Geodynamics related to late-stage Deccan volcanism: Insights from paleomagnetic studies on Dhule-Nandurbar (DND) dyke swarm

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Geodynamics related to late-stage Deccan volcanism: Insights from paleomagnetic studies on Dhule-Nandurbar (DND) dyke swarm

Ayanangshu Das[1], Jyotirmoy Mallik[1]*, and Rasia Shajahan[1,2]
[1]Department of Earth and Environmental Sciences, Indian Institute of Science Education and Research Bhopal, Bhopal-462066, Madhya Pradesh, India.
[2]*Current affiliation*: PhD student, Department of Earth Science at University of Turin, Italy
*Corresponding author: jmallik@iiserb.ac.in

ABSTRACT

Indian plate drifted northward during Deccan volcanism with an extremely high average velocity of 15-20 cm/year. This paper addresses if the motion accelerated during the late stage of the flood basalt eruption event. Paleomagnetic investigations on Dhule-Nandurbar Deccan (DND) dyke swarm and its country rocks from western India, provided unique opportunity to calculate the same. This dyke swarm pervasively intruded into the older Deccan flows. We present here paleolatitudes and paleopole for the dyke swarm and the intruded basaltic flow, by combining results from two separate studies from the northern and southern bank of the Tapi River together with newly acquired data. The additional new dataset includes samples from some very long dykes and a few more dykes from the southern end of the dyke swarm, not covered earlier. The combined dataset provides an improved stable mean characteristic remanent magnetisation (ChRM) direction for the dykes (D_m = 337°; I_m= -43° at $\alpha 95$ = 5.93°, N = 129). The paleolatitude of the Nandurbar-Dhule area during dyke swarm emplacement is estimated as 25.4°S and the corresponding paleopole, 38.35°N; 79.90°W. The paleolatitude during the emplacement of the flows forming the country rocks is 40°S, and the corresponding paleopole is 27°N, 90°W. This implies that the Indian plate shifted around 1670 km between the emplacement of the country-rock and the dykes over a period of ~4-5 Ma with a velocity of 25±8 cm/year, which is much higher than the previously reported average plate velocity. We suggest that the accelerated plate velocities caused enhanced tensional stresses on the Indian lithosphere, creating numerous long fractures along the existing weaker Narmada Son lineament (NSL), through which DND dykes got emplaced. We also discuss the implications of enhanced velocity of the Indian plate on the India-Eurasia collision.

Keywords: Deccan Traps, Dyke swarm, Paleomagnetism, Paleopole, Plate motion, and Indian subcontinent.

INTRODUCTION

Deccan flood basalts, covering a vast area of western and central India, are the product of prolific outburst of magma during the northward drift of the Indian plate that took place in late Cretaceous (Morgan, 1981). The Deccan volcanic rocks bear remarkable paleomagnetic signatures of India’s northward movement after its separation from Madagascar and Seychelles Island. Numerous investigations (Kono et al., 1972; Poornachandra Rao and Bhalla, 1981; Dhandapani and Subbarao, 1992; Vandamme and Courtillot, 1992; Prasad et al., 1996; Courtillot et al., 2000; Patil and Arora, 2003; Paul et al., 2008; Basavaiah et al., 2018) on the dykes and flows from the Deccan Province have been used to establish India’s position and the position of the corresponding magnetic poles during this gigantic eruption event. Vandamme et al. (1991) combined results from many such studies to calculate the mean paleopole during Deccan eruption, known as the Deccan Superpole (37°N, 79°W). Paleomagnetic methods have also been fruitfully used to establish magneto-stratigraphy for the Deccan flow sequences with respect to the Geomagnetic Polarity Time Scale (GPTS). A straightforward magnetostratigraphic sequence of normal-reverse-normal (N-R-N; polarities corresponding to the chrons 30N-29R-29N) was proposed based on the existing paleomagnetic data (Courtillot et al., 1986; Vandamme et al., 1991; Vandamme and Courtillot, 1992; Radhakrishna et al., 2019). However, Basavaiah et al. (2018) reported additional magnetozones (31N and 30R or 31R) from the dykes near Mumbai. A more recent study on the Koyna drill core samples by Radhakrishna et al. (2019), emphasized that there is a single geomagnetic polarity transition in the paleomagnetic data. It is known that a substantial fraction of the large volume of eruptions took place during Chron 29R (Vandamme et al., 1991; Patil and Arora, 2003). The majority of the dykes from the DND swarm belong to the 29N chron, and the rest belong to the 29R chron.

Geochronological data (^{40}Ar-^{39}Ar) from the Western Ghats indicate an age of ~ 67.4±0.7 Ma (Duncan and Pyle, 1988) to the Deccan volcanic event. Later on, Vandamme et al. (1991) reported the age of the same volcanic sequence to be ~ 65.5±2.5 Ma, using ^{40}Ar-^{39}Ar data. Available age data from the Deccan volcanic province is listed in Table 1. In earlier days, a very short duration (< 1Ma) was generally hypothesized for such a massive volcanic event (Courtillot et al., 1988; Duncan and Pyle, 1988; Hoffmann et al., 2000). However, Dhandapani and Subbarao (1992), Venkatesan et al. (1993) argued for an interval of about 3 Ma for the same.

Although most of the recent ‘dates’ now constrain the eruption age between ~65 and 66 Ma (Renne et al., 2015; Schoene et al., 2015; Parisio et al., 2016) straddling the K/T boundary, Sheth et al. (2001a, b) came up with an exemplary ^{40}Ar-^{39}Ar data set from the lava sequences of Mumbai and argued for a duration of ~8 Ma for Deccan volcanism which is currently believed to be accurate. Sheth et al. (2019) recently indicated a time gap of at least ~ 4.06 Ma between two dykes from the DND dyke swarm (dyke 3 and 5) using ^{40}Ar/^{39}Ar geochronology.

In general, most Continental Flood Basalt (CFB) provinces are found associated with dyke swarms (Deshmukh and Sehgal, 1988; Sant and Karanth, 1990; Ernst et al., 1995; Bondre et al., 2006). The Dhule-Nandurbar (DND) area is part of the Narmada-Satpura-Tapi (N-S-T) dyke swarm, which is one of the three regional dyke swarms related to the Deccan flood basalt event. The other two are, the West Coast dyke swarm and the Pune-Nasik dyke swarm. Prasad et al. *(*1996) and Sethna et al. (1999) reported individually paleomagnetic results from different parts of the DND dyke swarm with little areal study area overlap. Prasad et al. (1996) proposed emplacement of DND dyke swarm just after the peak phase of the Deccan eruption at about ~65 Ma. Additionally, they compiled a magnetostratigraphic sequence by analysing the polarity status of the studied dykes and country rocks and eventually adhered to a short duration for Deccan volcanism. They reported the paleolatitude of the DND area during dyke emplacement at 24.6°S and corresponding paleopole at 37.2°N, 80.5°W. From the overlap of paleopole positions from the dykes and the basalt flows, Prasad et al. (1996) noted no appreciable northward migration of the Indian continent at that time. However, they recommended a robust paleomagnetic investigation along with high precision numerical age data. Similarly, Sethna et al. (1999) suggested two distinct phases of DND dyke emplacements (with different magnetic polarities). They reported the paleolatitudes of the DND area during dyke emplacement at 24° S and corresponding paleopole at 37°N, 75°W. However, during the emplacement of the country rock, the DND area was at ~ 40°S, and the corresponding paleopole was at 27°N, 90°W. Thus, they argued, on the contrary to Prasad et al. (1996), a significant northward drift of the Indian plate during that time.

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Table 1. Radiometric age data for Deccan Volcanic Province (DVP).

Formation wise age data			
Formation	**Age (Ma)** ± 2σ	**Method**	**References**
Mahabaleshwar	63.1±1.0	^{40}Ar/^{39}Ar	Venkatesan *et al.* (1993)
Mahabaleshwar	64.9 ± 0.4	^{40}Ar/^{39}Ar	Knight *et al.* (2003)
Mahabaleshwar	65.3 ± 0.4	^{40}Ar/^{39}Ar	Knight *et al.* (2003)
Mahabaleshwar	69.7 ± 2.4	^{40}Ar/^{39}Ar	Duncan and Pyle (1988)
Ambaneli	64.3 ± 0.8	^{40}Ar/^{39}Ar	Knight *et al.* (2003)
Ambaneli	65.1 ± 1.0	^{40}Ar/^{39}Ar	Venkatesan *et al.* (1993)
Ambaneli	66.4 ± 0.5	^{40}Ar/^{39}Ar	Knight *et al.* (2003)
Poladpur	65.84 ± 0.58	^{40}Ar/^{39}Ar	Hooper *et al.* (2010)
Poladpur	68.04 ± 0.8	^{40}Ar/^{39}Ar	Venkatesan *et al.* (1993)
Bhimshankar	67.23 ± 0.6	^{40}Ar/^{39}Ar	Pande (2002)
Thakurvadi	67.5 ± 0.8	^{40}Ar/^{39}Ar	Venkatesan *et al.* (1993)
Thakurvadi	68.6 ± 0.6	^{40}Ar/^{39}Ar	Venkatesan *et al.* (1993)
Neral	68.0 ± 1.4	^{40}Ar/^{39}Ar	Duncan and Pyle (1988)
Igatpuri	66.5 ± 2.0	^{40}Ar/^{39}Ar	Hofmann *et al.* (2000)
Jawhar	65.7 ± 1.5	^{40}Ar/^{39}Ar	Hofmann *et al.* (2000)
Jawhar	66.4 ± 1.3	^{40}Ar/^{39}Ar	Hofmann *et al.* (2000)
Jawhar	67.8 ± 0.6	^{40}Ar/^{39}Ar	Venkatesan *et al.* (1993)
Area wise age data			
Gilbert Hill, Bombay	60.5 ± 1.2	^{40}Ar/^{39}Ar	Sheth *et al.*(2001a)
Bombay Trachyte	60.4 ± 0.6 and 61.8 ± 0.6	^{40}Ar/^{39}Ar	Sheth *et al.* (2001b)
Nandurbar-Dhule dykes	63.43±0.44/0.48; 67.49±0.85/0.89; and 67.06±0.56/0.60	^{40}Ar/^{39}Ar	Sheth *et al.* (2019)

It is to be noted that both paleomagnetic studies by Prasad et al. *(*1996) and Sethna et al. (1999), were restricted to the dykes around the city of Nandurbar, on either banks of the river Tapi, which is thought to be the centre of the dyke cluster. In this paper, we have reviewed and combined the results of these two earlier works with the new data from dykes from the furthest end of the dyke swarm (Figure 1). We believe that the combined dataset would be sufficiently representative of the swarm. We also provide rock-magnetic results (isothermal remanent magnetisation and thermo-remanent curves) from the newly analysed dyke samples. We used the difference between the paleolatitudes of the Indian plate during flow and dyke emplacement and their tentative time gap to assess the velocity of the Indian plate during the late phase of Deccan volcanism. We then discuss the role of accelerated plate velocity in imposing additional tensile stresses on the continental lithosphere, leading to robust fracturing along pre-existing weak lineaments enabling magma emplacement through them. Finally, we discuss such accelerated velocities of the Indian plate in light of the newly proposed 'multi-stage' collisional model between India and Eurasia.

GEOLOGICAL BACKGROUND

The DND dyke swarm consists of numerous mafic dykes (~210 mappable dykes) intruding the older Deccan basalt flows (Figure 1). Sr-Nd-Pd Isotopic data (e.g., Sheth et al., 1997; Mahoney et al., 2000; Sheth et al., 2004) indicate a geochemical resemblance between the dykes and the lava flows exposed in the Western Ghats. No felsic lavas are reported from this region. Localised deposits of the red bed are reported from the swarm. Sporadic exposures of dykes with crustal xenoliths are present in the southern part of the swarm (near Dhule), indicating a highly heterogeneous basement below the Deccan sequences (Ray et al., 2008). Cenozoic and Quaternary alluvial deposits (30 km wide and 200-400 m thick) cap the trap along the Tapi River. The base of the Deccan trap in this area is not exposed, and a total thickness of a few hundred meters has been proposed (Ray et al., 2007). Available geochemical and petrographic data for several DND dykes indicate the presence of shallow magma chambers (Melluso et al., 1999). Bhattacharji et al. (2004) also justified the presence of shallow magma chambers (7-8 km depth) based on gravity modelling. The lava flows are horizontal around Dhule and Dondaicha area and have distinct but gentle (5–10°) northward dips around Shahada and Kondaibar area (Figure 1). Being more erosion-resistant than the lavas, relatively fresh and unweathered dykes form linear, often prominent ridges that extend for kilometres for a few instances. It is thought that the DND dykes might have been feeders to the younger lava flows from the same area that are currently eroded (Ray et al., 2007; Sheth et al., 2019).

ACQUISITION OF NEW DATA

As it was felt that the existing paleomagnetic data did not have sufficient areal coverage, we sampled more dykes. The new sampling locations are shown in Figure 1 together with sampling locations of existing paleomagnetic data from Prasad et al. *(*1996) and Sethna et al. (1999). Prasad et al. *(*1996) did not provide a map where individual sampled dykes are clearly marked; instead, they marked sampling regions. We also had no choice but to stick to the same. The methodologies adopted in additional sampling done by us and in analysing the newly acquired data from the same is described below.

Sampling and Methodology

Multiple cylindrical cores (total 97) were drilled out from the block samples collected from thirteen different dykes of the swarm (Figure 1), as mentioned before. Most of the samples collected by Prasad et al. (1996) and Sethna et al. (1999) are from the Nandurbar, Dondaicha, and Nizampur areas. In the absence of a clearly demarcated map with sampling locations and different nomenclature conventions adopted by them, it is difficult to identify the individual dykes that have already been studied. As an optimum solution, we divide the swarm into three sampling regions (Region 1, 2, and 3; Figure 1) and combine our newly acquired data with the published data that belongs to the corresponding region.

Rock Magnetism

Isothermal Remanent Magnetisation (IRM) and back-field measurement

Isothermal Remanent Magnetisation (IRM) analysis was carried out on selective samples up to 1000 mT, following a stepwise approach. The IRM was then demagnetised at different backfields up to -100 mT. The magnetic field was imparted using an ASC impulse magnetizer (ASC Scientific, USA), and the remanence was measured with a Molspin spinner magnetometer (Magnetic Measurements, U.K) housed at the rock magnetic laboratory of the geology department in Savitribai Phule University, Pune.

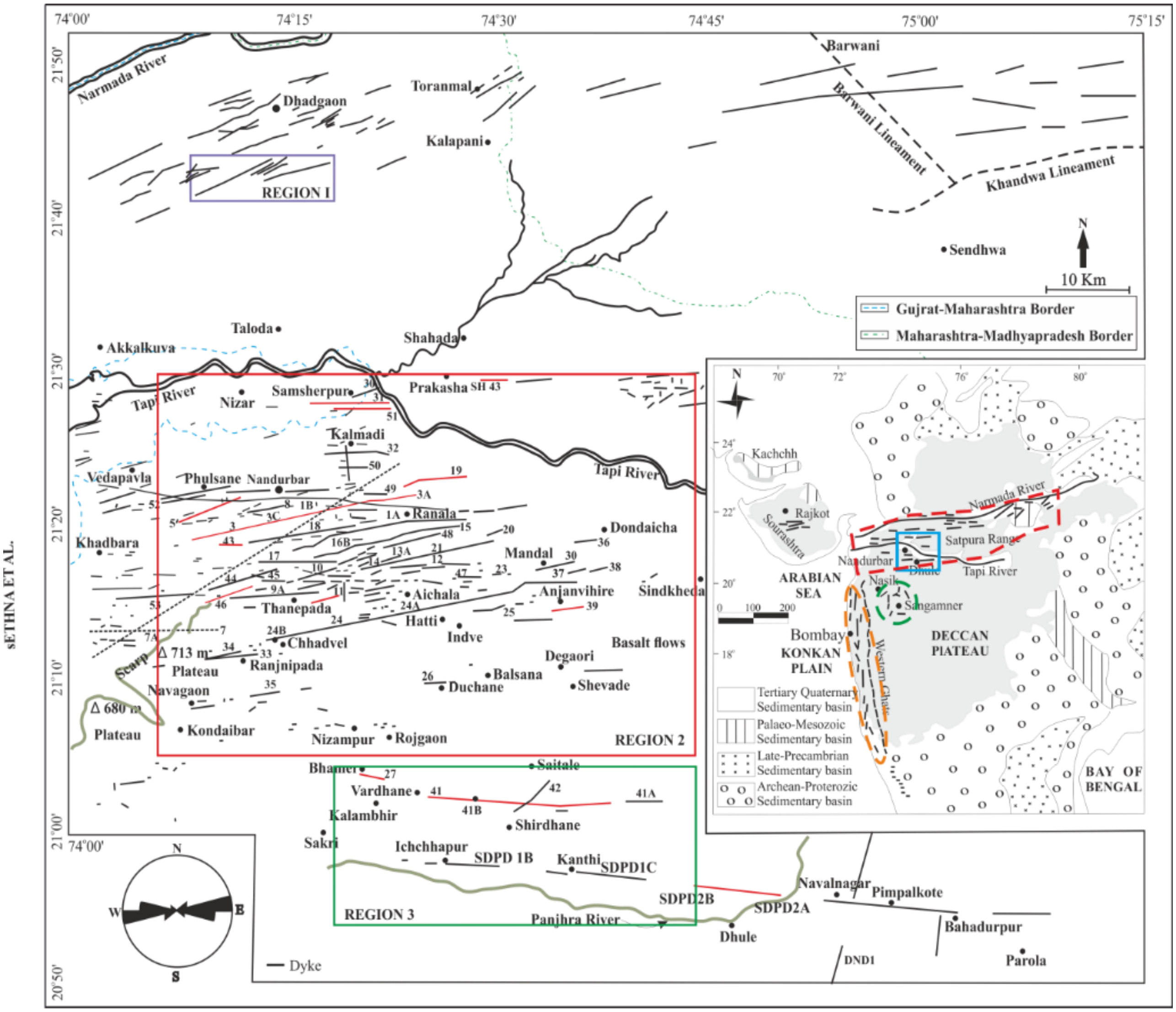

Figure 1. Geological map of the Nandurbar-Dhule dyke swarm showing networks of mafic dykes (Modified after Ray et al., 2007 and Prasad et al., 1996). Studied dykes are denoted with red line. Map in the top right inset shows the geographical extent of Deccan Volcanic Province (DVP) in the western India and three associated dyke swarms. Narmada-Satpura-Tapi, Pune-Nasik and West-coast dyke swarms are marked with red dotted rectangle, green circle and orange dotted envelop respectively. Study area is denoted with blue rectangle. Bottom left inset shows the angular distribution of dyke trends (mostly E-W).

Thermoremanent curves

Powdered samples from dykes were used for thermos remanent analyses, using an Advanced Variable Field Translation Balance (AVFTB, Magnetic Measurements, U.K) housed at CSIR-National Geophysical Research Institute, Hyderabad. Data were analysed using the Rock Mag Analyzer (version 1.1) software (Leonhardt, 2006).

Paleomagnetism

For paleomagnetic analysis, the samples were measured for their natural remanent magnetization (NRM), using a JR-6 spinner magnetometer (AGICO, Brno, Czech Republic) and bulk susceptibility using an MFK-1A (AGICO, Brno, Czech Republic). Progressive and stepwise demagnetisation was done using both thermal and alternating field (AF) demagnetisation techniques to isolate the characteristic remanent magnetisation (ChRM) directions. For AF demagnetisation, a Molspin Alternating Field demagnetizer (Magnetic Measurements, U.K) was used, and thermal demagnetisation was carried out in a magnetic field-free space using thermal demagnetizer (MMTD-80, Magnetic Measurements, U.K) at the CSIR-National Geophysical Research Institute, Hyderabad, India. The directional data were processed using principal component analysis (PCA) (Kirschvink, 1980) and plotted as zijderveld diagrams (Zijderveld, 1967), vector migration, and intensity decay curves.

RESULTS

Rockmagnetic results

Isothermal Remanent Magnetisation (IRM) and back-field measurement

IRM acquisition response and back-field curves (Figure 2a) show that the IRM reaches saturation at about 200 mT, which is a signature of the presence of magnetite (titanomagnetites) (Patil and Rao, 2002; Patil and Arora, 2003). The remanent coercivity (H_{cr}) ranges between 15 and 40 mT, revealing the presence of titanomagnetite (Cisowski, 1981; Dankers, 1981; Venkatachalapathy et al., 2009).

Thermoremanent curves

Das et al. (2021) provide a detailed account of the temperature-dependent susceptibility variation analysis for these dykes, where characteristic Curie temperatures are used to identify magnetic minerals. The heating and cooling curves of susceptibility (thermoremanent curves) for representative samples (Figure 2b) show a subtle decrease in susceptibility up to ~270°C, followed by a rapid decrease in magnetisation between 580°C and 600°C. For most samples, the shape of the cooling curve follows the heating curve but with lower susceptibility values. The thermoremanent curves are representative of the presence of magnetite (titanomagnetite) in the samples. Scanning Electron Microscopic (SEM) analysis supports our interpretation of titanomagnetite (Das and Mallik, 2020; Das et al., 2021).

Paleomagnetic results

Alternating field and thermal demagnetizations on 97 specimens from thirteen newly sampled dykes were conducted to isolate ChRM directions. Figure 3 shows the specimen's behaviour during AF demagnetization. Specimens 19(NB)C and 46(C)CI show northwest declinations with negative inclinations, and specimens 31A(NB)AI and 31(SB)A show southeast declinations with both positive and negative inclinations, indicating both normal and reverse polarities (Figure 3a).

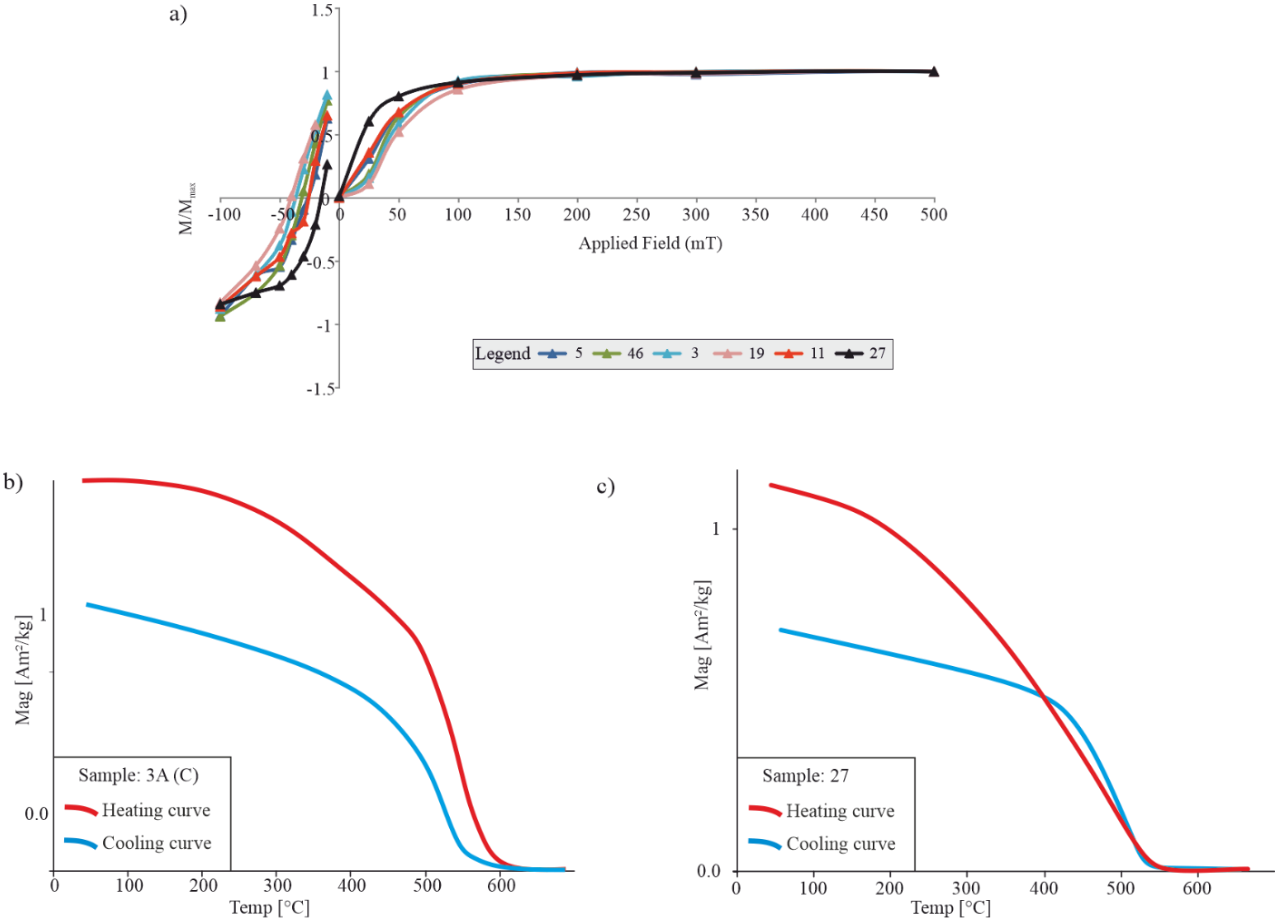

Figure 2. (a) Isothermal Remanence Magnetisation (IRM) acquisition and back-field curves. (b), and (c) Typical thermoremanent curves for representative DND dyke samples 3A and 27 respectively.

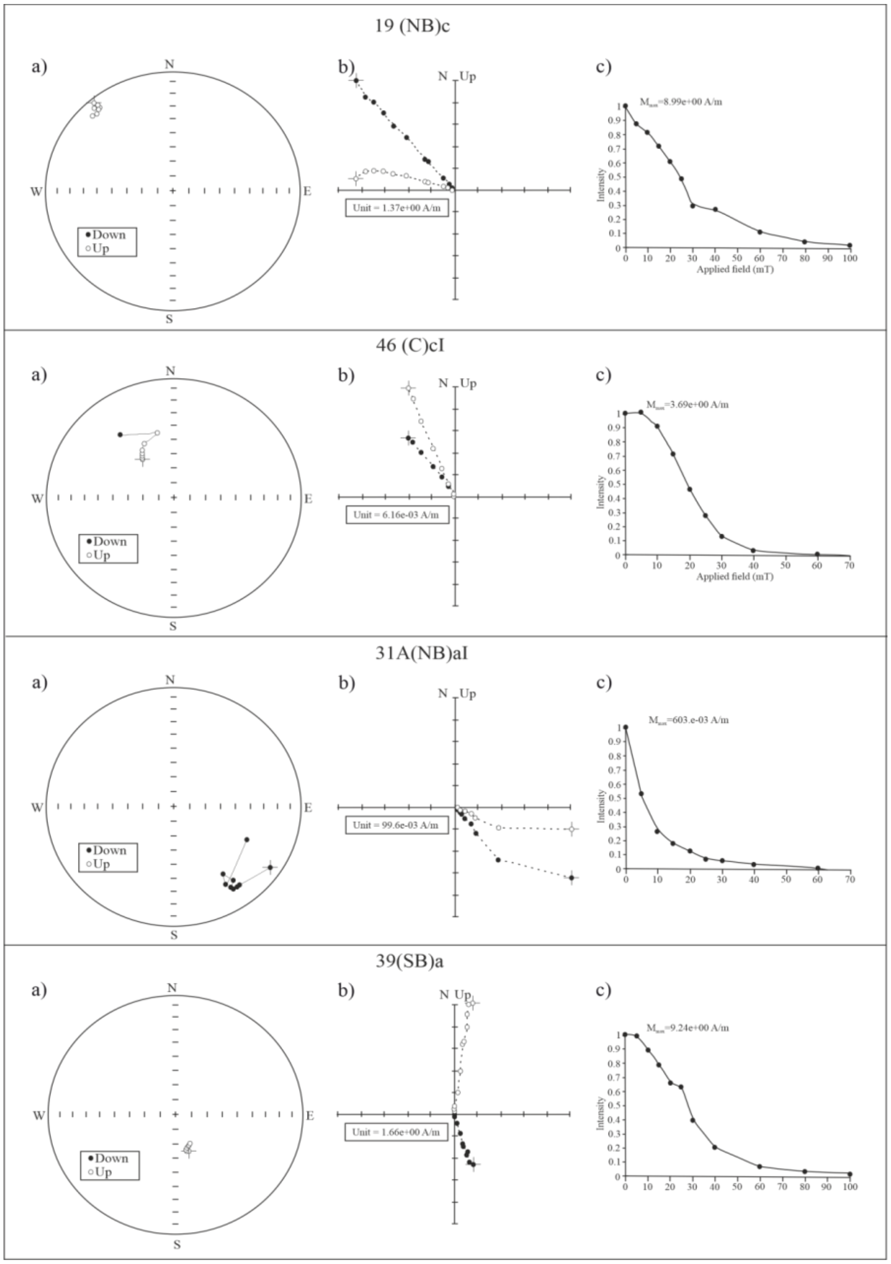

Figure 3. Sample behaviour during Alternating Field Demagnetization. (a) Vector migration diagrams; (b) Orthogonal projections, solid circles onto the horizontal plane and open circles on to the vertical plane; (c) intensity decay curves.

In Zijderveld diagrams (Figure 3b), most samples reveal a single component of magnetization. Intensity decay curves (Figure 3c) show a smooth decrease in intensity with ~90% after the 80 mT step. Figure 4 shows the specimen's behaviour during thermal demagnetization. Specimens demagnetized here are taken from the same samples as AF demagnetization to compare a consistency in vector behaviour during demagnetization. Specimens 19(NB)G and 46(C)CII show northwest declinations with negative inclinations, and specimens 3AI(SB)D and 31A(NB)EII show southeast to southwest declinations with positive inclinations, indicating both normal and reversed polarities (Figure 4a). In Zijderveld diagrams (Figure 4b), most samples show a single component magnetization, similar to AF demagnetization. Intensity decay curves (Figure 4c) show a steady and smooth decrease in intensity and saturate below 580°C. Specimen 46(C)CII shows a complete unblocking in intensity at 580°C, indicating magnetite as the main remanence carrier. Specimen 31A(NB)EII shows a gradual decrease in intensity between 350°C and 450°C, and the complete unblocking is observed much below 580°C, indicating titanomagnetite as the remanence carrier. We also measured the bulk susceptibility during thermal demagnetization and found no chemical alteration during the demagnetization experiment. Thermal demagnetization data are consistent with the AF demagnetisations, showing normal polarity for 8 dykes and reverse polarity for 5 dykes. In AF demagnetization, there is a remarkable improvement in the grouping of sample directions as well as sites, compared to thermal demagnetization. Thermal and AF demagnetization results are combined to obtain an estimated mean for ChRM directions within acceptable statistical range to calculate virtual geomagnetic pole (VGP) for individual dykes.

Table 2 summarizes the results of the DND dykes (new as well as earlier data) from the present study area. The region/dyke estimated mean ChRM directions are shown in Figure 5a. A good grouping/cluster of the region mean directions is observed for reverse polarity directions, but there is more scatter for normal polarity directions. All the reversely magnetized dykes show a mean ChRM direction at D_m=159.54° and I_m= 42.61° (k= 16.24, α_{95}= 8.14, N=52). On the other hand, dykes with normal polarity show a mean ChRM direction at D_m=335.06° and I_m=-43.38° (k=31.12, α_{95}=8.20°, N=129). The combined mean directions from dykes of normal and reversed polarity deviate from anti-parallelism by < 5°. The combined estimated mean declination (D_m) ≈ 337.3° and mean inclination (I_m) ≈ -43.51° (k=19.97, α_{95}=5.93°, N=129). As all of the dykes have vertical margins, no tectonic tilt correction was applied. The combined data from the DND swarm and other data from Deccan dykes and lava flows are compiled in Table 3.

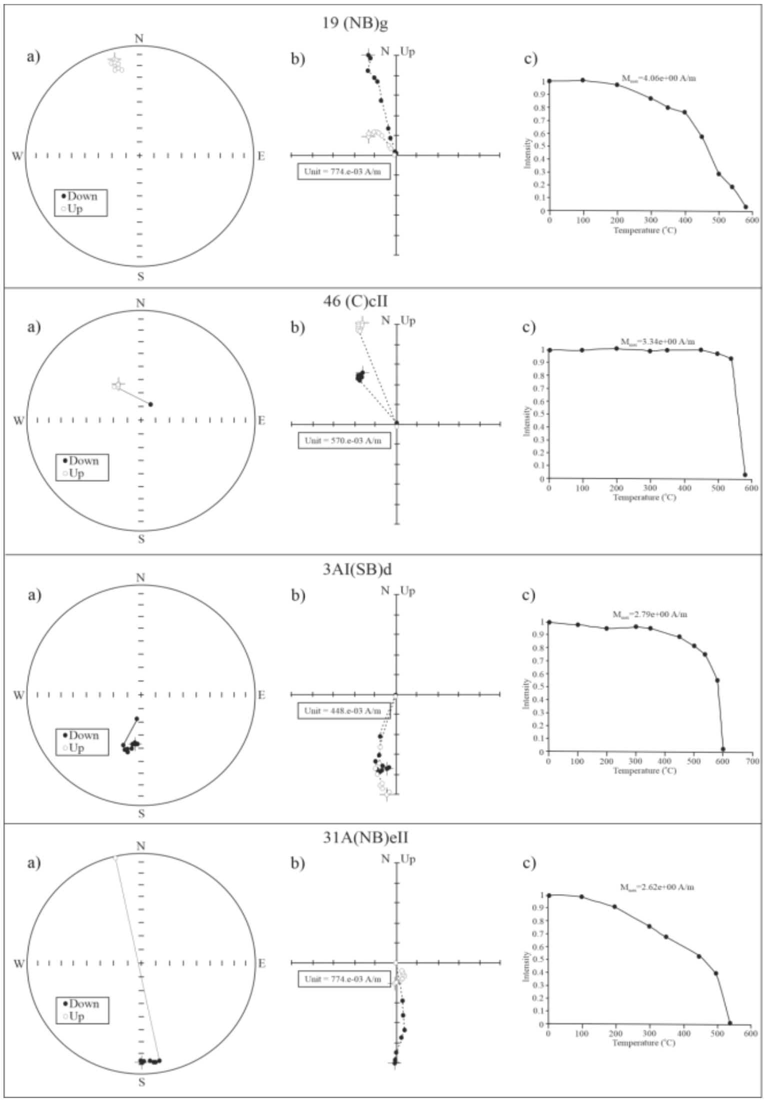

Figure 4. Sample behaviour during Thermal Demagnetization. (a) Vector migration diagrams; (b) Orthogonal projections, solid circles onto the horizontal plane and open circles on to the vertical plane; (c) intensity decay curves.

Table 2. Paleomagnetic results from Nandurbar-Dhule dykes. No.= Number; Lat.= Present latitude; Long.= Present longitude; N/n= Number of specimens analyzed/number of specimens used for statistical analysis; Dm=mean declination; Im=mean inclination; α_{95}= circle of confidence at 95% probability level; k=precision parameter; P=Polarity; λp= pole latitude; Lp= pole longitude; dp and dm= Semi-axes of the oval of 95 percent confidence about the VGP (Virtual Geomagnetic Pole); λm = Paleolatitude.

Dyke	ChRM (AF+Thermal)						VGP				λ_p (°S)	Data Source
	D_m	I_m	N	K	α_{95}	Polarity	Lat	Long	d_p	d_m		
REGION 1												
DDA	159	30	11	26.1	8.4	R	46.9	284.6				Prasad et al. 1996
DDB	154	35	9	15.7	13.4	R	41.7	288.0				
DDC	342	-22	8	36.2	9.3	N	52.4	284.1				
DDD	341	-62	5	117.0	7.1	N	22.7	269.2				
REGION 1 Mean	338.8	-37.2	33	21.50	20.28		42.8	281.5	13.96	23.79	20.8	
REGION 2												
5	336	-20	4	33.63	8.4	N	50.34	293.01				New data
31	139	23	4	40.31	8.7	R	-37.67	128.09				
39	173	57	3	27.90	11.6	R	-31.08	81.46				
3A	168	47	3	16.3	14.61	R	-38.8	87.4				
11	152	39	2	19.3	13.02	R	-38.51	107.91				
19	323	-13	2	52.78	9.3	N	44.10	311.05				
46	342	-62	2	27.50	12.9	N	23.81	268.39				
51	279	-63	2	25.16	13.6	N	8.68	300.33				
SH43	6	-36	2	29.73	12.5	N	47.86	245.43				
43	338	-27	2	36.18	15.4	N	48.30	287.37				
DHA	5	-52	5	41.6	12.0	N	35.9	249.1				Prasad et al. 1996
DHB	314	-55	4	26.1	18.3	N	18.4	292.4				
DHE	181	50	6	57.5	8.9	R	37.9	106.8				
DHF	336	-31	5	58.9	8.3	N	45.3	287.9				
DHG	321	-40	5	36.7	12.8	N	31.8	297.4				
DHK	319	-46	5	67.1	9.4	N	27.2	295.2				
DHM	164	48	4	72.0	0.9	R	37.3	88.1				
D2	7	-55	5	69.18	6.71	N	33	248				Sethna et al. 1996
D3	324	-64	2	31.44	12.13	N	15	280				
D5	339	-39	1	372.40	3.97	N	42	281				
D18	322	-50	2	197.02	4.79	N	26	291				
D11	326	-34	4	49.46	6.56	N	38	297				
D12	338	-30	4	103.51	5.47	N	47	286				
D13	176	43	7	48.18	7.03	R	43	101				
D9	329	-31	3	17.76	11.79	N	41	295				
REGION 2 Mean	336	-44.73	88	19.02	6.97		36.95	281.46	5.54	8.79	26.3	
REGION 3												
27	142	46	3	24.64	11.4	R	-29.30	113.27				New data
SDPD2B	331	-50	3	171.1	4.2	N	30.77	283.80				
41	354	-27	2	16.69	12.9	N	80.90	298.94				
REGION 3 Mean	337.3	-41.89	8	20.98	27.62		39.46	281.39	20.75	33.85	24.2	
Mean (Overall)	337.3	-43.51	129	19.97	5.93	-	38.35	280.71	4.60	7.39	25.4	

Table 3. Paleomagnetic pole positions from different dykes and flows of Deccan Traps.

Location	No. of flows and dykes	Mean ChRM			Paleolatitude (°S)	N Pole position		References
		D_m(°)	I_m (°)	α_{95}		Lat (°N)	Long (°W)	
Nandurbar-Dhule (N-D) dyke swarm	-	337.3	-43.51	5.93	25.4	38.35	79.9	Present study
Mumbai dykes	19	323.4	-44.7	11.84	~23.2	40.20	75.88	Basavaiah *et al.* (2018)
Murud	6	341	-42	5.7	24	44.0	83.0	Patil and Arora (2003)
Goa	9	156	47	9.9	28	41.0	78.0	Patil and Rao (2002)
Kerala	8	163	61	10.1	31.6	34.6	86	Radhakrishna *et al.* (1994)
Dongergaon to Nagpur to Bombay to Puna traverse	20	336.10	-44.86	2.4	30	36.9	78.7	Vandamme *et al.* (1991); Updated after Courtillot *et al.* (1986)
Hulyiyurdurga	5	328.9	-54.5	3.3	34	33.9	72.3	Kumar *et al.* (1988)
Mandaleshwar dykes	5	350	-50	5.0	32	37.0	94.0	Subbarao *et al.* (1988)
Kalsubai	24	152	52	-	33	31.0	79.0	Khadri *et al.* (1988)
Nagpur to Bombay traverse	21	147.5	46.8	4.6	28.8	32.5	69.5	Courtillot *et al.* (1986)
Dhar traps	7	143 320	46 -48	5.5 -	30 -	29.0 -	67.0 -	Poornachandra Rao and Bhalla (1981)
Mount Pavagarh	16	334	-38	5.4	25	39.0	74.0	Verma and Mital (1974)
Sagar	-	156	40	3.0	25	38.0	73.0	Bhalla and Anjaneyulu (1974)
Ellichpur	24	159	48	5.0	30	35.0	80.0	Wensink (1973)
Jabalpur to Dindori	13	340	-31	4.5	18	46.0	69.0	Verma *et al.* (1973)
Mount Girnar	14	336	-38	4.4	25	41.0	79.0	Verma and Mittal (1972)
Mahabaleshwar	28	160	47	6.7	28	38.3	83.7	Kono *et al.* (1972)
Amboli	5	174	51	10.2	32	41.4	80.0	Kono *et al.* (1972)
Aurangabad	25	150	48	5.5	30	33.0	73.0	Athavale and Anjaneyulu (1972)
Jabalpur	8	343	-28	5.0	17	48.0	74.0	Verma and Pullaiah (1971)
Malwa	-	164	49	11.9	32	36.0	90.0	Pal *et al.* (1971)
Mysore	4	357.7	-51.2	22.69	32.1	45.4	101.05	Hasnain and Qureshy (1971)
Western Ghats	90	152	50	3.8	30	34.0	76.0	Wensink and Klootwijk (1971)
Khandala	-	147	58	5.0	39	25	79	Sahasrabudhe (1963)
Overall mean	-	336.9	-46.12	3.35	27.5	36.3	80.03	Combining all the data

DISCUSSION

The thermoremanence and IRM curves suggest magnetite (titanomagnetite) as the dominant remanence carrier (Dunlop, 1986) in these dyke samples. We obtained data from thirteen DND dykes with both normal and reverse polarities and combined these results with the existing data sets in Table 2.

Paleomagnetic implications

It is evident from the Table 2 that a set of dykes yields normal polarity representing Chron 29N, and the rest of the dykes yield reverse polarity representing 29R or younger. However, we do not find any cross-cutting field evidence to assess the relative ages of normal and reverse polarity dykes. The Paleopole during the DND Deccan dyke swarm emplacement, calculated by combining the new data with the existing datasets given by Prasad et al. (1996) and Sethna et al. (1999), is 38.3°N and 79.9°W (dp=4.60; dm=7.39 and N=129). The calculated paleopole is then plotted along the synthetic APWP for India based on the GAWPWaP model of Torsvik et al. (2012) and is shown in Figure 5b. The Deccan Superpole (Vandamme et al., 1991) was also plotted for reference. The paleopole calculated from the country-rock by Sethna et al. (1999) is positioned southernly from the same calculated from the dykes.

The pole position derived in this study is close to previously reported Deccan Trap (DT) poles. India's rapid northward migration coupled with an anticlockwise rotation was considered to be the explanation behind the large scatter in the DT poles (e.g., Poornachandra Rao and Bhalla, 1981). Dhandapani and Subbarao (1992) proposed a Normal-Reverse-Normal (30N-29R-29N) magnetostratigraphic sequence for Deccan flows near Barwani, a few kilometres east of our study area (Figure 1). Such a sequence was also reported from several exposures at the southern side of the Narmada River (Sreenivasa Rao et al., 1985; Dhandapani and Subbarao, 1992). Prasad et al. (1996) validated the sequence in the DND region and found that the basalt flows are of reverse polarity. All of the dykes we studied intruded the reverse polarity lava sequence from the middle part of the N-R-N sequence. The dual polarity of the studied dykes, their cross-cutting relationships (on map), and the gap in the time of emplacement (Sheth et al., 2019) indicate that these dykes were intruded during the upwelling of different batches of tholeiitic magma at different times. Vanderklyusen et al. (2011) argued that DND dykes might have acted as feeders to some of the lower and middle flow sequences from the Western Ghats. Recently, Sheth et al. (2019) supported the hypothesis based on the observed geochemical similarities of these dykes with the flows of Western Ghat sequences. In the present study, the dykes of normal polarity could have acted as feeders to the upper, normally magnetized flows of the Desur, Panhala, and Mahabaleshwar formations.

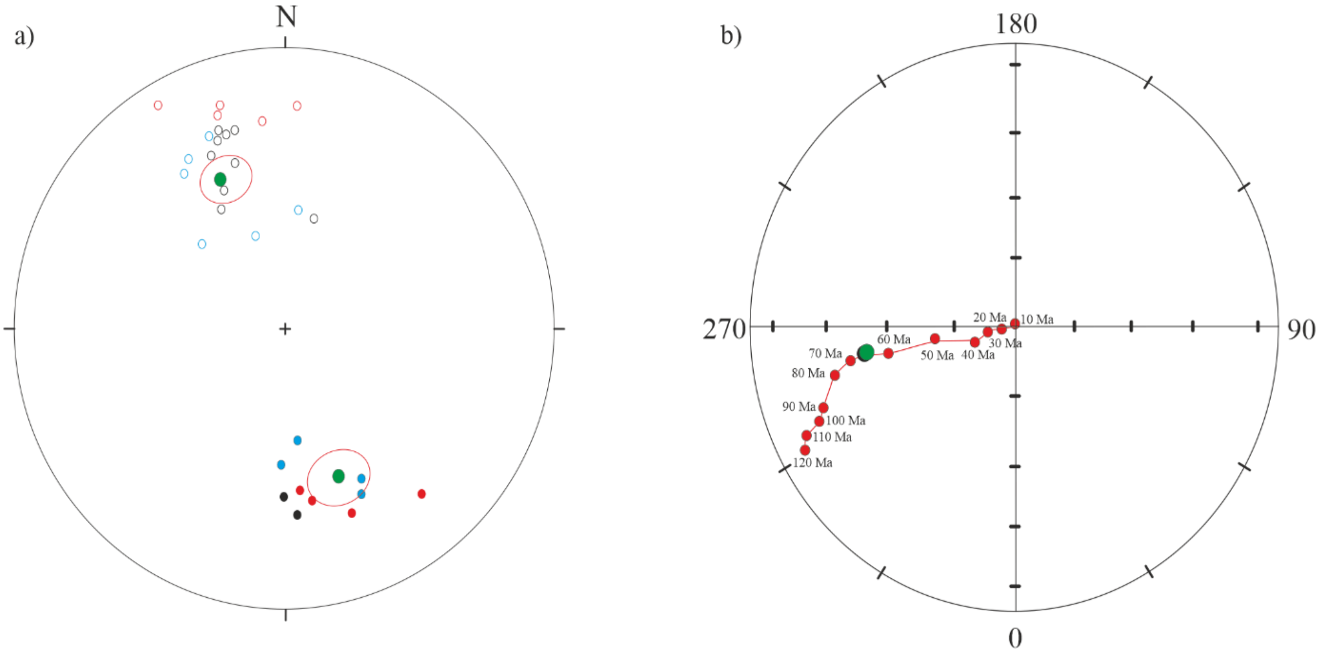

Figure 5. a) Site mean Characteristic Remanent Magnetization (ChRM) directions along with location mean direction in green color and circle of confidence (α_{95}) in red colour of the samples from Nandurbar-Dhule. New data are denoted with red color dot (both hollow and solid respectively for normal and reverse polarity dykes); Data from Prasad et al. (1996) are denoted with blue color dot (both hollow and solid respectively for normal and reverse polarity dykes); Data from Sethna et al. (1999) are denoted with blue color dot (both hollow and solid respectively for normal and reverse polarity dykes). b) The mean paleomagnetic pole data of the Rajmahal Traps (RT) plotted along with the synthetic APWP for India based on GAWPWaP model by Torsvik et al. (2012). The green circle is the pole position from this study [38.3°N, 280.7°E (79.3° W)]. The black solid circle corresponds to the Deccan Mean Pole (DSP, 36.9°N; 78.7°W) derived by Vandamme et al. (1991).

Paleosecular variation

Mean paleomagnetic directions of any lava sequence provide a spot estimate of the ancient-geomagnetic field. Hence, it is possible to have a broad insight into the geomagnetic field and its secular variation. The secular variation can be understood from the angular dispersion of the ChRM directions or that of the VGPs (Cox and Doell, 1964). We followed the second procedure. Assuming the duration of the volcanic pursuit in each of the dykes is in the order of a few thousand years, we calculated the angular dispersion of the VGP's for normal polarity DND dyke to give an estimate of paleosecular variation. Only Region-2 consists of the maximum number of dykes, so we analysed the dispersion of the dykes from that region. The angular dispersion of VGPs has been estimated according to the method used by Doell (1970) following the relationship

$$S_T = (N-1)^{-1/2}\,(\textstyle\sum_{i=1}^{N} \Delta i^{2})$$

Where, S_T= Total angular dispersion, N= Sample number

The observed S_T is related to the 'between site angular dispersion (S_B)' and 'within site dispersion (S_W)' following the equation (Doell, 1970)

$$S_T^2 = S_B^2+S_W^2/\underline{N}$$

Where, $\underline{N}$ = Average sample number.

The estimated angular dispersion from the normal polarity dykes of region-2 is plotted against paleolatitude of the corresponding site in Figure 6. along with the published data from other continents (Hawaii, Galapagos, New Zealand, etc.) and different parts (Mahabaleshwar, Pavagar, etc.) of Deccan province to compare with two theoretical models given by Cox (1970) and Doell (1970). The first theoretical model, termed as model 'C,' expresses a combined effect of a non-dipole field similar to the present one and a dipole wobble of 11^0 (Cox, 1970). The second model demonstrates the effect of dipole wobble only (Doell, 1970) that considers a maximum value of about 11^0 corresponding to that of Hawaii.

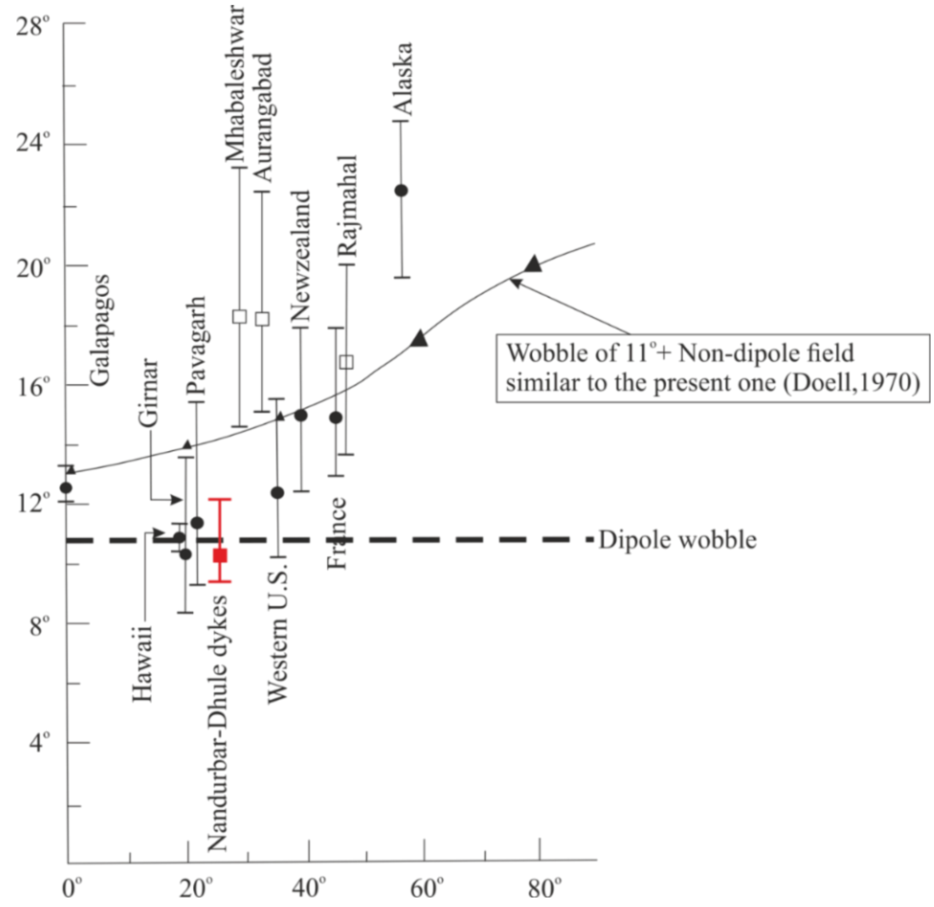

Figure 6. Angular dispersion of VGPs for different Deccan flows (Mt. Girnar, Mt. Pavagarh, Mahabelshwar etc.) and Dhule-Nandurbar Deccan (DND) dykes plotted against paleolatitudes of the sites in addition with data from Western U.S., France, Alaska, Galapagos, Hawaii, New Zealand etc. (Doell, 1970 and references therein).

In this present study, we obtained, $S_T \approx 10.7^0$, $S_B \approx 8.3^0$, and $S_W \approx 12.2^0$. We also calculated the 95% confidence limits for the angular dispersion using the table published by Cox (1969). The involvement of the non-dipole field concerning the dipole field and the dipole wobble cause the angular dispersion. Dispersion of VGP's due to dipole wobble remains constant across different latitudes (Doell, 1970), unlike that of the directions. On the contrary, randomly distributed non-dipole components of uniform size in collaboration with the dipole field across latitudes give rise to dispersion that varies with latitude irrespective of analysed parameters, i.e., poles or directions (Cox, 1970). Here the total observed angular dispersion for the normal field from DND (region-2) dykes can mainly be explained in terms of dipole wobble. However, it is to be noted that total numbers of dykes in region-2 are overestimated because the dykes that we studied cannot be combined with the dykes studied by Sethna et al. (1999) and Prasad et al. (1996) due to lack of proper location data in that literature. If it is possible to identify individual dykes with our studied dykes, then the average sample number for each dyke will increase, and within-site dispersion will decrease accordingly leading to the values that are more consistent with the published data.

From Figure 6, it is clearly evident that angular dispersion has covered a wide range during Deccan volcanism. The angular dispersion during reverse polarity Deccan volcanics from Mahabaleshwar, Khandala, and Aurangabad were caused by the combined effect of a substantial proportion of non-dipole field and that of the dipole wobble. Although effects of minor non-dipole field components are evident from the normal polarity sequence of Mount Girnar and Pavagarh, the observed angular dispersion was mostly due to dipole wobble. Our analysis of DND dykes strengthens the evidence in favour of the effect of the dipole wobble at 11^0.

Continental drift

The paleolatitudes (Figure 7) depict the northward drift of the Indian plate (after Klootwijk, 1976). The youngest and oldest dates for the DND dykes are 63.43 ± 0.44/0.48 Ma and 67.49 ± 0.85/0.89 Ma (Sheth et al., 2019). It implies that the dyke swarm must have been emplaced over a period of at least ~4.06 Ma. The distance between the estimated paleolatitudes corresponding to the dykes and the country rocks is around ~1670 Km. It suggests that the Indian plate may have travelled for at least 1670 Km between the emplacement of the country-rock and the dyke swarm. Sheth et al. (2001a, b) claimed the total duration for Deccan eruption to be 8 Myr (From ~60.5 up to ~68.5 Ma). If the Deccan flow that constitutes the country rocks of the DND swarm got emplaced at the early phase of the Deccan eruption, then the gap between flow emplacement and dyke emplacement could have been around 4 to 5 Ma. Considering the gap and differences in the paleolatitudes of the Deccan flows and the dykes, we calculated a plate velocity of around ≈ 25±8 cm/year during the last stage of Deccan volcanism.

It is a well-known fact that the Indian plate accelerated anomalously since 90 Ma (Torsvik et al., 2000; Barndintzeff et al., 2010) until it faced subduction along the Trans-Tethyan subduction zone (TTSZ) situated near the equator followed by rapid deceleration (Jagoutz et al., 2015). Deccan volcanism and Trans-Tethyan subduction were landmark geodynamical events during this period. According to the multistage collisional model for the India-Eurasia collision, India first collided with TTSZ at around 50-55 Ma and then with Eurasia at ~ 40 Ma (Figure 8). The several ophiolites (Bela, Khost and Muslimbagh) and intra-oceanic Kohistan-Ladakh arc along the northern Indian margin in western Himalaya demonstrate the remnant of TTSZ (Tapponnier et al., 1981; Beck et al., 1996). Recently, Martin et al. (2020) dated Khardung volcanics from northern Kohistan–Ladakh arc using $^{206}Pb/^{238}U$ chronometry and reported 4.46 Ma duration of arc activity between ~ 62-66 Ma at a paleolatitude of 8.1±5.6º N. Given that the timing of India's arrival to the TTSZ is well constrained along with its paleolatitudinal positions since Deccan eruption, both Deccan and TTSZ serve a unique opportunity to verify India's plate velocity since Cretaceous.

If the Indian plate migrated with a velocity of ~ 25±8 cm/year since the emplacement of the DND swarm, it would reach TTSZ around 51-54 Ma. Hence, our estimated plate velocity of ~25±8 cm/year, specifically during the emplacement of Dhule- Nandurbar Deccan (DND) dyke swarm, unlike hitherto reported velocity of ~15/20 cm/year, fully attests to the timing of India's collision with TTSZ situated at 8°N (Martin et al., 2020). Hence, the obtained velocity suggests that the Indian plate must have accelerated further at the late phase of Deccan eruptions.

The estimated faster speed could be caused by the extra-push from the Reunion hotspot (Cande and Stegman, 2011), which is unlikely because such rapid acceleration cannot be explained by the arrival of a mere plume head as argued by Gurnis and Torsvik (1994). Instead, it was more likely to have been triggered by the ridge push coming from the Central Indian Ridge, while combined pull exerted by TTSZ and Khsiroda-Eurasian convergence could have played a major role (Jagoutz et al., 2015).

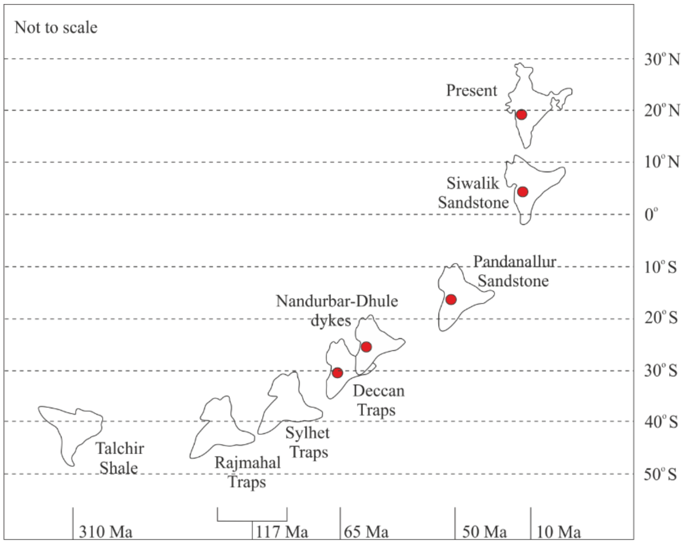

Figure 7. The red circle indicates the paleolatitude position of Indian plate during different time period since Deccan eruption (Redrawn after C. T. Klootwijk, 1976).

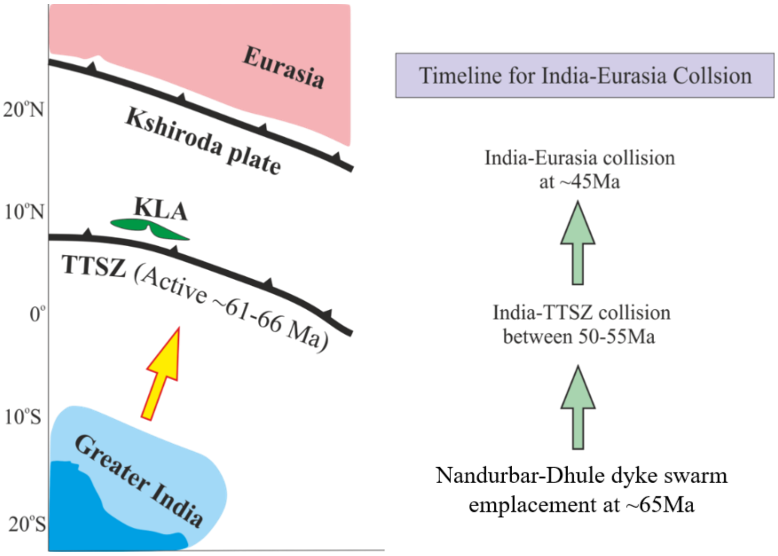

Figure 8. Paleogeographical disposition of Indian plate and Eurasian plate before India-Eurasia collision (modifiedafter Martin et al., 2020). Multistage collisional model suggests that the Indian plate was separated from Kshiroda plate by Trans-Tethyan subduction zone. India collided with TTSZ between 50-55 Ma and then with Eurasia at ~ 45 Ma (Martin et al., 2020, Jagoutz et al., 2015).

Moreover, the weakening of the Indian continental lithosphere-asthenosphere coupling due to contemporaneous volcanic activity facilitated this acceleration (Negi et al., 1986; Pandey and Agrawal, 1999; Kumar et al., 2007; Jagoutz et al., 2015).While the Indian plate started moving faster than usual, it could have experienced an enhanced drag from the attached asthenosphere, resulting in elevated tensional stress on the Indian lithosphere. The signature of such extension is clearly evident from ENE-WSW-oriented DND dykes. Bhattacharji et al. (2004) detected multiple discreet shallow crustal magma chambers (with an average density of ~2.96 g/cm^3) at an average depth of around 6 to 10 km along the west coast and N-S-T lineaments. These anomalies could be genetically linked to a comparatively larger, deep-sourced magma reservoir at a depth of about ~25 km. In the first place, emplacement of such shallow crustal magma chambers demands the crust to be under severe extension. In one of our recent publications, we reported polycentric flow pattern in and around the DND swarm using the Anisotropy of Magnetic Susceptibility

(AMS) analysis (Das et al., 2021). We found subvertical to inclined flow for the majority of the DND dykes, and lateral flows only for three dykes. However, the obtained primary flow axes and absolute flow directions do not essentially demonstrate any pattern as suggested by Gudmundson (1990), Ernst et al. (1995), Fialko and Rubin (1999), etc. Such random flow directions over a regional scale indicate that the magma was pouring out from multiple subsurface magma chambers. Thereby, the polycentric flow seems to be the most plausible scenario that also agrees well with other works (e.g., Bhattacharji et al., 2004; Singh et al., 2014; Sheth et al., 2019 etc.). So, it can be argued that tectonic control was prevalent on the Deccan dykes, especially the N-S-T swarm. Such tectonic extension possibly facilitates the emplacement of the shallow crustal magma chamber, which supplied magma through the dykes.

It is well known that the Proterozoic Narmada-Son lineament (NSL) is a weaker linear crustal zone compared to its stable surroundings and experienced extensional fractures parallel to the lineament in response to lithospheric extension perpendicular to the zone. Through these extensional cracks or fractures, the tholeiitic lava got emplaced and possibly formed DND dyke swarm (Figure 9). Given that the dykes of the DND swarm fed the younger Deccan flows (from the paleomagnetic signatures presented in this study; Prasad et al., 1996; Sethna et al., 1999) and the geochemical evidences presented in Sheth et al. (2019), the hypothesis of fissure fed volcanism being responsible for at least the late stage of Deccan eruption, appear reasonable.

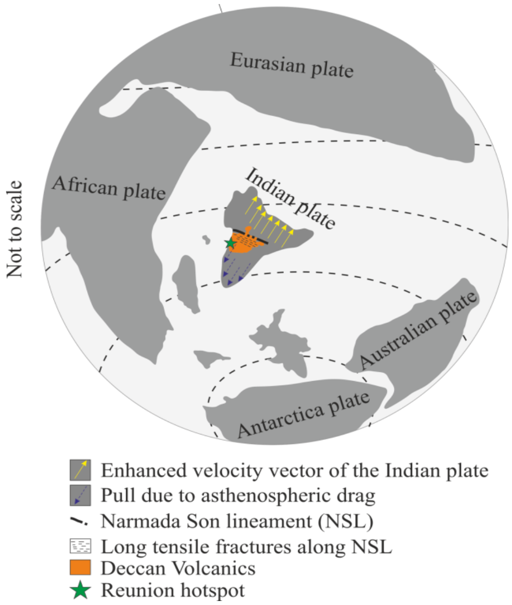

Figure 9. Hypothetical diagram depicting northward drift of Indian plate (modified after Cande and Stegman, 2011). Due to extra push from Reunion plume Indian plate migrated rapidly experiencing extra asthenospheric drag on its lithosphere. As a result, long tensile fractures are created along Narmada-Son lineament facilitating the emplacement of Dhule-Nandurbar Deccan (DND) dyke swarm.

The separation of the Indian subcontinent from the Seychelles Islands through the opening of the Arabian Sea is a significant tectonic event during the youngest phase of Deccan volcanism (Pandey, 2020). Several authors (Courtillot et al., 1986; Vandamme and Courtillot, 1992) proposed a contribution of this tectonic event to the emplacement of the major Deccan Trap dyke swarms. This event might have played an important role in forming weaker crustal conditions along the western part of the Indian subcontinent, making it easy for the dykes to intrude (Ju et al., 2013).

CONCLUSIONS

1. Thermoremanent and IRM curves confirm the presence of magnetite (titanomagnetite) as the remanence carrier.
2. The normal and reverse polarity dykes exhibit ChRM directions at D_m=335.06°, I_m= -43.38° (k=31.12, α_{95}=8.20°, N=77) and D_m=159.54°, I_m= 42.61° (k= 16.24, α_{95}= 8.14, N=52) respectively with an overall paleomagnetic pole at 38.3°N and 79.9°W.
3. The dykes yield a paleolatitude of 25.4°S, which is conformable with previously documented

paleolatitudes. Interestingly, the estimated paleolatitude position plotted younger to the main Deccan event indicating the concluding eruption phase of the Deccan volcanism. The estimated paleolatitude position from the dykes indicates a rapid northward drift of the Indian subcontinent during this late phase of magmatism.

4. A maximum northward drift of the Indian plate is derived to be around 25±8 cm/year during the late phase of Deccan emplacement.
5. Our finding of the rapid motion of the Indian plate would support the newly proposed 'multi-stage collisional' model between India and Eurasia.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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