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Palaeomagnetism of Dyke Swarms from the Deccan Volcanic Province of India

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Palaeomagnetic results of 19 dykes situated south of Narmada river (21°30′ N, 74°15′ E) in Dhule district of the Maharashtra state, India are reported. Of the 19 dykes, 11 dykes exhibit a normal magnetic polarity, and 4 dykes a reverse polarity. The remaining 4 dykes yielded mostly scattered and unstable sample directions. The normal and reverse directions are almost antipodal. The characteristic remanence is indicated to reside in magnetite, and is most probably primary. The N-Pole position corresponding to the mean directions of 11 dykes (7 normal and 4 reversed) based on a minimum of 4 sample characteristic directions per dyke is at 37.2°N, 80.5°W ($A_{95} = 9.7°$). This pole is concordant with the Deccan Superpole, indicating a similar age of magnetization for the Deccan basalt flows and the dykes intruding them. A joint consideration of similarity of palaeopoles of the dykes and the lava flows, magnetic polarity of dykes, and their stratigraphic positions of intrusions in the lava flow sequence support the view that the volcanic activity in the Deccan area spanned a short duration. The post-trappean tectonic activity resulting in the dyke swarms may possibly have coincided with the opening of the Arabian Sea and the rifting of the Seychelles-Mascarene oceanic plateau.

1. Introduction

Since the pioneering work on the palaeomagnetism of Deccan traps (DT) by Clegg *et al.* (1956) and Deutsch *et al.* (1958, 1959), there has been a number of published reports on the palaeomagnetic investigation of DT from different parts of the Deccan Volacanic Province. These investigations have led to a better understanding of the nature of the geomagnetic field relative to Indian sub-continent during the interval of Deccan basalt eruption and the magnetostratigraphy of the flow sequence. The palaeomagnetic data, accumulated over three decades of work, suggest a normal-reverse-normal (NRN) magnetostratigraphy which can be correlated with chrons 30 N-29 R-29 N (Courtillot *et al.*, 1986; Vandamme *et al.*, 1991; Vandamme and Courtillot, 1992). From the large scale topography of the RN boundary (between the chrons 29 R and 29 N) throughout the vast expanse of the lava flows, Vandamme and Courtillot (1992) have inferred the main structural features of the lava pile which are consistent with geochemical and seismic data. According to their conclusion, the palaeomagnetic data suggest a prominent dome in the West Coast dissected by the synform-antiform rift structures parallel to the Narmada-Son rift system. The Narmada-Son system is believed to be the failed arm of a former triple rift system whose junction occurs in the Cambay graben. The other two arms have reached the ocean-opening stage. The rifted western part has been carried away as the Arabian sea formed, and is now found under the sea to the east of the Seychelles islands. It is, however, to be noted that the precise age, total duration and rapid northward movement of India during the period of volcanism still remain disputable. The controversy about the precise age and duration of volcanism has been highlighted recently in the published reports of Dhandapani and Subbarao (1992), Venkatesan *et al.* (1993, 1994), Feraud and Courtillot (1994). From a detailed geochronological studies of 2.5 km thick lava pile in Western Ghats, Duncan and Pyle (1988) have suggested the age to be 67.4 ± 0.7 Ma as compared to 65.5 ± 2.5 Ma reported by Vandamme *et al.* (1991). In both these studies, a short duration of less than 1 Ma straddling the Cretaceous-Tertiary Boundary (KTB), is suggested for the Deccan volcanism. This view has been reinforced in some other studies (Courtillot *et al.*, 1986, 1988; Vandamme and Courtillot, 1992) which, however, is strongly disputed by

Venkatesan *et al.* (1993, 1994) who suggest the duration to be not less than 3 Ma with eruption pre-dating the KTB by at least 1.0 Ma. An upper bound of 3 Ma for a large part of the lava flow sequence was also arrived at by Kono (1973) from a combined statistical analysis of the reversal time scale and emplacement of the flows. A larger duration of more than 6 Ma is favored by Dhandapani and Subbarao (1992) who have identified the lowermost Deccan normal interval with the Cretaceous Long Normal superchron. Thus the debate on age and duration of Deccan volcanism seems to linger requiring further studies on different aspects of volcanic eruption.

Palaeomagnetic studies have so far been confined mainly to the basalt flows. Dykes in the Deccan area have drawn little attention of the investigators. Till date, as far as the authors are aware, only one report (Subbarao *et al.*, 1988) has been published from the dykes of the Deccan area. In order to have a better understanding of the volcanic episode, it is desirable to study the associated intrusive phases. Towards this end, we are presenting palaeomagnetic results from some of the mafic dykes in the Narmada-Tapti tectonic belt of the Deccan Volcanic Province. In the Deccan area, numerous dykes occur in the form of clusters and swarms in the Narmada-Tapti as well as West Coast tectonic belts (Fig. 1). Although no radiometric age data are available for the dykes investigated in this study, Courtillot *et al.* (1988) have reported $^{40}Ar/^{39}Ar$ age of 63.6 ± 0.5 Ma from a dyke in the Narmada-Tapti swarm belt, close to our study area. A few more K-Ar dates reported on the dykes of Deccan area (listed in Table 1) are all from the West Coast belt. The age data suggest a large age bracket from 81 Ma to 34 Ma. Notwithstanding the inherent problems with K-Ar age, some radiometric studies of Deccan basalts indicate a similar K-Ar age ranging

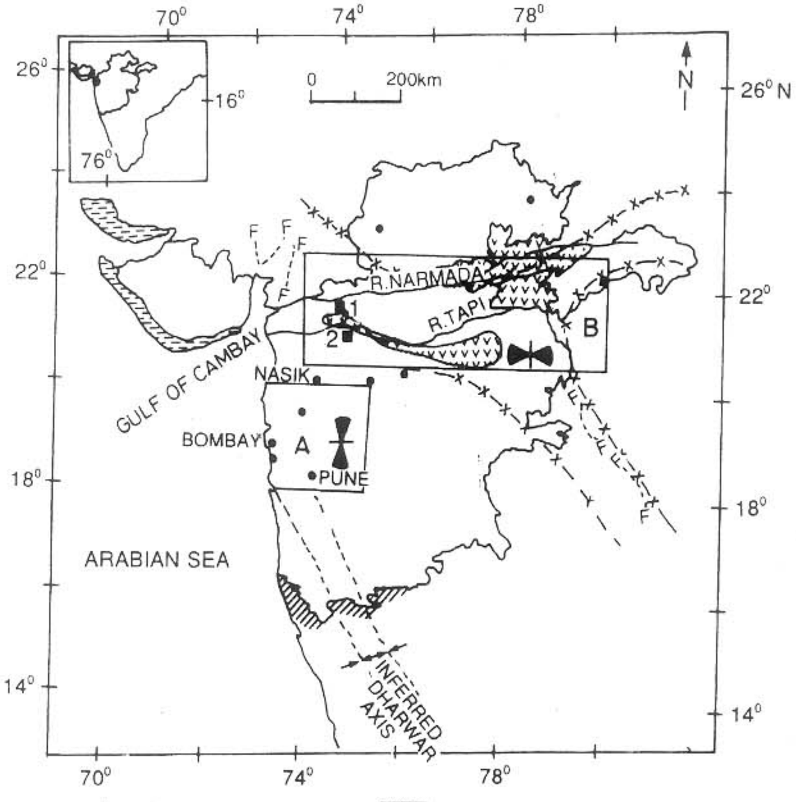


Fig. 1. Generalized geology and important tectonic features of the Deccan Volcanic Province (after Deshmukh and Sehgal, 1988). Areas enclosed by rectangles A, B indicate the dyke swarm belts of the West coast and Narmada-Tapti lineament respectively. Nos. 1 and 2 indicate the location of sampling sites.

Table 1. Radiometric dates of dykes in the Deccan Volcanic Province.

Sr. No.	Locality	Lat.; Long.	K-Ar age (Ma)	Reference
1	Babra, Saurashtra	21°47′ N; 71°16′ E	81.0 ± 3.0	Balasubrahmanyan and Snelling (1981)
2	Gundari, Saurashtra	21°29′ N; 70°55′ E	64.0 ± 2.0	Balasubrahmanyan and Snelling (1981)
3	Pachmari, M.P.	22°30′ N; 78°27′ E	72.0 ± 4.0	Balasubrahmanyan and Snelling (1981)
4	Karjat, Maharashtra	18°53′ N; 73°20′ E	63.5 ± 1.5	Agrawal and Rama (1976)
5	Karjat, Maharashtra	18°53′ N; 73°20′ E	57.0 ± 1.5	Agrawal and Rama (1976)
6	Karjat, Maharashtra	18°53′ N; 73°20′ E	47.2 ± 4.0	Agrawal and Rama (1976)
7	Karjat, Maharashtra	18°53′ N; 73°20′ E	34.1 ± 1.0	Agrawal and Rama (1976)
8	Khandala, Maharashtra	18°44′ N; 73°29′ E	43.2 ± 1.7	Agrawal and Rama (1976)
9	Nagpur, Maharashtra	21°10′ N; 79°12′ E	37.3 ± 1.8	Agrawal and Rama (1976)
10	Nagpur, Maharashtra	21°10′ N; 79°12′ E	47.8 ± 2.3	Agrawal and Rama (1976)
11	Nasik, Maharashtra	19.9°N; 73.8°E	62.0 ± 1.5	Agrawal and Rama (1976)
12	Nasik, Maharashtra	19.9°N; 73.8°E	57.0 ± 2.0	Agrawal and Rama (1976)
13	Saurashtra	21.5°N; 70.9°E	46.0 ± 1.5	Alexander (1981)
14	Pachmari	22.5°N; 78.5°E	61.3 ± 2.0	Alexander (1981)
15	Khalghat		63.6 ± 0.3	Vandamme *et al*. (1991)
16	Lonavala	18°46′ N; 73°44′ E	43.1 ± 6.0	Vandamme *et al*. (1991)
17	Girnar		68.6 ± 2.4	Vandamme *et al*. (1991)
18	Near Barwani (Indore to Bombay Road)	22.0°N; 75°E	63.6 ± 0.5	Courtillot *et al*. (1988)

from 85 Ma to 30 Ma (Agrawal and Rama, 1976; Alexander, 1977, 1981; Kaneoka, 1980). Thus a contemporaneity in the ages of dykes and flows is indicated by the radiometric dates. From geological considerations, however, the dykes represent the post-trap hypabyssal injections (Auden, 1949; Agashe and Gupte, 1972). Palaeomagnetism offers an opportunity to infer any significant time difference between the emplacement of basalt flows and the intrusion of dykes through their palaeomagnetic signatures. Therefore, our main objective in this study has been to obtain a reliable record of the geomagnetic field from the dykes for a comparison with palaeomagnetic record of the Deccan basalt flows.

2. Geology

The effusion of Deccan flood basalts is considered to be the result of reactivated rifting on a pre-existing (Palaeozoic ?) Narmada-Son rift system when material from a hot spot source impinged on the Indian lithosphere (Courtillot *et al*., 1986). Faulting and fracturing of the crust produced a number of lineaments in the Deccan area. Majority of these lineaments, considered as zones of crustal instability, are parallel to the trend of tectonic belts in which they occur. Following the trends of the lineaments, majority of the dykes are roughly aligned in the E-W direction in the Narmada-Tapti belt and in the N-S direction along the West Coast (Fig. 1). Only few dykes deviate from the tectonic trends, suggesting a lineament control over the emplacement of dykes (Deshmukh and Sehgal, 1988).

The geology of the West Coast dykes was first reported by Clark (1869) and that of Narmada-Tapti belt by Blanford (1869). Since then a number of investigators (e.g. Auden, 1949; Krishnamurthy, 1972; Subba Rao, 1972a, b; Krishnamurthy and Cox, 1980; Vishwanathan and Chandrashekharam, 1984 etc.) have studied the petrology and geochemistry of the dykes. The information that has emerged from the above studies and a recent report (Deshmukh and Sehgal, 1988) is summarized below.

Dyke swarms cover areas of 32,500 km^2 and 87,000 km^2 in the Narmada-Tapti and West Coast belts respectively. These dykes are mainly dolerites of tholeiitic character. They generally occupy dilatory tensional fractures which are formed due to tectonic movements in the two tectonic belts. Maximum

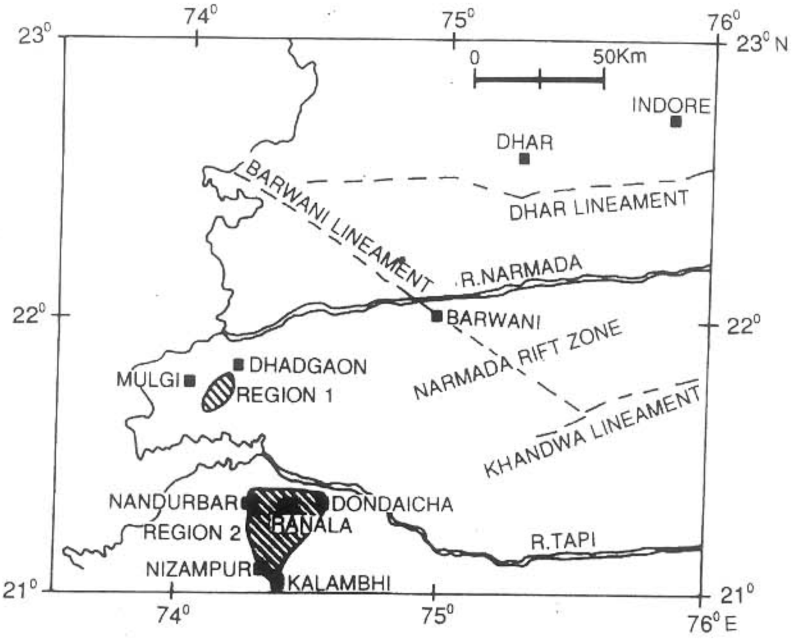


Fig. 2. Sampling localities of Regions 1 and 2 in the Narmada-Tapti tectonic belt.

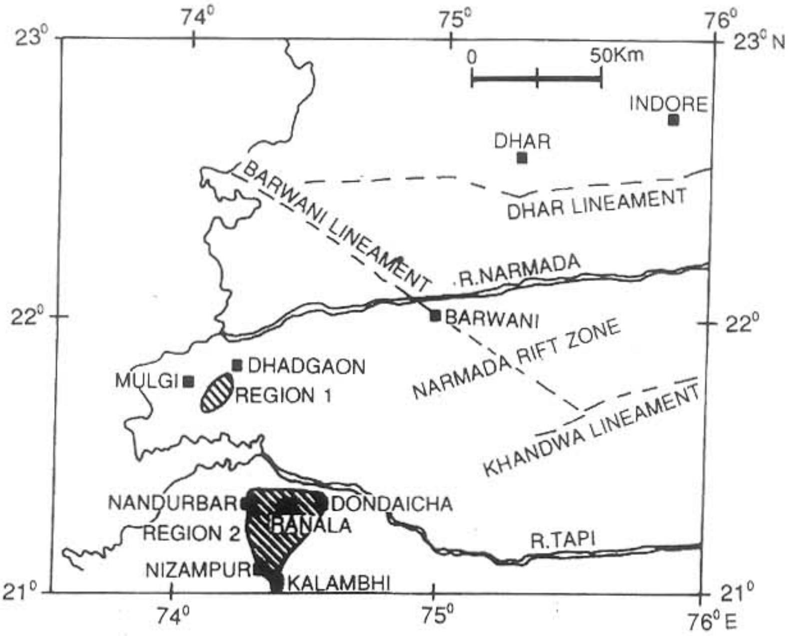
number of dykes occur in the highly disturbed zones of the two belts. The dykes occur as parallel to subparallel linear vertical bodies intruding the lava pile. Majority of the dykes are confined in the lower part of the flow sequence. They generally occur at elevations ranging from 500 m to 700 m, reaching up to 1200 m at some places in the plateau region east of the coastal belt. They occur up to 750 m in Barwani area of the Narmada rift zone (Fig. 2). Widths of dykes vary from a fraction of a meter to 60 m with a majority ranging from 0.5 m to 20 m. They extend linearly over a distance from a few hundred meters to 70 km or more. The dykes show sharp contacts with the basalt flows and have chilled margins. Along their margins they send offshoots and apophyses into the flows. The mineral contents of the dykes are mainly plagioclase, augite, pigeonite and iron oxides with small amounts of olvine and apatite. Pigeonite occurs in significant amount within the host augite crystals as exsolved patches. Such occurrence of pigeonite is rare in the Deccan lava flows (S. F. Sethna, private communication, 1995).

Based on the analyses of available field data, Deshmukh and Sehgal (1988) suggest that the N-S dykes in the West Coast belt are the youngest intrusives, while the E-W, NW-SE and NE-SW dykes represent older intrusive phases in this belt. In the Narmada-Tapti belt, the dykes emplaced along E-W, ENE-WSW and WNW-ESE represent older intrusive phases. A minor proportion of dykes trending N-S, NE-SW and NW-SE directions in this belt are younger in sequence.

3. Sampling and Measurement

Oriented block samples were collected from the E-W trending dykes from two regions (Fig. 2). Region 1 is located south of Narmada river near Dhadgaon area (21°45′ N and 74°15′ E), and region 2 is in the south of Tapti river near Nandurbar and Dondaicha areas (21°15′ N and 74°20′ E). 9 samples of basalt flows from Region 2 were also collected. In the laboratory, block samples were cored and cut into cylindrical specimens of height 2.2 cm and diameter 2.5 cm. In all 133 samples (470 specimens) from 19 dykes were palaeomagnetically investigated. The distribution of samples as per the region is as follows. Region 1:6 dykes (symbol DDA-DDF), 73 samples (224 specimens) with a minimum of 9 samples per dyke. Region 2:13 dykes (symbol DHA-DHM), 60 samples (246 specimens) with a minimum of 4 sample per dyke plus 9 basalt samples (38 specimens).

The natural remanent magnetization (NRM) and intensity (Jn) of specimens were measured with JR



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The natural remanent magnetization (NRM) and intensity (Jn) of specimens were measured with JR spinner magnetometer having a maximum sensitivity of 3 pT and an astatic magnetometer (model LM-1)—both from Geofyzika, Brno, Czech Republic. The astatic magnetometer was used in the NRM measurements for stronger specimens with intensity of the order of 10^{-5} T (7.96 A/m) or more. The NRM directions were highly scattered with their intensities ranging from 0.1 to 3.7 A/m. A few samples, however, yielded comparatively higher intensity in the range of 30 A/m to 65.7 A/m. The strongly magnetized samples showed anomalous directions upon magnetic cleaning. This could perhaps be the result of sampling from an area close to lightning strike. The scattered NRM directions indicated the presence of both normal and reverse magnetizations, suggesting the presence of stable components. Low field susceptibility was measured by Bartington's apparatus (model MS 2) for some representative specimens from all the dykes and Koenigsberger ratio (Qn) was calculated. Susceptibility lies in the range $\times 10^{-2}$ to 6×10^{-2} SI. Qn is greater than 1 for more than 60% of the specimens which suggests the thermoremanence to reside in single to pseudo-single domain size grains (Stacey, 1967) for a majority of the specimens.

Both the alternating field (AF) and thermal demagnetization techniques were used to isolate the characteristic magnetization. Generally 3–6 specimens per sample were subjected to demagnetization. Stepwise thermal demagnetization was carried out by using a Magnetic Vacuum Control System (MAVACS) from Geofyzika, Brno, Czech Republic (for details see Prihoda *et al.*, 1989). In this system, not only the static earth's magnetic field but also its time variations are compensated for by the use of a triaxial Helmholtz's induction coil, rotating coil magnetometer and an induction coil control unit. A heating chamber is provided at the center of the system which enables thermal cleaning in air of about 30 specimens in a near "magnetic vacuum" within ±3 nT in 5 liter volume. AF demagnetization was carried out by using the facility similar to the one described by Creer (1959), available at NGRI, Hyderabad, India and a Molspin demagnetizer.

4. Results and Analysis

Region 1

Thermal demagnetization was carried out in 6 to 10 steps from 100°C to 600°C. A number of specimens yielded unstable directions following the thermal treatment with intensity dropping sharply at 00°C step. This suggests that the remanence in these specimens is probably carried by some form of multi-domain (titano) magnetite. Also, in some specimens the intensity increased significantly at high temperatures above 300°C with directions becoming random in consecutive high temperature steps. This suggests a mineralogical change in the rocks leading to the production of new magnetite from Ti-rich titano-magnetite. Samples which yielded a stable characteristic direction are represented by Fig. 3. The specimens from 2 separate dykes in this figure exhibit a reverse (specimen DDA 6.1a) and a normal (specimen DDD 1.1a) characteristic direction in the temperature range 300°C–500°C. As seen from the figure, the stereonet plot reveals very little change in the direction, but a substantial reduction in the intensity in the above range of temperatures. On the vector diagram (Zidjerveld, 1967), this corresponds to a straight line directed towards the origin, suggesting the recovery of a single component characteristic magnetization. The characteristic direction for this specimen and in all such specimens where a stable end point is attained was computed by taking the mean of directions in the stable range. All the specimens used for thermal treatment were completely demagnetized. In no case more than 1–2% of NRM intensity was left in the specimens after the last step of magnetization.

Unlike the thermal demagnetization, where all the specimens were demagnetized through detailed steps, AF demagnetization was carried out initially on 14 pilot specimens choosing at least 2 specimens from different samples of a dyke by using the facility at NGRI, Hyderabad, India. 10 steps of peak AF fields between 2.5 mT to 100 mT were chosen for this purpose. It was observed that low coercivity secondary components were erased between the peak fields of 2.5 mT–15 mT. A characteristic component was identified mostly between 15 mT–30 mT. The intensity dropped sharply between 2.5–20 mT and tapered off at higher fields. Demagnetization behavior of 2 representative specimens are shown on

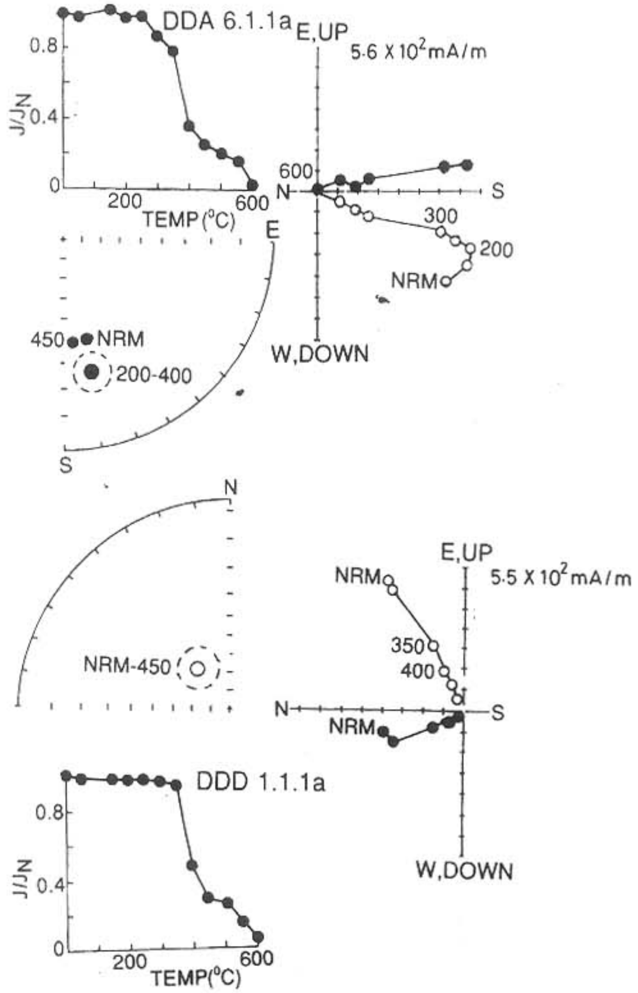
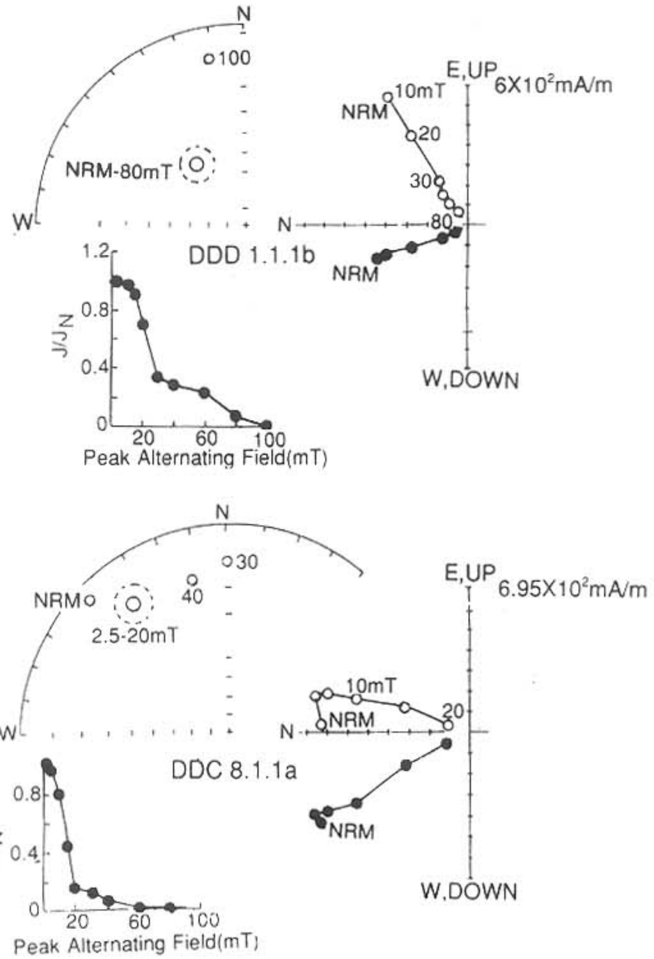


Fig. 3. Thermal demagnetization results of two specimens from region 1. Stereographic projections and intensity decay (left), Zijderveld diagrams (right). On the stereonet, Solid (open) circles are projections on the lower (upper) hemisphere. Dashed outline indicates directions in the temperature intervals shown and have no statistical significance. On the Zijderveld diagrams, open circles are projections of the end points of demagnetization vector on a north-south vertical plane, solid circles on the horizontal plane. J/J_N denotes normalized intensity.

stereonet and vector diagrams in Fig. 4. It is seen that at fields higher than 30 mT, the directions become random and no stable component could be identified. 40 more specimens were subjected to AF treatment through the above detailed steps on Molspin AF demagnetizer when the facility became available at the laboratory in the course of present investigation. No noticeable change in the demagnetization behavior was observed on this unit also. Having observed the consistent behaviour of pilot specimens, rest of the specimens meant for AF treatment were subjected to single step AF demagnetization at 20 mT peak. The directions so obtained were compared with the stable directions obtained through the detailed steps of pilot specimens. If the specimen directions in single step demagnetization were found similar to that revealed by the pilot specimens of the dyke, they have been considered as the characteristic directions. Single step directions widely divergent (>30°) from the pilot stable directions were rejected. 33 samples (109 specimens) yielded characteristic directions from this region.

4.2 Region 2

Samples from this region broadly exhibited a similar behaviour as that of Region 1 after thermal and AF treatments. All specimens in this region were subjected to 6–8 steps of thermal and AF treatments to isolate the stable remanent vector. Dykes of both the normal and reverse polarity magnetizations were



4. AF demagnetization results of two specimens from Region 1. Symbols and other explanations as in Fig. 3 (read "field" in place of "temperature").

entified from this region. Figures 5 and 6 represent the results on a pair of specimens from 2 samples aken from separate dykes. The twin specimens of the sample yielding a normal polarity characteristic agnetization (Figs. 5a and 6a) show northerly and shallow upward directed NRM, migrating systematially to moderately steeper inclinations at higher AFs or temperatures. The direction stabilizes in the AF nge 30–60 mT or temperature range 350°–500°C. The vector diagrams show overlapping coercivity and ocking temperature spectra in the range 10–30 mT and 200°–350°C respectively. However, at higher elds/temperatures a univectorial decay to the origin is indicated. The reverse polarity characteristic ection (Figs. 5b and 6b) was isolated in the AF range 5–20 mT or temperature range 450°–540°C. haracteristic directions were thus isolated from 34 samples (117 specimens) in this region. The basalt ow samples exhibited reverse polarity, but scattered directions similar to the (reversely magnetized) ykes. 5 samples out of a total of 9 yielded a characteristic magnetization.

Fisher's (1953) statistics has been used at each hierarchical levels for averaging the characteristic ecimen directions obtained through thermal and AF demagnetizations. Only those dykes with a nimum of 3 sample characteristic directions and Fisherian parameters, $k > 10$ and $\alpha_{95} < 20°$, have been nsidered acceptable for the calculation of VGPs. Data from only 11 dykes, 7 of normal polarity and 4 reverse polarity, are found consistent with the above criteria. Among the remaining 8 dykes, 4 dykes ave exhibited normal polarity but their means are either based on less than 3 samples, or the associated atistical parameters, $k < 10$ and $\alpha_{95} > 20°$. They are therefore excluded from the palaeopole calculation. Samples from the rest 4 dykes yielded anomalous and highly scattered directions from which the sign of

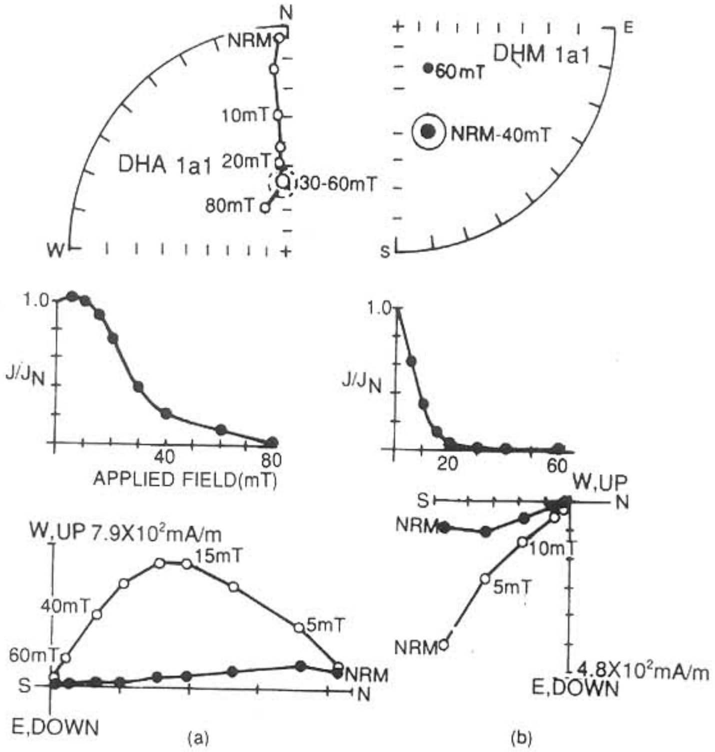


Fig. 5. AF demagnetization results of two specimens from Region 2. Stereonet plot (top), Intensity decay (middle), and Zijderveld diagrams (bottom). Symbols as in Fig. 4.

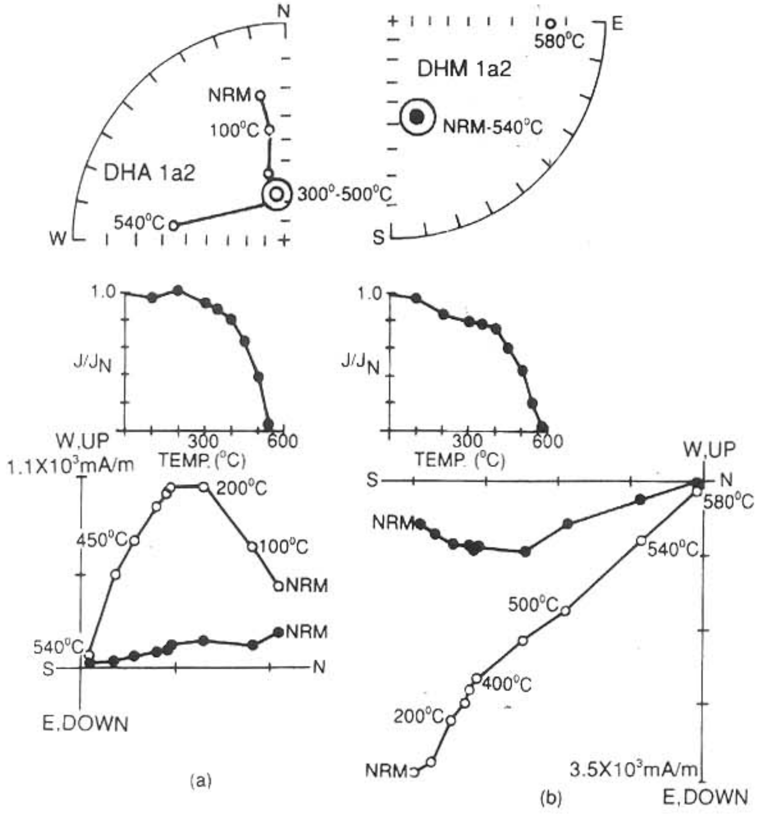


Fig. 6. Thermal demagnetization results of two specimens from Region 2. Other explanations as in Fig. 5.

Table 2. Palaeomagnetic results from Dhule dyke swarms.

Dyke No.	Mean directions (thermal)					Mean directions (AF)					Mean directions (thermal + AF)					VGP			
	D_m	I_m	N	K	α_{95}	D_m	I_m	N	K	α_{95}	D_m	I_m	N	K	α_{95}	Lat. (°N)	Long. (°W)	d_p	d_m
DDA	158	31	10	26.1	9.6	158	29	10	21.5	10.7	159	30	11	30.4	8.4	46.9	75.4	5.2	9.3
DDB	151	30	8	13.1	15.9	157	37	9	13.8	14.4	154	35	9	15.7	13.4	41.7	72.0	8.9	15.4
DDC	341	−18	6	31.5	12.1	343	−25	7	30.1	11.2	342	−22	8	36.2	9.3	52.4	75.9	5.2	9.8
DDD	339	−61	4	58.5	12.1	345	−63	5	73.6	9.0	341	−62	5	117.0	7.1	22.7	90.8	8.5	11.0
DDF*	346	−16	4	14.6	24.9	350	−06	2	—	—	343	−15	4	15.5	24.1	—	—	—	—
DHA	6	−53	5	34.3	13.2	4	−54	4	59.7	12.0	5	−52	5	41.6	12.0	35.9	110.9	1.2	16.4
DHB	317	−54	4	22.9	19.6	310	−57	4	26.3	18.2	314	−55	4	26.1	18.3	18.4	67.6	18.4	26.0
DHC*	341	−39	1	—	—	337	−42	1	—	—	339	−41	1	—	—	—	—	—	—
DHE	176	50	5	29.6	14.3	183	48	6	54.0	9.2	181	50	6	57.5	8.9	37.9	106.8	7.9	11.9
DHF	340	−31	3	106.7	12.0	335	−30	4	66.6	11.3	336	−31	5	85.9	8.3	45.3	72.1	5.2	9.3
DHG	322	−41	4	37.2	15.2	322	−41	5	31.7	13.8	321	−40	5	36.7	12.8	31.8	62.6	9.3	15.4
DHI*	356	−27	1	—	—	350	−18	1	—	—	353	−23	1	—	—	—	—	—	—
DHK	315	−50	4	51.4	12.9	323	−43	5	33.7	13.4	319	−46	5	67.1	9.4	27.2	64.8	7.7	12.0
DHL*	303	−30	4	8.3	33.9	298	−27	3	11.2	38.7	302	−26	4	10.6	29.6	—	—	—	—
DHM	167	53	3	40.2	19.7	162	46	4	44.9	13.9	164	48	4	72.0	10.9	37.3	88.1	9.3	14.2
Mean (R)	159	37	26	16.0	7.3	163	38	29	17.1	6.7	162	38	30	19.4	6.1	43.8	82.2	4.3	7.2
Mean (N)	336	−44	30	13.5	7.4	335	−44	34	15.3	6.5	335	−43	37	15.4	6.2	37.7	76.8	4.8	7.7
Overall mean											338	−44	11	24.6	9.4	37.2	80.5		

Notes: Lat., Long. of the sampling sites: Region 1: 21°45′ N, 74°10′ E. Region 2: 21°20′ N, 74°20′ E.

$K = 23.0$, $A_{95} = 9.7$, s.d. = 16.8.

D_m, I_m: Mean declination, inclination in degrees clockwise from geographic north.

N: Number of samples (dykes in case of overall mean).

K: Fisher's precision parameter.

(R), (N): Reverse, Normal directions.

α_{95}: Circle of confidence at 95% probability level.

d_p, d_m: Semi-axes of the oval of 95% confidence for the VGPs.

Overall mean: Fisherian mean of characteristic dyke directions and VGPs calculated from all the dykes except those with asterisk(*)

polarity could not be inferred unambiguously.

The dyke means with their associated Fisherian parameters are summarized in Table 2. Means calculated separately from the AF and thermal demagnetization results are also included in this Table. The thermal and AF results being in good agreement, have been combined at sample levels to compute dyke means for VGP calculations. The characteristic sample directions and dyke means used for VGP calculations are plotted in Fig. 7. This figure shows a large scatter in the characteristic sample directions and dyke means. The mean, giving unit weight to samples, for the reverse component is at $D_m = 162°$, $I_m = 38°$ ($k = 18.8$, $\alpha_{95} = 6.3°$, $N = 29$ samples), and for the normal component, at $D_m = 337°$, $I_m = -43°$ ($k = 14.7$, $\alpha_{95} = 6.6°$N$= 34$ samples). No tilt correction is required for the present data as the flows intruded by the dykes are almost horizontal (dip 1°–2°) in the sampled area. The mean direction for the basalt flow is at $D = 137°$, $I = 56°$ ($k = 10.6$, $\alpha_{95} = 24.6°$, $N = 5$ samples). The means of normal and reverse directions of dykes depart from antiparallelism by approximately 5°. This could be due either to apparent polar

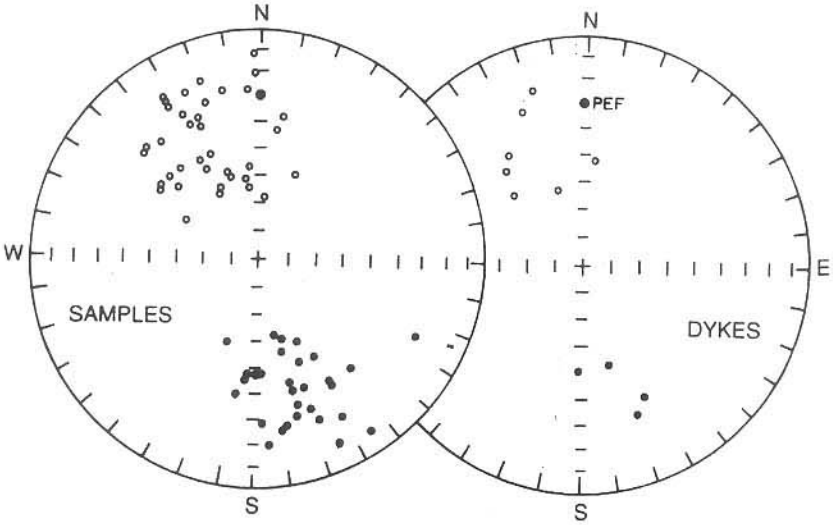


Fig. 7. Characteristic sample and site mean directions. Equal area plot. Symbols as in Fig. 3.

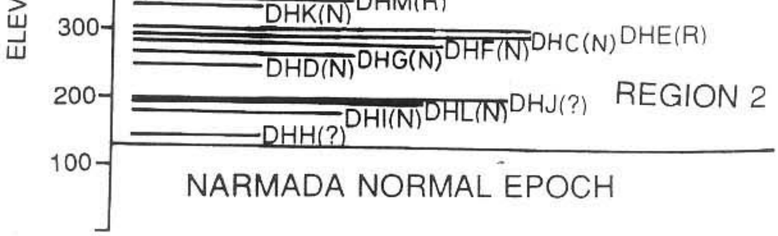


Fig. 8. Generalized magnetostratigraphy of the Deccan lava flows in the south of the Narmada river. The stratigraphic levels of dykes intruding the lava flows are shown by lines. Symbols N and R in the brackets after the dyke nos. indicate the magnetic polarity of the dykes.

Table 3. Palaeomagnetic pole positions from the dykes and flows of Deccan Volcanic Province.

Pole No.	Locality	No. of flows/dykes	Age (Ma)	Magnetic directions			Palaeo-latitude (°S)	N-Pole position				Reference
				D_m	I_m	α_{95}		Lat. (°N)	Long. (°W)	d_p	d_m	
1	Dhule dykes	11	—	338	−44	9.4	26	37.2	80.5	($A_{95} = 9.7°$)		This study
2	Mandaleshwar dykes	5	—	350	−50	5.0	32	37.0	94.0	4.6	6.8	Subbarao *et al*. (1988)
3	Mandaleshwar dykes	3	—	153	44	16.6	27	36.0	74.0	13.0	20.8	Subbarao *et al*. (1988)
4	Mandla and Rajahmundry	12	64.8 ± 1.9	152	48	9.1	—	31.0	71.0	($A_{95} = 9.7°$)		Vandamme and Courtillot (1992)
5	Kalsubai	24	—	152	52	—	33	31.0	79.0	—	—	Khadri *et al*. (1988)
6	Deccan Traps from Nagpur to Bombay	21	19.7 ± 12.0 to 66.2 ± 3.9	147	47	4.6	29	32.5	69.5	($A_{95} = 5.0°$)		Courtillot *et al*. (1986)
7	Dhar Traps	7	62	143	46	5.5	30	29.0	67.0	4.5	7.0	Poornachandra Rao and Bhalla (1981)
				320	−48	—	—	—	—	—	—	
8	Mount Pavagarh	16	67.6 ± 1.7	334	−38	5.4	25	39.0	74.0	4.0	6.8	Verma and Mital (1974)
9	Sagar	—	67.6 ± 2.0	156	40	3.0	25	38.0	73.0	2.2	3.6	Bhalla and Anjaneyulu (1974)
10	Ellichpur	24	61.4 ± 1.8	159	48	5.0	30	35.0	80.0	4.5	6.9	Wensink (1973)
11	Jabalpur to Dindori	13	—	340	−31	4.5	18	46.0	69.0	3.0	5.0	Verma *et al*. (1973)
12	Mount Girnar	14	64 ± 1.9	336	−38	4.4	25	41.0	79.0	3.0	5.0	Verma and Mital (1972)
13	Mahabaleshwar	28	57.1 ± 2.7	160	47	6.7	28	38.3	83.7	5.6	8.6	Kono *et al*. (1972)
14	Amboli	5	61.7 ± 2.1	174	51	10.2	32	41.4	80.0	9.3	13.8	Kono *et al*. (1972)
15	Western Ghats	90	66.6–68.5	152	50	3.8	30	34.0	76.0	3.4	5.1	Wensink and Klootwijk (1971)
16	Aurangabad	25	60	150	48	5.5	30	33.0	73.0	4.7	7.0	Athavale and Anjaneyulu (1972)
17	Jabalpur	8	Mid-Cret.	343	−28	5.0	17	48.0	74.0	3.0	5.5	Verma and Pullaiah (1971)
18	Malwa	—	—	164	49	11.9	32	36.0	90.0	10.3	15.6	Pal *et al*. (1971)
19	Deccan Trap Superpole	163	67.2 ± 6.6	—	—	—	—	36.9	78.7	($A_{95} = 2.4°$)		Vandamme *et al*. (1991)

Notes: Symbols are as given in Table 2.

Ages are as quoted by respective authors or published elsewhere on the same formation.

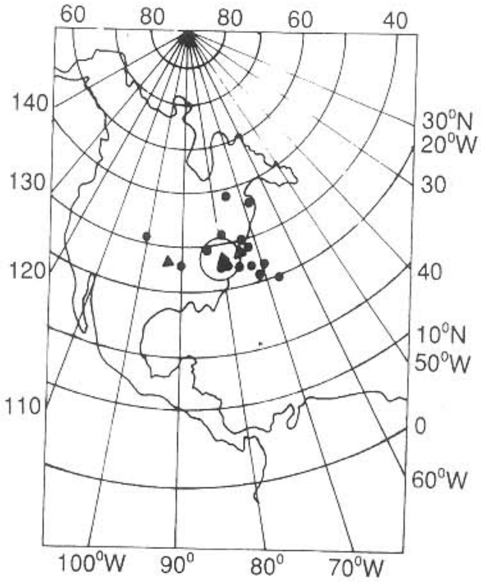


Fig. 9. Pole positions from the Deccan lava flows (circles) and dykes (triangles). The pole from the present study is plotted with its A_{95} confidence circle (see Table 3).

wander between the normal and reverse periods of the geomagnetic field, or a small non-dipole field components. The α_{95} cones of confidence, however, overlap when one of them is inverted to its opposite polarity. Thus the difference in the mean directions corresponding to the normal and reverse polarities do not appear to be statistically significant. We conclude that the present palaeomagnetic data is free from a systematic secondary overprint, and that the secular variation has been adequately averaged out. Inverting the characteristic dyke directions of reverse polarity, the overall mean is obtained at $D_m = 338°$, $I_m = -44°$ ($k = 24.6$, $\alpha_{95} = 9.4°$, $N = 11$ dykes). The resulting palaeolatitude reduced at Nagpur is 25.5°S ± 9°. The final pole position is computed from the dyke VGPs at 37.2°N, 80.5°W ($A_{95} = 9.7°$) This pole is plotted along with the poles from the flows and dykes of the Deccan Volcanic Province (listed in Table 3) in Fig. 9.

5. Discussion

It is probable that the magnetization isolated from the dykes in the present study are primary. AF and thermal cleaning characteristics strongly indicate the remanent magnetization to reside in magnetite. Our results show that both AF and thermally cleaned directions are in excellent agreement and the overall means for normal and reverse components are almost antipodal. All these findings further strengthen our view in the primary nature of the isolated magnetizations. The pole position calculated from this study fall in the same general area as the other scattered DT poles reported from various parts of the Deccan area. The large scatter in the DT poles has often been interpreted (e.g. Poornachandra Rao and Bhalla, 1981) as the rapid northward drift associated with an anticlockwise rotation of India during the period of volcanic eruption. However, after an extensive review of all the palaeomagnetic data gathered during three decades of studies on the Deccan traps, Vandamme *et al.* (1991) have proposed a Deccan Superpole for the period of basalt eruption at 37°N, 79°W ($A_{95} = 2.4°$). This pole is almost coincident with the pole obtained in the present study, suggesting the same age of magnetization for both the basalt flows and the dykes investigated in this study. The contemporaneity of dykes and flows indicated by the radiometric dates is, therefore, supported by the present palaeomagnetic result.

In Fig. 8, the stratigraphic levels of dykes with their polarities are shown in the framework of generalized magnetostratigraphy of the lava flow sequence. The generalized Normal-Reverse-Normal (N-R-N) polarity sequence of the lava flows shown in this figure is unambiguously established in the uthern side of the Narmada river (Sreenivasa Rao *et al.*, 1985; Dhandapani and Subbarao, 1992). The vations of reversal boundaries indicated in the figure have been observed a few tens of kilometers west our sampling localities in a section near Barwani between lat. 21°48′–22°7′ N, long. 74°45′–74°55′ E handapani and Subbarao, 1992). It is assumed here that the above magnetostratigraphic sequence of the va flows is valid in our sampling locality also. This extrapolation seems reasonable as the reverse larity of basalt samples observed in the present study is consistent with the above magnetostratigraphy. e R-N boundary at about 600 m elevation seen in Fig. 8 is reported (Vandamme and Courtillot, 1992) have general validity in the areas around the Narmada rift zone. As shown in Fig. 8, all the dykes are ruding the middle (reversely magnetized) lava pile. A majority of dykes have a normal polarity in cordance with the reverse polarity of the intruded flow sequence. This suggests their intrusion post-ting the emplacement of the lower (normal) and middle (reverse) flow sequence. Out of the 4 reversely gnetized dykes, 2 dykes (DDA and DDB) are indicated to post-date the lower (normal) and a larger part the middle (reverse) flow sequence. The remaining two reverse dykes (DHE and DHM) occur in the wer part of the reverse flow sequence. This correlation of magnetic polarity of dykes with the flows on e one hand, and a perfect concordance of the two palaeopoles on the other, indicates the dyke intrusions one of the episodic events in the semi-permanent Deccan activity. This event appears to have occurred on after the eruption of much of the lava pile. Possibly this intrusive phase marks the end of volcanic tivity in the Deccan area. We, therefore, concur with the view that the volcanic activity in the Deccan lcanic Province may have spanned a very short duration as reported by other investigators (Courtillot *al.*, 1986, 1988; Vandamme and Courtillot, 1992; Feraud and Courtillot, 1994) on the basis of ochronological, palaeontological and palaeomagnetic studies. Obviously, no observable northward ift of India during the period of Deccan volcanism is indicated by the present palaeomagnetic data.

It is pertinent at this point to refer to an earlier study on the dykes of Narmada-Tapti belt (Subbarao *al.*, 1988). From the joint studies of geochemistry and palaeomagnetism, the authors in the above study ave concluded that the dykes of normal and reverse polarities may have acted as feeders to the respective larity lava flows occurring at higher stratigraphic levels. While the present result is compatible with the ove interpretation, the rarity of characteristic features of eruptive fissure (Deshmukh and Sehgal, 1988) oint out a post-lava nature of most of the dykes in the swarm belts. A possible post-trap tectonic activity curring soon after the cessation of Deccan Volcanism was the opening of the Arabian Sea and the rifting the Seychelles-Mascarene oceanic plateau. Courtillot *et al.* (1986) examined the possibility of a causal lationship between this geodynamic event and the Deccan Volcanism. They believed that a peak of agmatic activity observed at about 63 Ma in the Seychelles probably corresponded to the end of Deccan lcanism and/or to the initiation of rifting in the Arabian Sea. Their prediction is reported (Vandamme d Courtillot, 1992) to be confirmed by deep sea drilling during Leg 115 of the ocean drilling program DP) whereby the western extent of the Deccan traps is found to the east of the Seychelles islands under e sea. The intrusion of dyke swarms in weaker crustal zones of the western part of India may be attributed this geodynamic event. A complete picture of this intrusive phase in the Deccan basalt, however, could reconstructed only after a systematic geochronological study in the two tectonic belts coupled with a tailed palaeomagnetic study in the West Coast. Also desirable is the palaeomagnetic investigation of e dykes whose trends deviate significantly from the dominant tectonic trends in the areas of their ccurrence with support from radiometric dating.

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