	N350E	20,377	1.027	1.024	1.052	0.074	351	5	92	67	259	22
H	14.112	76.993	N343E	34,186	1.031	1.006	1.040	0.667	65	24	162	16	284	60
I	14.778	76.786	N335E	23,868	1.013	1.020	1.033	−0.231	341	24	198	61	78	16
N	15.662	76.342	N350E	25,684	1.015	1.004	1.020	0.551	345	25	243	24	115	54
O	15.705	76.331	N338E	23,068	1.011	1.021	1.033	−0.321	72	29	173	18	290	55
P	15.777	76.301	N358E	30,566	1.013	1.016	1.029	−0.090	100	7	5	33	201	57
Q West	15.773	76.301	N350E	19,476	1.007	1.005	1.013	0.130	56	36	167	26	283	43
Q East	15.773	76.301	N350E	30,631	1.018	1.018	1.037	−0.002	104	2	14	10	203	80

K_{max}, K_{int} and K_{min} are the maximum, intermediate and minimum susceptibility intensities, respectively; K_m: Bulk Susceptibility (×10^{-6} SI units); F: Magnetic foliation; L: Magnetic lineation; P_j: Corrected anisotropy degree; T: Jelink's shape parameter; D: Declination; I: Inclination in degrees.

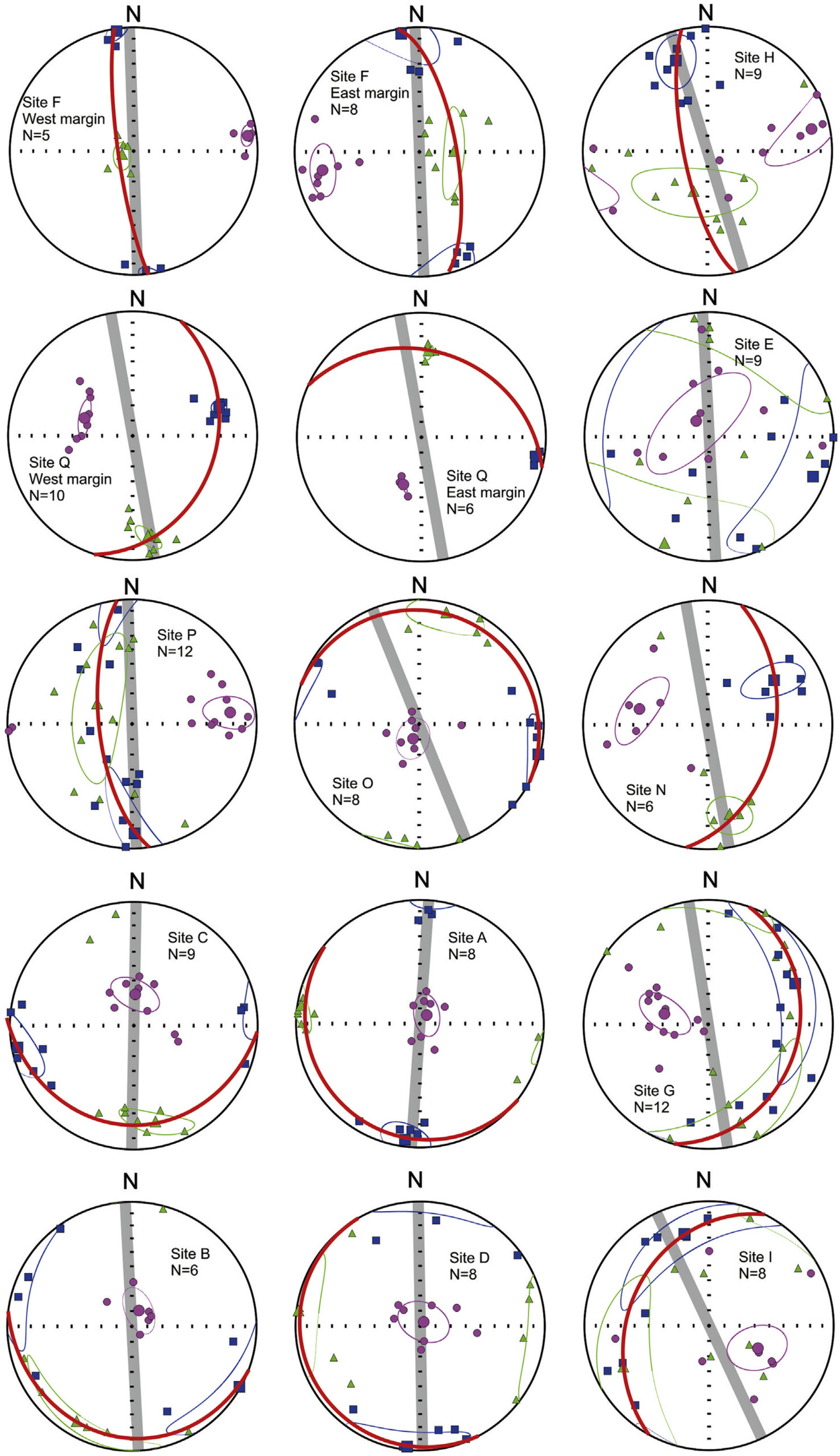

Figure 4. Lower hemisphere projection of eigenvectors K_{max} (blue square), K_{int} (green triangle) and K_{min} (purple circle) from representative sites of AKLD. Dyke trends are shown as grey lines. Red line indicates foliation trend.

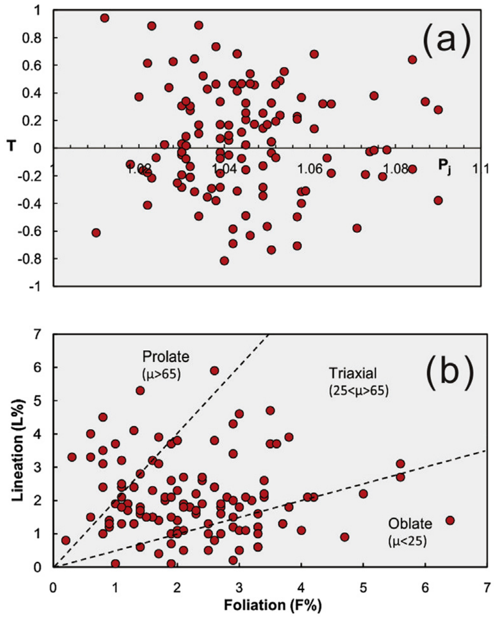

Figure 5. (a) Degree of magnetic anisotropy (P_j) versus shape anisotropy parameter (T) for AKLD sites and (b) Plot of magnetic lineation (L%) vs. magnetic foliation (F%) for specimens from all sites with a graphical representation of magnetic susceptibility ellipsoid shape (μ).

approach was applied to infer the flow directions in lavas (Cañón-Tapia, 2004). Similarly, the mirrored imbrication of the magnetic foliations along with well-defined magnetic lineations was noticed from site F and Q suggests a significant degree of lateral magma flow in this dyke. The origin of inverse magnetic fabric is likely that the strong magnetization in those samples leads to the interchange of AMS axes. From this study, it is evident that the inverse K_{max} axes are in symmetry with normal K_{min} axes. Although opposed imbrications was not possible in all sites, only a preferred azimuth of flow is obtained from AMS measurements.

Eigen vectors of the AMS tensor obtained from all the sites either normal or inverse fabric, from south to north, that is from the deepest (amphibolite facies) to the shallowest (upper greenschist facies) crustal levels from sites A through Q suggests a pattern that align generally along the dyke plane (nearly N–S) and dipping at less than 25°. While the declination could suggest the direction of magma flow, the consistently shallow inclination all along the dyke can be argued as due to flattening of the magnetic fabric perpendicular to the plane of the dyke, caused due to the fairly high pressure exerted on the magma at deep mid crustal depths (present exposure level) of not less than 15 km in the northern part and even deeper in the southern region as indicated by the *P-T* estimates (discussed in the preceding section). This inference is supported by an even distribution of samples along the dyke presenting inverse and intermediate fabric, wherein the minimum axis of the AMS tensor (K_{min}) is vertical. However, this deduction is not supported by the presence of normal fabric (intermediate axis is vertical) samples in the central and northern parts of the dyke. Also the consistent characteristic remanent magnetic directions (with moderately high grand mean inclination of −62°; Kumar et al., 2012a, b; Nagaraju et al., 2018a) presented by all the sites along the profile despite the large difference in depths of about 10 km from the southern (∼25 km deep) to the northern sites (∼15 km deep) do not indicate any such effects. Moreover, horizontal flow is known to occur in several other large dyke swarms, the best example being the Mackenzie swarm, where the magma flow occurs laterally for a long distance of 300–1000 km, radiating from a common source (Ernst and Baragar, 1992). Our AMS data with consistent horizontal flow (Schematic model, Fig. 7) pattern, therefore, suggests that all the sampled sites on the AKLD could have been several hundred kilometres away from the focal area of the magma source (mantle plume?) perhaps not within the present day Dharwar craton, but in a neighbouring continent (probably Superior or Slave; Kumar et al., 2012b) in a Paleoproterozoic protocontinent existing during that time. Alternately, the large distances of horizontal magma propagation, like that observed here, could be due to the large compressive stress exerted by the thick (>15 km) overlying upper crust inhibiting vertical propagation and eruption (Pinel and Jaupart, 2004).

6. Conclusion

AMS results from all 13 sites along the length of AKLD indicate a low degree of anisotropy and their ellipsoid of magnetic susceptibility is triaxial. Magnetogranulometry studies infers multi domain (MD)/single domain (SD) magnetite or titanomagnetite governs the AMS. AMS data along the AKLD, though not conclusive, indicate sub-horizontal flow even at deep mid crustal levels which could probably be governed by the location of the focal region of the

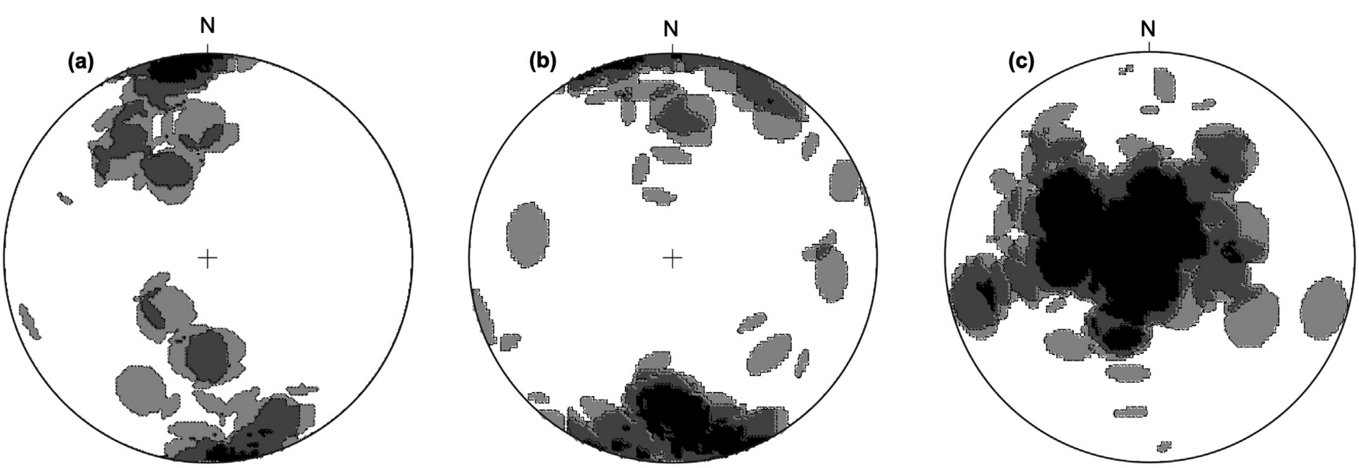

Figure 6. AMS data contoured in equal area projections from (a) K_{max} directions of 'normal' magnetic fabric, (b) K_{int} directions of 'inverse' magnetic fabric showing direction of magma flow and (c) K_{min} directions from 'intermediate' and 'inverse' magnetic fabric observed sites on AKLD dyke.

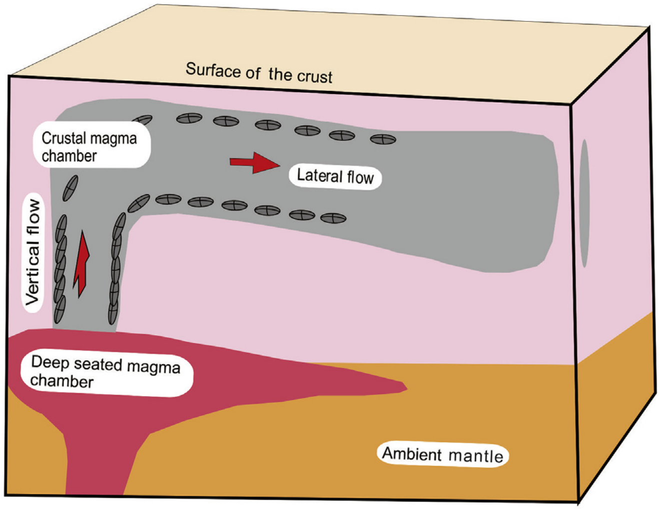

Figure 7. Cartoon represents impact of mantle plume head beneath the crust; proposed lateral flow (arrows) of a dyke within the crust along the level of neutral magma buoyancy (not to scale); and doming of the Earth's surface caused by plume-related thermo-mechanical uplift (modified after Fialko and Rubin (1999) and Hastie et al. (2014)).

magma source (mantle plume?), flow dynamics together with the compressive stresses exerted by the overlying crust.

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