Borehole magnetic fabric anomalies in KBH 07 Deccan basalt core from Deep Continental Drilling, western Maharashtra, India

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The anisotropy of magnetic susceptibility (AMS) record generated from 112 levels in 1248 m long KBH 07 borehole up to the basement in Deccan Volcanic Province of Koyna region depicts episodic variation in the magnetic fabrics. Anomalies in the AMS parameters: volume susceptibility (K), degree of anisotropy (Pj), shape factor (T), degree of lineation/foliation (L/F), inclinations of principle susceptibility axes (K_{max} and K_{min}) are inferred along with previously published rock magnetic data for the KBH 07. A major change observed at ~ 600 m level based on magnetic mineralogy and fabrics, density and lava thickness pattern is attributed to shift in magmatic compositional trends in agreement with the high-Mg to low-Mg magma reported previously in the same core (Banerjee and Mondal 2021). Further, the higher-order anomalies depict smaller episodes influencing the fabrics possibly due to differential dynamic viscosities governed by composition in addition to cooling trends. Whereas the major trends can be assigned to compositionally controlled viscosities and hence can be correlated to larger stratigraphic intervals based on the AMS studies.

Keywords. Deccan basalt; anisotropy of magnetic susceptibility; Koyna deep borehole; India.

1. Introduction

Anisotropy of magnetic susceptibility (AMS) is routinely practiced to estimate the strain-related fabrics in most of the weakly to strongly deformed rocks (Pares 2015). It can efficiently record the flow-related fabrics in undeformed lava flows and sediments (Callot *et al.* 2004; Mondal *et al.* 2017; Sangode *et al.* 2017a; Lakshmi *et al.* 2020; Kapawar

et al. 2021). Advanced instrumentation combined with tensorial computations enables precise determination of the magnetic fabrics from almost all types of rocks. Interpretation of the magnetic fabrics is, however, critical depending upon the geological processes experienced by the rocks. The undeformed lava flows present some of the simplistic mechanisms, although the fabrics show a large variety of distribution due to complexities

within the magmatic processes, the viscosity shear and variable gravity settling forces (Sangode *et al.* 2017a, b, 2021).

The Deccan volcanic province represents one of the most ideal set-up to understand the fabrics amongst lava flows. Few attempts were made on discrete outcrops of the Deccan traps (Schobel and De Wall 2014; Sangode *et al.* 2017a, 2021; Das and Mallik 2020; Patil *et al.* 2020) while a close interval study on the borehole core is absent. We present here the AMS study from a ~ 1250 m borehole core (KBH 07) in the western Deccan province obtained during the Deep Continental Drilling Program at Koyna, India by the Ministry of Earth Sciences, New Delhi. So far this is the first detailed record of the AMS by Z-axis orientation represented by 112 sequential specimen sampling. Figure 1 shows the Geological Map of the Deccan Flood Basalt province and the location of the continental deep drilling Project drill hole KBH 07.

The Deccan basalts represent titanomagnetite rich assemblage of magnetic mineralogy which results in strong magnetic susceptibilities of the samples, thus producing a noise-free AMS surpassing the fabrics contribution from other para or diamagnetic minerals within (Radhakrishnamurty *et al.* 1977, Radhakrishnamurty and Subba Rao 1990; Chenet *et al.* 2008; Sangode *et al.* 2017a, b). The AMS in Deccan basalts is therefore controlled by various factors including the concentration and domain size of the ferrimagnetic titanomagnetites. The second aspect of the variability of AMS in lava flows is their cooling history which is poorly understood in the context of fabric development (e.g., Sangode *et al.* 2017a). In the present attempt on the borehole core (figure 1), we analyze the changes in AMS parameters in time for this majority of the Middle to Upper Deccan trap lava formations representing about 47 flows.

2. Methods

The borehole core KBH 07 was sampled at an average interval of 10 m by precisely cutting 2.2 cm slices representing all the 47 flows. These slices were then drilled into cylindrical cores of 2.5 cm diameter and 2.2 cm height keeping the top and bottom intact with an arbitrary fiducial mark to represent an imaginary north for reference purpose and z-axis orientation. Since the top and bottom remain intact, we used all the parameters except the directional fabric parameters. We further augmented our data with the previously published routine rock magnetic results from this core (Sangode *et al.* 2017b). The AMS was measured on MFK1-FA-Kappabridge (AGICO, Czechoslovakia) at CSIR-National Geophysical Research Institute, Hyderabad in two sequences of before and after alternating field demagnetization of 100 mT. Both the results are discussed and finally, the after-demagnetization data was processed for inferences.
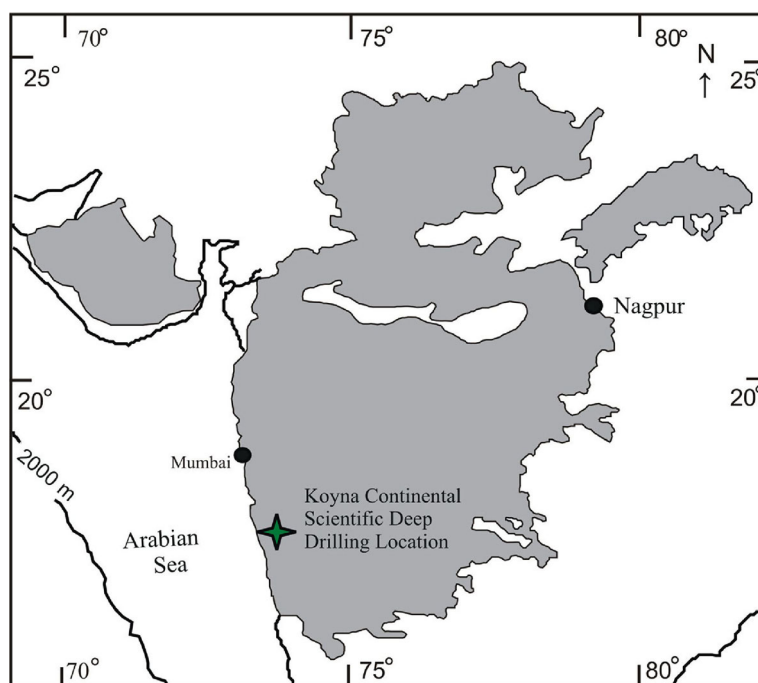

Figure 1. Geological map showing the areal spread of the Deccan flood basalt eruptions and location of the Koyna Continental Scientific Deep Drilling Project drill hole (KBH-07) of this study.
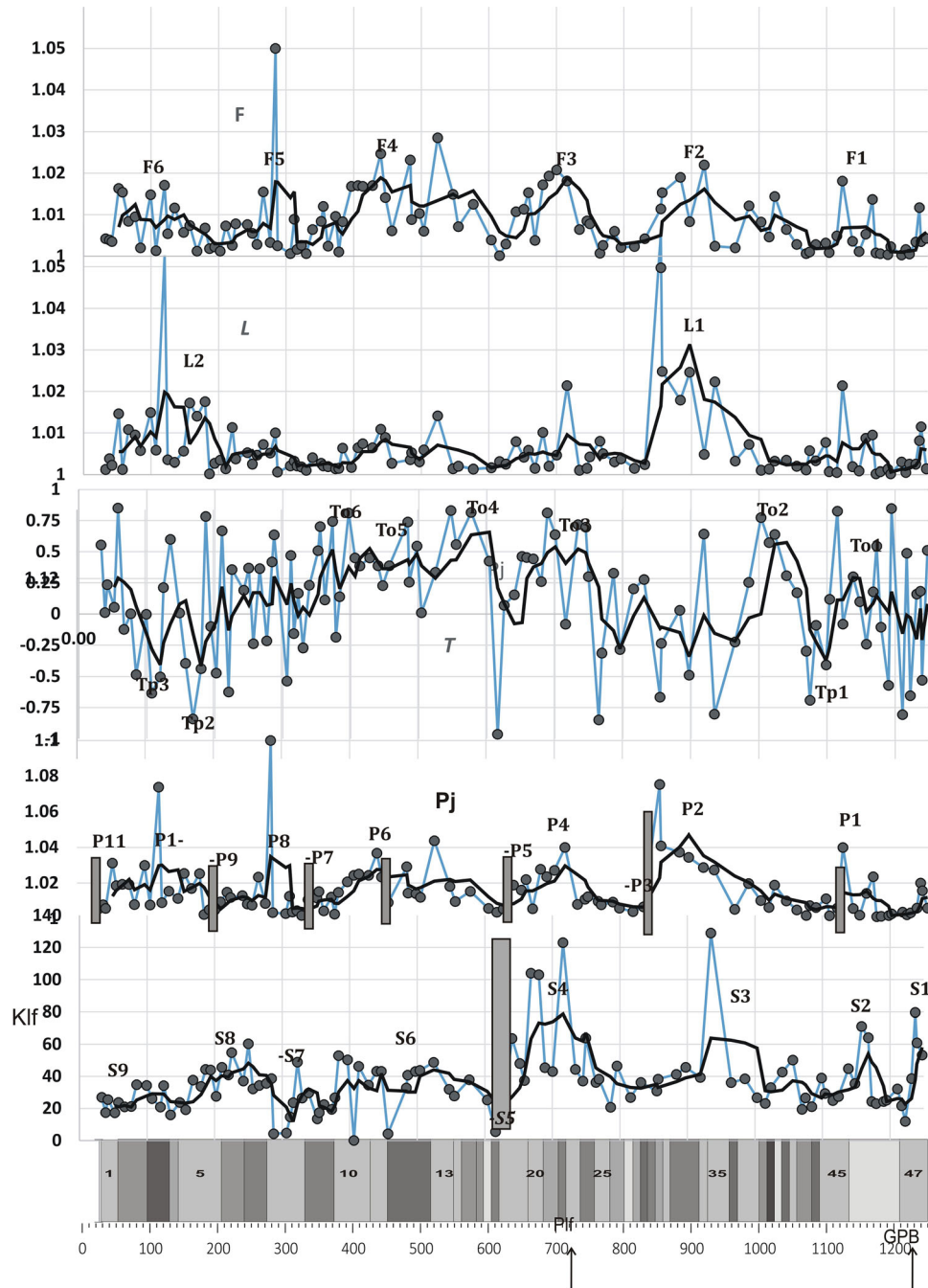
Figure 2. Variation amongst AMS parameters along the core KBH 07. The lithology shows lava flow numbers and filled circle data points are arranged with their depth (/height in stratigraphic column). The dark line curve is moving average with a period of 4. The anomalies are marked by denoting the number for each parameter being +ve or −ve. Major distinction at 600 m is described in the text. Anomalies represent: S1–S9: Volume susceptibility, P1–P11: degree of anisotropy, To: oblate shape factor, Tp: prolate shape factor, L1–L2: degree of lineation, F1–F6: degree of foliation.

3. Results and discussion

The AMS measured before and after demagnetization is presented in tables S1–S3 (supplementary data file) in order to produce a precise database. Figure 2 shows the variation amongst AMS parameters along the core. The mean Klf is increased from 35 to 37×10^{-5} after demagnetization probably due to the removal of internal demagnetization factor. Rest of the other parameters show decrease in Kurtosis and skewness depicting the laboratory smoothing after demagnetization. There is a decrease in degree of lineation (L), foliation (F) and anisotropy (P as well as Pj) after demagnetization. This indicates a notable change in AMS parameters marked by decrease in overall fabric anisotropy. The

most notable change observed was by the change in shape parameters (T and U) from weakly prolate to weakly oblate. In case of directional data, the K1 shows change in median rather than mean values. There is decrease in inclination from 34 to 32 after demagnetization; on the other hand, the inclination of K3 increases from 36.77 to 42.12. We, therefore, preclude that the demagnetization in highly ferrimagnetic mineral assemblage of the Deccan basalt removes spurious remanence and internal demagnetizations improving the smoothness of the data towards paleo record of AMS.

The removal of the effect of internal demagnetization improves correlation of rock magnetic parameters with AMS data. In order to avoid any hypothetical inferences by correlation, we adopted first order simplistic correlation, to get the pronounced relationship amongst the rock magnetic and AMS parameters. The density parameter (ρ) shows fairly positive correlation with all the AMS parameters including L, F, Pj, T and U. Previously Sangode *et al.* (2017b) noted that the density is independent of majority of the rock magnetic parameters in this core. This depicts that the density of the lava has played an influencing role over the fabrics rather than the mineralogy and it is likely to be governed by the magma composition. The Xlf shows fairly positive correlation with shape parameters T and U depicting that higher ferrimagnetic concentration increases the oblateness of the fabrics. This is also attested by the parameter SIRM which is governed by the ferrimagnetic concentration. Otherwise, there is only moderate to fair correlation of most rock magnetic parameters (concentration or domain size) with the AMS parameters. This indicates that the AMS fabric is fairly independent of magnetic mineral concentration and domain size, and is governed by the dynamics of the lava flow or the compositional assemblages other than titanomagnetites. We, however, plot the key rock magnetic parameters along with AMS parameters to generate information on mineralogical attributes during changes in the fabric parameters. The directions being arbitrary, we did not use the declination–inclination values for principle susceptibility axis (K1, K2 and K3), although their inclinations are used, since the Z axis for all the core samples is common.

The AMS parameters are plotted with depth of the core and are assigned by the lava flow number. The broad variability in Klf shows two distinct trends separated at ∼600 m depths. The lower part (>600 m) depicts broad peaks with higher

ferrimagnetic concentration than the upper part. The upper part (above 600 m) in general shows low variation and lower intensity of peaks in the Klf. The degree of anisotropy (Pj) shows a gradual increasing trend up to 850 m followed by a drop. The highest peak in Pj coincides with F and L at this interval (∼850 m) shows the highest inclination for K1 (with lowest K3–I). Thus, we identify prominent changes as anomalies being positive and negative with respective peaks and drops, and are described below in detail.

Figure 3 shows inclination anomalies of principle susceptibility axes. The lowermost flow (no. 47) shows positive anomaly of S1+ coinciding with low-density anomaly (d1−) and K1+. Decrease in susceptibility, density and the inclination of K1 within this lava flow depict a short independent episode. Further the lava flow no. 46 is one of the thickest in this part and show large change in anomaly with peak in susceptibility (S2), –K2 to K3/1, and a large transition in density. However, the changes in anomaly are continued beyond the lava flow boundary upwards. The K1 inclinations have fluctuated to higher values with K3 being lower. The density peak is restricted within the lava flow no. 46. Variations in most of the parameters are continued across the flows upwards, and up to the flow no. 38 indicating that this anomaly (K3+ up to –K3/2, d2+ and To1) is independent of the flow units and indicates a new magma episode. This episode continues with increasing frequency of the thinner lava flows (LFT/2). This set of the lava flows (LFT/2) shows the most anomalous peak with the highest K3 inclinations (K3/3) matching with the lowest K1 inclinations (K4−) along with highest density (d3+). The highest K3–I (K3/3+) coincide with highest density (d3+) and major change from prolate to oblate fabrics (To2). This depicts the role of viscosity shear in the thinner lava flows, while the peak in density indicates higher viscosities of these lava flows developing K1 imbricated fabrics marked by higher K3 inclinations. This follows the peak in degree of anisotropy (P2), peak in K1 (K5+), drop in K3 (K3/4) with peak degree of lineation (L1) and foliation (F2) and higher density (d4). This zone also records a higher thickness of the lava flow followed by the flows of lower thickness depicting a magmatic pulse (LFT3). This is followed by an episode of intermediate lava flow thicknesses (lava flow nos. 27 to 19) maintaining the higher densities, higher K3 (K3/5 and K3/6), and a broad peak in foliation (F3). This episode ends with a significant drop in
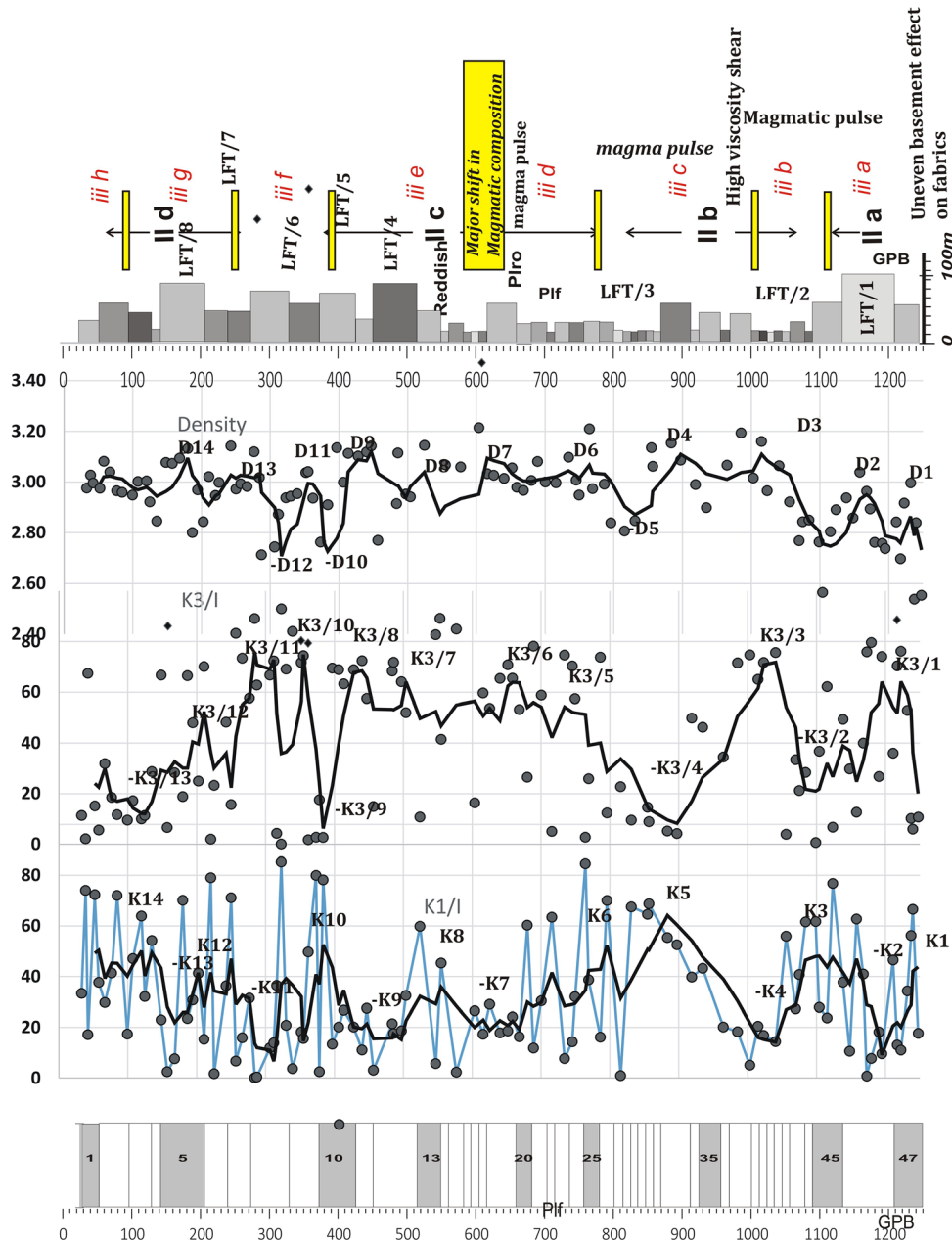
Figure 3. Inclination anomalies of the principle susceptibility axes. Anomalies: K1–K14: inclination of the principle susceptibility axis K1, K3/1,..., K3/13: inclination of the minimum susceptibility axis, i.e., K3. D1–D14 density anomalies. The lithocolumn shown is for thicknesses of individual lava flows. While the major shift in magmatic episode is shown at ∼600 m, the lava flow episodes are marked by a combination of pulses of varied thicknesses (LFT 1–LFT 8) and the mineral magnetic episodes derived from Sangode *et al.* (2017a, b) integrated with the AMS anomalies from the present study. The roman numbers (ii and iii) represent the second-order and third-order changes. The inferred major shift in magmatic composition at ∼600 m coincides with the shift in the lava flow thickness attitude towards thicker flows above 600 m.

susceptibility (–S5) coinciding with drop in P (–P5) and the drop in density at about 600 m. After this event, the susceptibility remains low with most of the negative anomalies in density. Similarly, there is a change in the tendency of the lava flow thicknesses being increased frequency of thicker lava flows, with the thinner lava flows almost absent. This interval therefore at 600 m can be considered for a major change in magmatic

compositional episode traceable in the KBH 07 borehole.

Previously, Banerjee and Mondal (2021) indicated that the lower part of the KBH 07 core comprises high Mg-low Ti type magma in contrast to the low Mg magma of the upper part. This suggests that the major change in fabric parameters, density and some of the rock magnetic parameters at about 600 m could be an artefact of the change in magmatic

compositional episode. We find a major change in the Xlf (as well as SIRM) values averaged for below and above this 600 m interval (see table S4 in supplementary data) which indicates significantly higher mean Xlf of 109 in the lower section compared to the upper part showing 84×10^{-8} m^3/kg. The lower zone depicts low density-high susceptibility-lower coercivity in contrast to the upper zone (table S4) indicating magma compositional/assemblage change between the two units. Thereafter, the fluctuating behaviour in the anomalies is maintained till a major anomaly occur at about 400 m marked by drop in K3 (–K3/9) and peak marked by K10 along with major drop in density (–d9). Also, from 400 m onwards, the fabrics tend to move towards prolateness along with declining K3–I values. This indicates majority of the lineation type fabrics are developed under lower density conditions.

4. Source of variability

Although the drill core KBH 07 represents a point location, the temporal variability amongst majority of the rock magnetic and AMS parameters is notable. In addition to this, the parameters themselves show large variation making the visual correlation difficult. Since the sampling interval does not represent an equal interval time series and the time horizons being unknown, any advanced statistics could not be performed. The reasons for vertical variability, therefore, can be attributed to the different cooling histories imparting the final fabrics amongst lava flows and also within the flow. Application of the moving average normalized the data in a window of 10–40 m enabling the inter-parametric correlations as achieved in figures 2 and 3. Therefore, the episodes are derived based on the combination of assessments from rock magnetic, geochemical, AMS parameters and the lava flow thicknesses.

Considering Xlf to represent the Fe concentration, it is likely that the viscosity of primary magma at equivalent high temperatures might have been controlled by the above factors of composition being Mg and Fe content. However, the fabrics being responded to the dynamic viscosity governed by temperatures rather than composition, do not show a strong correlation with the Xlf, density or other concentration and mineral dependent parameters. In order to further check such relationship amongst density, the mineral magnetic parameter (Xlf, SIRM, ARM, B(o)CR) and the fabric parameters (Pj, T, K3–I), we applied agglomerative hierarchical
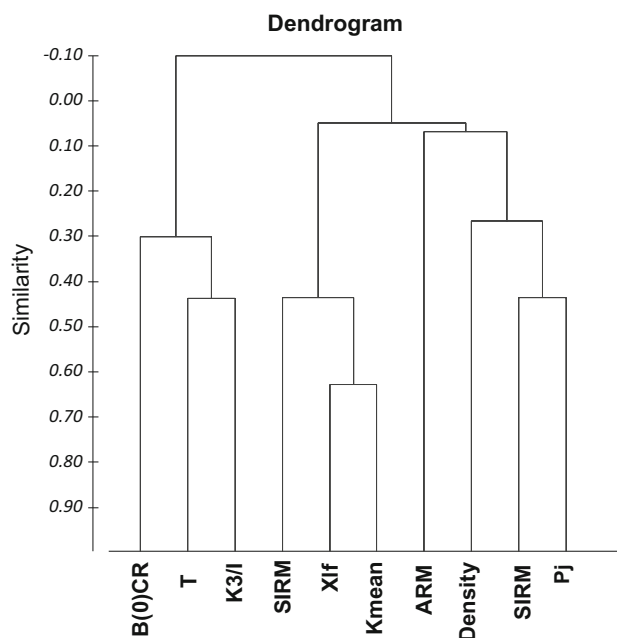

Figure 4. Agglomerative hierarchical clustering amongst representative rock magnetic and AMS parameters and the density.

clustering amongst these parameters producing a dendrogram (figure 4). The cluster analysis too did not show a significant similarity amongst majority of these parameters.

The density is probably the reflection of melt viscosity and represents the resultant of individual mineral densities and voids representing the volatile contents. Hence the density is in fact the final representation of the state of the chief constituents like plagioclase, pyroxene, titanomagnetites and olivine'. There is a large density variation which needs to be normalized for their concentration. In this attempt, we find density having variable relation with all these parameters, when studied in bulk for the entire core resulting in weak bulk correlation or clustering (e.g., see figure 4). The episodic inferences derived collectively from the combination of data are therefore governed both by composition and cooling history of the lava flows. In the absence of detailed mineralogical studies, present data from the KBH 07 core is therefore grossly valid for its inter-core correlation based on combination of AMS and rock magnetic parameters.

5. Conclusions

The close interval magnetic fabric studies of Deccan traps from Koyna borehole core KBH 07 indicate its complex and multiple controls governed by the variability in magma composition and cooling

history. The magnetic fabrics appear to have been governed by various factors including density and hence the viscosity and composition of the magma at the formation level producing magmatic episodes of the order of ~ 100 to 200 m independent of the lava flow unit. These episodic variations characterized by multiple rock magnetic and magnetic fabric parameters can be developed as robust tools of inter-core as well as stratigraphic correlation.

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Author statement

Mamilla Venkateshwarlu: Conceptualization, visualization, sample collection, data generation, and writing (review and editing). S J Sangode: Visualization, sample collection, processing of data, and writing (review and editing).

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