ELSEVIER

Physics of the Earth and Planetary Interiors 133 (2002) 111–125

PHYSICS OF THE EARTH AND PLANETARY INTERIORS

www.elsevier.com/locate/pepi

Palaeomagnetic and rock magnetic studies on the dykes of Goa, west coast of Indian Precambrian Shield

S.K. Patil*, D.R.K. Rao

Indian Institute of Geomagnetism, Dr. Nanabhai Moos Marg, Colaba, Mumbai 400005, India

Received 18 March 2002; received in revised form 9 May 2002; accepted 1 July 2002

Abstract

Detailed alternating field (AF) and thermal demagnetization techniques on 120 samples belonging to 10 dykes of the Goa region along the west coast of the Indian Precambrian Shield, have yielded characteristic remanent magnetization (ChRM) directions from 9 dykes of which 6 dykes exhibited a reverse magnetic polarity direction ($D = 150°$, $I = 44.30°$, $k = 58$, $\alpha_{95} = 5.8$, $N = 6$ dykes), while 3 dykes exhibited normal polarity $D = 351°$, $I = -50°$, $k = 21$, $\alpha_{95} = 14.9$, $N = 3$ dykes) direction. The remaining 1 dyke has shown stable direction, but with a strong overprint of the present earth field (PEF) direction, which could not be removed by either AF or thermal cleaning techniques. A Palaeomagnetic pole, computed by averaging the VGPs of 9 dykes is situated at 41.2°N 78.1°W ($N = 9$ dykes; $A_{95} = 9.81°$), which is close to that of the Deccan super pole (36.9°N, 78.8°W), suggesting that the dykes in the Goa region are related to the Deccan basaltic eruptions. Recently published $^{40}Ar/^{39}Ar$ dating on the normal polarity dykes of the studied area have assigned the ages as 62.8 ± 0.2 Ma. These results demonstrate that the Deccan magnetism continued to affect western India for at least 1–2 Ma after the peak Deccan eruption during the *K–T* boundary. On the basis of published geological and geochemical information along with our Palaeomagnetic results, these intrusive bodies could be attributed as the feeders for the uppermost formations of Wai subgroup of the Western Ghat Deccan basalts, or to the major geodynamic events such as the opening of the Arabian Sea and the rifting of the Seychelles–Mascarene oceanic plateau, which occurred soon after the cessation of the Deccan volcanism. Rock magnetic experiments such as the Lowrie–Fuller test along with low-temperature magnetic susceptibility and isothermal remanent magnetization (IRM) measurements have identified single domain (SD) type titano-magnetite as the major characteristic remanent magnetization carrying magnetic mineral in the dyke samples.

Keywords: Palaeomagnetism; Deccan traps; Precambrian Shield; Feeder dykes; *K–T* boundary

1. Introduction

In recent years Palaeomagnetic investigations on dyke swarms have received much attention due to their scope and application in differentiating dykes of different generations and establishing their emplacement ages as well as related crystal evolution and tectonics. The Indian Precambrian Shield hosts different generations of dykes ranging from early Proterozoic to Phanerozoic. Based on the available geochronological data, Murthy (1995) grouped the dykes of Peninsular India into five generations of which four are related to Proterozoic magmatism at (i) 2400–2000; (ii) 1900–1700; (iii) 1600–1400, and (iv) 1400–1200 Ma while the fifth generation is related to Phanerozoic magmatism at 475–70 Ma, indicating

* Corresponding author. Tel.: +91-22-21-89-053; fax: +91-22-21-89-568.
E-mail address: skpatil@iig.iigm.res.in (S.K. Patil).

0031-9201/02/$ – see front matter © 2002 Published by Elsevier Science B.V.
PII: S0031-9201(02)00094-8

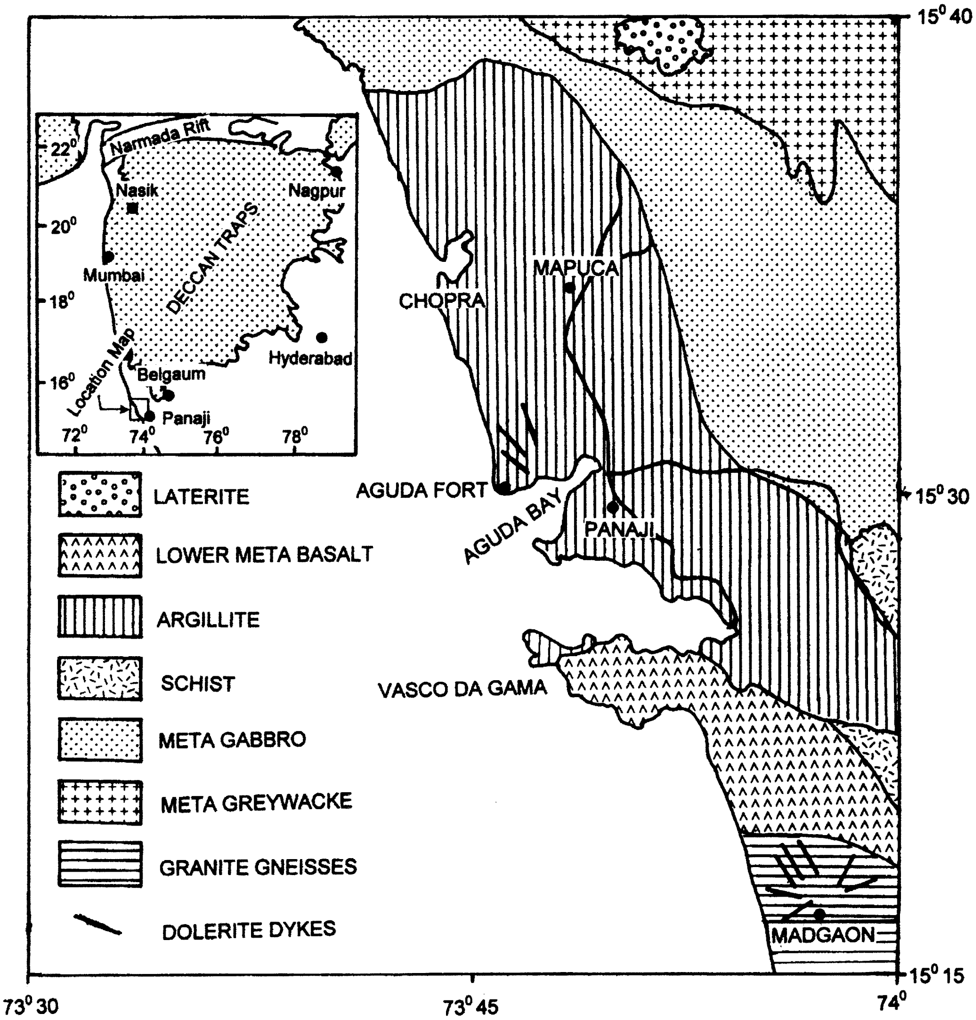

Fig. 1. Geological map of Goa region showing the locations of the dykes.

that some of them belong to the Deccan trap magmatism. Compared to geological and geochemical studies on these dykes, geochronological and palaeomagnetic studies are very scanty. Moreover, petrological and geochemical studies on the dykes cannot be used for age correlation, so geochronological and palaeomagnetic studies on the dykes are getting higher priority in establishing magnetic episodes and their correlation with regional and global tectonics. In an attempt to classify the dykes on the basis of their magnetic signatures, we have undertaken a project to carry out Palaeomagnetic and rock magnetic studies on the mafic dykes intruded into the Dharwar craton along a subtransect, which runs roughly eastwest from Raichur to Goa in the Indian Precambrian Shield. In this communication the first Palaeomagnetic results on the dolerite dykes, in the Goa region along the west coast of India (Fig. 1) are presented.

2. Geology of the area

The Goa region is covered by the Precambrian rocks represented by granite gneiss, quartzite, phyllites, schists, metagraywackes and banded hematite quartzites. Geneissic granite of the Peninsular

Geneissic Complex is exposed around Madgaon in the south Goa. The rocks of Dharwar Super Group overlie the Peninsular gneiss and occupy a major part of the studied area. The regional trend of these Precambrian rocks are NNW–SSE in the north and EW in the south. The Deccan traps cover these formations in the northeast part of Goa state, and laterite capping of variable thickness occurs from the high plateaus to sea level. Quaternary coastal sand occurs in several places along the western coast. Iyer et al. (1990) observed three episodes of folding of the country rocks along NW–SE, E–W and ESE–WNW directions, and noted that the majority of the lineaments trended NW–SE, NE–SW and a few towards ENE–WSW. The majority of basic dykes exposed along the coast follow the NNW–SSE trend and occupy the dilations in the domal upwarps in the Peninsular gneiss basement between the major greenstone belt downwarps (Murthy, 1995). Petrographically two types of dykes have been noticed by Iyer et al. (1990). They are dolerite and basalt dykes, with the former dominant at places cutting across the basalts. The dolerite dykes are medium to coarse grained with porphyritic, sub-ophitic and glomeroporphyritic textures. Plagioclase is most dominant, followed by pyroxene and few olivine and opaques. In contrast, the basalts are fine grained with intergrannular and microporphyritic textures formed by plagioclase and pyroxene. As all the dykes intrude the Precambrian basement, their ages are only speculative. However, on the basis of $^{40}Ar/^{39}Ar$ data associated with geochemical studies, Widdowson et al. (2000), described (some of) the Goan dykes as feeders to the younger formations of the Wai subgroup of Deccan basalts, assigning an Early Palaeocene age.

The widths of the dykes in the present study range from 20 to 30 m and strike trends NW–SE (7 dykes) to NNE–SSW (3 dykes) extending over a few kilometres. The dyke contacts are sharp against the country rocks such as granite Gneisses and metagraywacks at Madgaon and Aguda Fort Beach respectively.

3. Field work and laboratory measurements

The 120 oriented block samples were collected using a Brunton compass from 7 dykes of Madgaon region (15°16′N; 73°58′E), 3 dykes of Aguda Fort Beach (15°30′N; 73°46′E) and from the country rocks into which the dykes have intruded. From the total of 120 samples, 93 samples belong to 10 dykes and remaining 27 samples to the country rocks such as Argillites and granitic Gneisses. The Madgaon dyke samples are fresh as the samples that were collected from excavated quarries, whereas the Aguda Fort dykes are found to be somewhat weathered as these dykes are along the sea coast. The in situ magnetic susceptibilities were measured with a portable Kappabridge along the dykes and adjoining the country rocks. It was noticed that the dyke susceptibilities are an order of magnitude higher than those of the country rocks. This also helped to identify the margins of the dykes in the field.

In the laboratory, the oriented samples were cored and shaped into standard cylindrical specimens of 2.2 cm length and 2.5 cm diameter. A minimum of five specimens per sample were used in Palaeomagnetic measurements. Magnetic susceptibility of all the specimens were measured by using the Bartington susceptibility meter (MS-2B). Remanence directions including natural remanent magnetization (NRM) intensities were measured with JR-5A Spinner magnetometer (M/S Agico, Czech Republic) with a sensitivity of 3 pT. The stability of NRM was tested by thermal (MAVACS, Geofyzica, Brono) and by AF demagnetization methods (M/S Molspin AF demagnetizer). Isothermal remanent magnetizations (IRM) on representative specimens were studied with pulse magnetizer manufactured by M/S Molspin, England and low-temperature susceptibilities were determined by the method developed by Radhakrishnamurthy (1985).

4. Results and analysis

Initially, 40 specimens (20 samples) representing all 10 dykes and country rocks have been selected for AF pilot studies. Eleven steps of peak AF fields (2.5, 5, 7.5, 10, 15, 20, 30.40, 60, 80 and 100 mT) were applied on the pilot samples to yield the characteristic remanent directions. For thermal pilot demagnetizations, 25 specimens (20 samples) were selected and demagnetizations were carried out in 10 steps (100, 200, 300, 350, 400, 450, 500, 560, 585 and 600 °C). Prior to demagnetizations of the specimens, their room temperature magnetic susceptibilities (k) and

Table 1
Statistical parameters of NRM intensity, susceptibility and Q-ratios for dykes and country rocks (Argillites and Gneisses)

Dyke no.	NRM (A/m)				Sus (*10E−6 SI)				Q-ratio				No. of specimens
	Minimum	Maximum	Medium	Mean	Minimum	Maximum	Medium	Mean	Minimum	Maximum	Medium	Mean	
M1	1.23	1.96	1.58	1.58	50550	61150	59075	58025	0.613	0.809	0.67	0.683	22
M2	2.70	5.91	5.11	4.71	63400	69250	66175	66250	1.024	2.343	1.898	1.791	28
M3	3.62	6.46	4.18	4.47	36150	50350	40200	42217	2.252	4.312	2.424	2.702	24
M4	0.80	7.46	1.38	2.37	35350	47150	38875	40742	0.566	4.909	0.738	1.505	25
MS	3.55	5.50	5.04	4.70	40900	53500	49950	48550	2.157	2.63	2.573	2.425	20
M6	1.82	2.63	2.25	2.24	21400	29350	25575	25475	1.884	3.083	2.013	2.249	18
M7	1.85	6.78	5.78	4.57	46050	49700	49600	48810	0.939	3.428	3.156	2.364	27
A1	1.22	2.02	1.65	1.64	41700	42800	42275	42262	0.732	1.187	0.986	0.973	22
A2	0.52	0.66	0.58	0.58	16800	27850	23600	22220	0.562	0.897	0.615	0.682	28
A3	2.72	4.17	3.52	3.47	23350	30450	24350	25750	2.37	4.487	3.639	3.465	27
Argillite	0.0001	0.0001	0.0001	0.0001	238	413	244	298	0.009	0.014	0.011	0.011	15
Gneisses	0.0009	0.0028	0.0009	0.0009	246	346	331	308	0.069	0.087	0.077	0.078	16

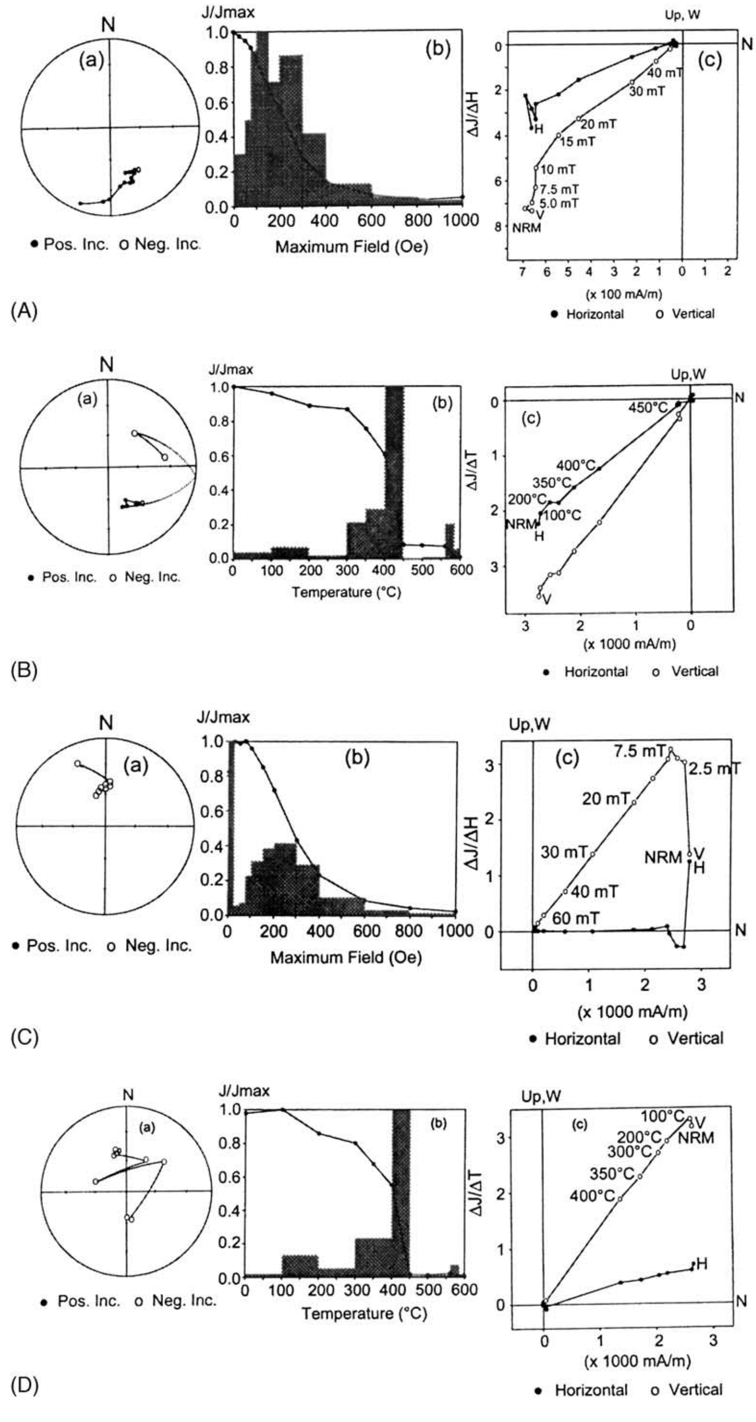

Fig. 2. (A) and (B) represent AF and thermal demagnetization results of the specimens from the reverse polarity dyke respectively, (C) and (D) represent AF and thermal demagnetization results of the specimens from the normal polarity dyke, respectively: (a) stereographic projections; (b) normalized intensity decay (J/J_{max}) along with PTRM (hatched histograms, $\Delta J/\Delta H$ for AF demagnetizations and $\Delta J/\Delta T$ for thermal demagnetizations), and (c) Zijderveld diagram.

Table 2
Pelaeomagnetic results from the Goa dykes

Dyke no.	Mean directions (AF)					Mean direction (thermal)					Mean directions (AF + thermal)					VGP			
	Dm	Im	K	α_{95}	N (n)	Dm	Im	K	α_{95}	N (n)	Dm	Im	K	α_{95}	N	Latitude (°N)	Longitude (°W)	dp	Dm
M1	161	34	34	8.5	12 (22)	157	43	38	8.4	12 (18)	160	38	33	5.9	12	48	77	4.1	7
M2	160	37	50	7.4	9 (22)	157	38	52	7.2	9 (14)	158	38	53	4.8	9	48	75	3.3	5.7
M3	149	57	59	6.8	9 (18)	146	57	229	3.4	9 (13)	147	57	99	3.5	9	28	77	3.7	5.1
M4	141	50	21	15	11 (22)	137	48	20	16	11 (18)	139	49	22	9.5	11	30	65	8.3	12.6
M5	355	−66	37	8.5	9 (12)	343	−64	31	10	8 (14)	349	−66	35	6.1	9	26	98	8	9.9
M6	145	47	81	28	9 (17)	137	47	272	15	9 (13)	141	47	148	7.6	9	32	65	6.3	9.8
M7	155	32	188	4	8 (17)	150	36	84	6.6	8 (15)	152	34	108	3.7	8	46	66	2.4	4.2
A1	348	−28	107	5.4	8 (14)	341	−30	156	4.9	8 (13)	345	−29	110	3.7	8	56	80	2.2	4.1
A2[a]	348	32	37	8.6	9 (17)	350	53	44	7.9	9 (15)	349	42	23	7.3	9	76	27	5.5	9
A3	3.2	−56	55	7	9 (19)	2	−55	48	8.1	8 (16)	3	−56	55	4.9	9	38	109	5	7
Mean of reverse polarity dykes											150.3	44.3	58	5.8	58	38.8	70.6		
Mean of normal polarity dykes											351	−50.1	21	14.9	26	40.5	97.0		
Over all mean											156.1	46.7			9	41.2	78.1	(A_{95}=9.81°)	

Dm, Im: mean declination, inclination in degrees clockwise from geographic north; N (n): number of samples (specimens), N: indicates the number of dykes in the case of overall mean, K: Fisher's precision parameter.

[a] A2 dyke is not considered in the calculation of the overall mean.

NRM directions along with remanence intensities (Mo) have been measured and Koenigsberger ratios (Q-ratio = Mo/kH) were calculated.

The NRM intensities, susceptibilities, Q-ratios along with the number of specimens for each of the dykes (M1–M7 and A1–A3) and the country rocks (Gneisses and Argillites) are given in Table 1. From the results in Table 1, it can be noticed that the susceptibilities and the NRM intensities of dyke samples are higher than those of the country rocks. The mean NRM intensities for the dykes range from 0.58 to 4.71 A/m whereas for the country rocks the similar intensities ranges from 0.0001 to 0.0009 A/m, while the magnetic susceptibility is two-order higher for the dykes than those of country rocks. Q-ratio is more than or nearly 1 for the dykes and less than 1 (0.011–0.078) for the country rocks. High Q-values indicate that dykes samples are suitable for Palaeomagnetic studies. Pilot AF and thermal demagnetizations on the country rocks did not yield any stable directions and hence Palaeomagnetic studies on the country rocks were not carried out further.

Almost all the samples belonging to 9 dykes have shown good grouping with in-site (dyke) as well as between-sites (dykes), after the removal of a very small secondary component of viscous origin. This viscous component was successfully erased by applying the ac peak fields of about 10 mT or by thermal demagnetization step at 100 °C. The AF demagnetization spectra on the pilot specimens have shown that the coercivity of NRM is generally high, with medium destructive fields (MDF) of about 20–30 mT, suggesting the carrier of remanence is predominantly single domain (SD) to pseudo single domain titano-magnetite (Dunlop and Ozdemir, 1997). Six dykes from the Madgaon area, M1–M7 (except dyke M5), have shown reverse polarity directions with positive inclinations, whereas two Aguda Fort dykes A1 and A3 along with Madgao's M5 dyke have yielded normal polarity with medium negative inclinations. Fig. 2(A) shows a typical AF demagnetization behavior for the reverse polarity dyke samples. A lower coercivity component is removed in the AF fields of about 7.5 mT and characteristic directions are obtained between 10 and 40 mT ranges. NRM intensity is decreased to 50% at the fields of 20 mT, and further reduction to less than 10% at 60 mT; and at above fields the directions are randomized with gradual intensity decay. The orthogonal vector (Zijderveld, 1967) diagram shows 10–60 mT range correspond to a straight line directing towards the origin suggesting the recovery of a single stable component. Fig. 2(B) represents the thermal demagnetization response on these dyke samples. From the Fig. 2(B), it can be noticed that lower unblocking temperature component is removed at or about 200 °C and the stable characteristic remanent magnetization (ChRM) directions were unblocked in the temperature ranges of 300–450 °C. At the 450 °C step, the NRM intensity dropped steeply to less than 10%, indicating that the ChRM resides mostly in the titano-magnetite. After the heating step of 560 °C, the directions moved abnormally towards northwest directions showing negative inclinations.

In Fig. 2(C) and (D) the response of AF and thermal demagnetizations respectively on the normal polarity exhibiting dyke specimens from Aguda Fort dykes are depicted. In the case of dyke Al specimen, lower coercivity and low blocking temperature components of secondary origin are removed at 7.5 mT and l00 °C respectively and the stable component was found in 7.5–100 mT and 100–400 °C ranges. The ChRM directions are found N–NNW declination along with intermediate negative inclinations (Fig. 2(C)). Less than 1% NRM intensity remained after applying the 100 mT peak AF field. In the thermal case, intensity was reduced to zero at 450 °C, suggesting the titano-magnetite as the major magnetic mineral carrying the ChRM directions; then further increase of temperature-step directions were scattered indicating mineralogical changes in the samples.

The dyke A2 shows stable directions ($D = 349°$, $I = 42°$), but overprinted by the present earth's field (PEF) direction. The AF and thermal demagnetizations could not remove the powerful PEF component from these samples (not illustrated with figure).

Principal component analysis (Kirshvink, 1980) has been used to get stable directions from the pilot AF and thermal demagnetizations. Maximum angular deviations for each magnetic component determination were found, in most cases, to be smaller than 5°. After examining these pilot results, AF peak fields of 30, 40 and 50 mT and temperatures of 350, 400 and 500 °C were applied to the remaining specimen to get the ChRMs. Fisher's (1953) statistics were applied at each hierarchical level for averaging the ChRMs obtained through thermal and AF demagnetizations. The dyke means with their associated Fisherian parameters are summarized in Table 2. Means calculated separately from AF and thermal demagnetization results are also included in the Table. The AF and thermal cleaning methods are found equally effective in isolating ChRMs from the samples and are in good agreement with each other. Both the results are combined at sample level to compute dyke means. The reverse polarity mean directions are computed as $D = 150.3°$, $I = 44.3°$ ($k = 58$, $\alpha_{95} = 5.8$, $N = 6$ dykes). The isolated normal polarity mean vector is $D = 351.0°$, $I = -50.0°$ ($k = 21$, $\alpha_{95} = 14.9$, $N = 3$ dykes). The ChRMs for the dykes are plotted in Fig. 3. The mean of normal and reverse polarity directions depart from the perfect antipodal situation by approximately 5°, which could be due to either apparent polar wander between the normal and reverse periods of the geomagnetic field, or due to the minor secondary components which could not be removed properly (especially from the normal polarity dykes A1 and A3). However, the α_{95} confidence cones overlap when one of them is inverted to its opposite polarity, showing that the difference in the mean directions do not appear statistically significant. Inverting the characteristic dyke directions of normal polarity, the overall mean is obtained at $D = 156.1°$ $I = 46.7°$ ($A_{95} = 9.81°$, $N = 9$ dykes). The resulting palaeolatitude reduced at Nagpur (latitude 21.1°N; longitude 79.0°E) is 24.2°S.

As all the sampled dykes were observed in the field to be vertical and were not tilted after their intrusions,

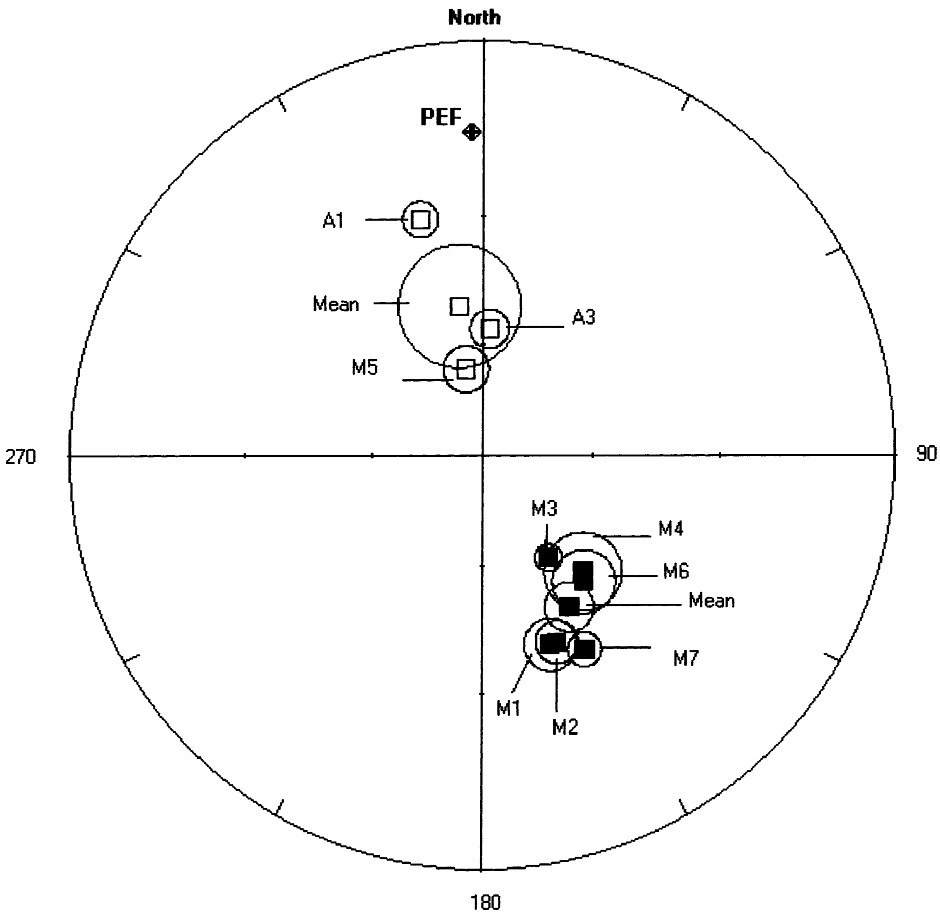

Fig. 3. Characteristic mean directions of three normal polarity and six reverse polarity dykes along with their corresponding α_{95} confidence circle. Open (full) squares indicate projections in the upper (lower) hemisphere.

no tilt and tectonic corrections were applied on the Palaeomagnetic data.

5. Rock magnetic studies

Low-temperature magnetic studies, isothermal remanence magnetizations and the Lowrie–Fuller (1971) test were conducted on the representative samples to understand the magnetic mineralogy and their grain-sizes which are carrying the stable ChRMs in the samples.

Radhakrishnamurthy (1985) developed a simple technique of observing the variation of susceptibility between liquid nitrogen (−196 °C or 77 K) and room temperature (27 °C or 300 K) that can provide information about the composition and the grain-size distribution of magnetic minerals in the igneous rocks. In this experiment the specimen is dipped for about 2 min in the liquid nitrogen and then is transferred into the receiving unit of the susceptibility-bridge. A spot reading at −196 °C for the specimen can be noted quickly by transferring the cooled one into the pickup coil. After this, the susceptibility values are continuously noted while the specimen warms up from liquid nitrogen temperature to the room temperature. Fig. 4(A) show the master curves on using the technique. The multi-domain (MD) magnetite, if present in the sample, shows a peak characteristic susceptibility at −153 °C (120 K), starting with a relative susceptibility value (RS $= k_{-196\,^{\circ}\mathrm{C}}/k_{27\,^{\circ}\mathrm{C}}$) of about 0.4–0.5. On the other hand, single domain type titano-magnetite, TM60–TM70 grains show very low values of RS around 0.1 and TM30–TM40 grains exhibit 0.4–0.7, then gradually reach the unity value at room temperature without showing any peak. In the present study 10 specimens belonging to 10 dykes were selected and low-temperature studies were carried out as described above. From the Fig. 4(B) it can be noticed that, majority of the specimens from 6 dykes (M1, M2, M5, M6 M7 and A3) show TM30–TM40 type magnetic grains, and 2 dykes A1 and M3 exhibit TM60 type magnetic grains. The other 2 dykes M4 and A2 represent the CD or TM10 type magnetic grains.

A pulse magnetizer with a maximum field of 1 T has been used for the isothermal remanence acquisition. The specimens were magnetized by increasing fields in steps from 50 to 1000 mT, and the intensity

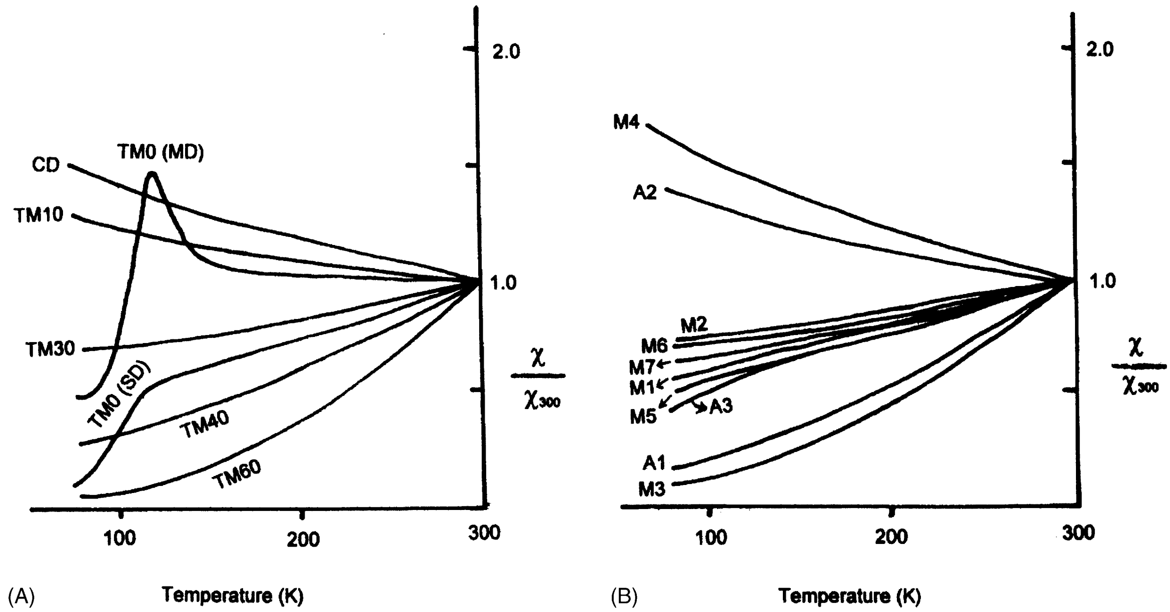

Fig. 4. Normalized susceptibility variations with temperature (from liquid nitrogen temperature to the room temperature): (A) master curves proposed by Radhakrishnamurthy (1985), and (B) results from the Goa dykes samples.

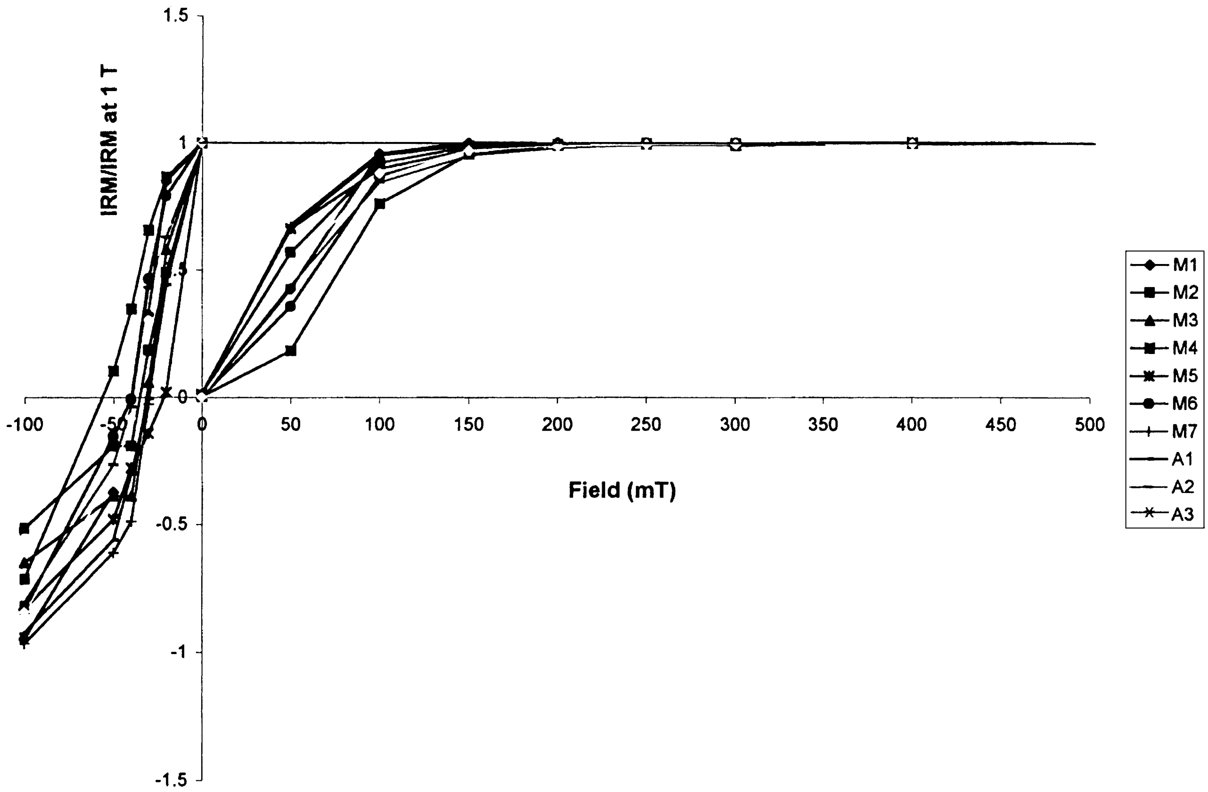

Fig. 5. IRM acquisition and back-field curves normalized to the highest applied field (1 T). Note that in the figure the curves were shown up to 0.5 and 0.1 T for the forward and back-fields respectively for the clarity of the figure.

of isothermal remanent magnetization was measured after each step. The magnetization was reduced to zero by applying reverse fields, which was continued until saturation IRM in the opposite direction was achieved. Fig. 5 shows the typical behavior of the IRM acquisition and back-field curves of the measured specimens. The IRM curves saturate at low fields such as 200 mT, and indicate that titano-magnetite as the main ChRM carrying magnetic mineral. The coercivity of remanence was found around 40 mT revealing the grain-size as SD to PSD type (Cisowski, 1981; Dankers, 1981; Sharma, 1994).

The Fig. 6 represents the characteristic behavior of the specimens for the *L–F* test. In the present study, 10 specimens were subjected to AF demagnetizations with increasing peak fields reaching to 100 mT. Then the saturated isothermal remanence magnetization at 1 T was imparted to all the specimens and the AF demagnetization was repeated in the similar steps as those in the NRM demagnetizations. From the results in Fig. 6, it can be seen that the NRM demagnetizations were harder than those of SIRM demagnetizations, indicating the presence of SD type magnetic minerals in the samples.

6. Discussion and conclusion

The isolation of normal and reverse polarity directions through detailed AF and thermal demagnetizations on statistically significant number of samples, indicate that the Palaeomagnetic data is free from secondary components and that the secular variation has been averaged out correctly. The overall mean VGP for these dykes is estimated as 41.2°N and 78.1°W ($N = 9$ dyke; $A_{95} = 9.81°$) and is plotted along with some well-established dykes poles (see Table 3) of the Deccan volcanic province (see Fig. 7). The mean pole

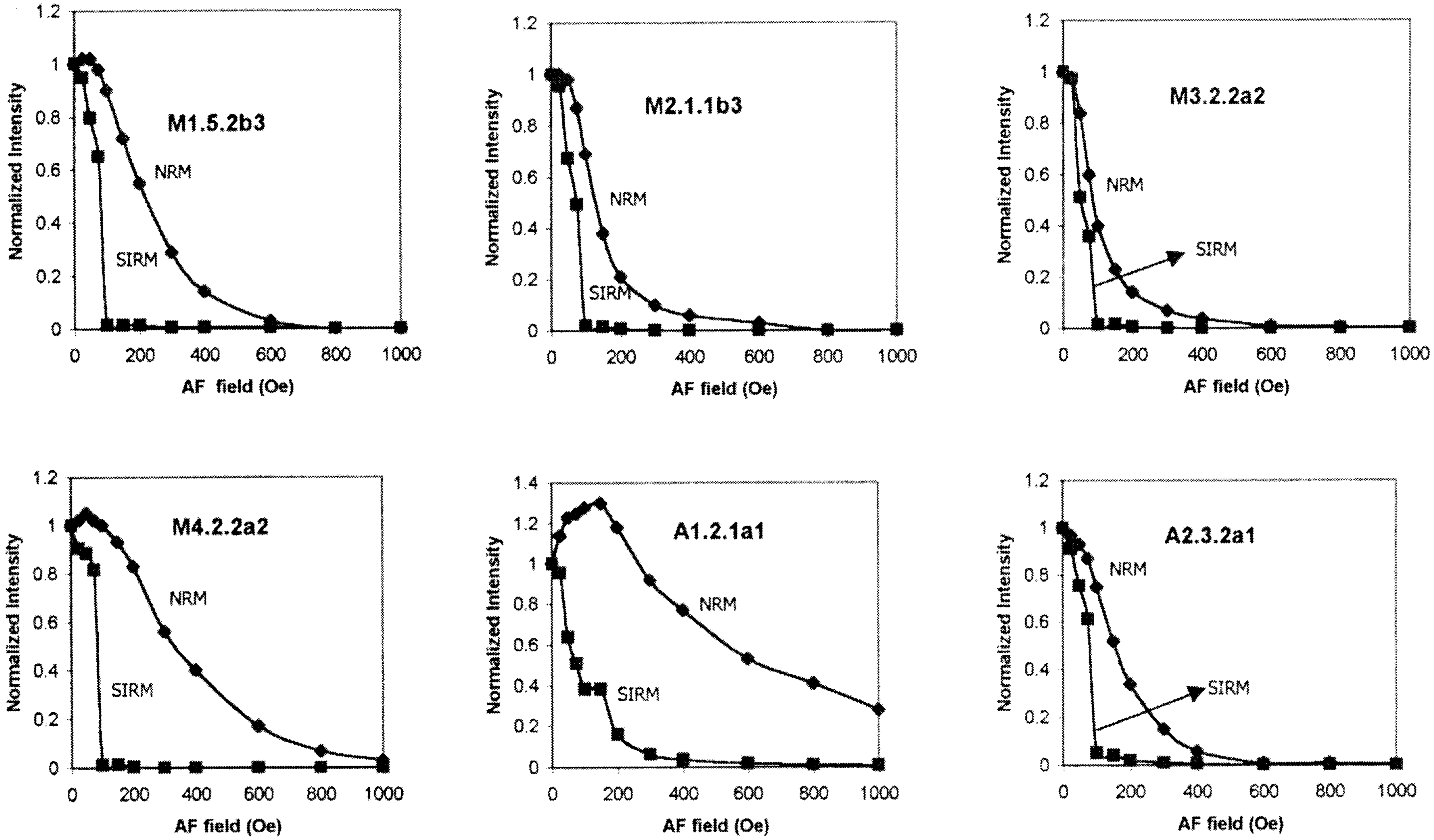

Fig. 6. Normalized AF demagnetizations for the NRM and SIRM (*L–F* test).

Table 3
Palaeomagnetic pole positions from the Deccan related dykes and the Deccan super pole

Pole no.	Locality	N	Age (Ma)	Magnetic	Directions		VGP				Palaeo latitude (°S)	References
				Dm	Im	α_{95}	Latitude (°N)	Longitude (°W)	dp	Dm		
1	Goa[a]	9		156.1	46.7	9.9	41.2	78.1	(A_{95} = 9.81)		27.9	This study
2	Hulyiyurdurga[a]	5	69–84 (K-Ar)	328.9	−54.5	3.3	33.9	72.3	4.1	2.9	34	Kumar et al. (1988)
3	Kerala[a]	6	69 ± 1 (Ar/Ar)	163	61	10.1	34.6	85.9			31.6	Radhakrishna et al. (1994)
4	Mysore[a]	4		357.7	−51.2	22.69	45.4	101.05	20.96	30.84	32.1	Hasnain and Qureshy (1971)
5	Dhule[b]	11		338	−44	9.4	37.2	80.5	(A_{95} = 9.7)		26	Prasad et al. (1996)
6	Mandaleswar[b]	5		350	−50	5	37	94	4.6	6.8	32	Subbarao et al. (1988)
7	Mandaleswar[b]	3		153	44	16.6	36	74	13	20.8	27	Subbarao et al. (1988)
8	Deccan super pole	163	67.2 ± 6.6				36.9	78.7	(A_{95} = 2.4)			Vandamme et al. (1991)

Symbols are as in the Table 2.

[a] Localities existing in the Precambrian Shield.

[b] Localities existing in the Deccan volcanic province, for the Deccan super pole 'N' indicates the number of flows. Ages are as quoted by the respective authors.

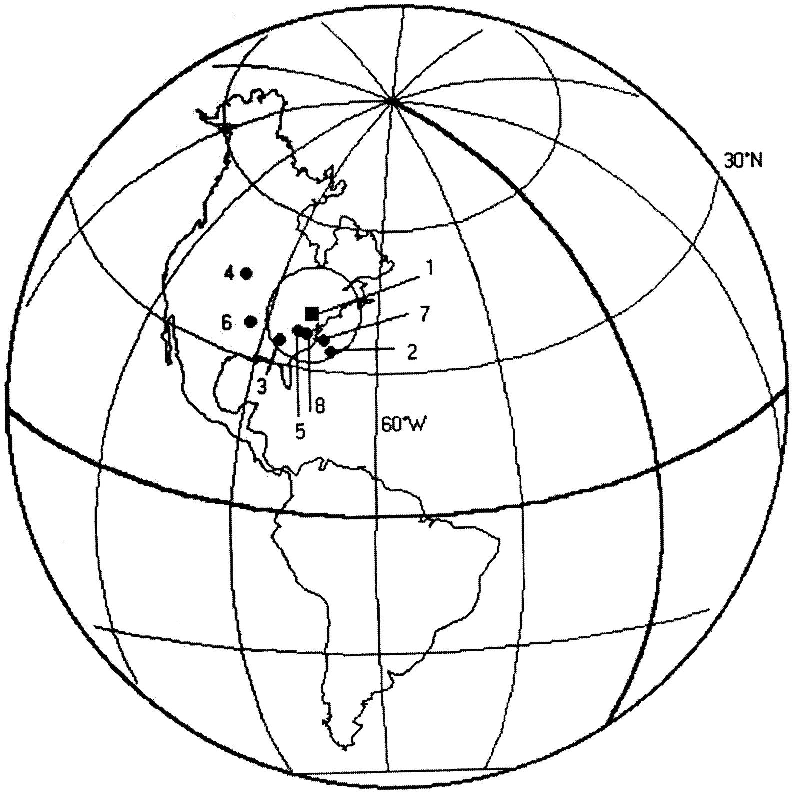

Fig. 7. Mean VGP for the Goa dykes along with some of the well established Deccan poles listed in the Table 2. The pole from the present study (filled square) is plotted with its A99 confidence circle.

position calculated from the present study is almost concordant with the Deccan traps super pole (36.9°N; 78.7°W), proposed by Vandamme et al. (1991) indicating a similar age of magnetization for these dykes and the Deccan flood basalts. A recent study of $^{40}Ar/^{39}Ar$ dating yielded the ages as 62.8 ± 0.2 Ma for the Aguda Fort normal polarity dykes, (Widdowson et al., 2000). This further strengthens our Palaeomagnetic results.

The occurrence of these dykes in the Precambrian Shield, around 70 km beyond the southern margin of the Deccan province, is an important aspect for the discussion about the original extent of the traps, their emplacement age and the span of volcanism. The most widely accepted model for the cause of the eruption of Deccan basalts was a consequence of the passage of the northerly drifting Indian subcontinent over the Reunion plume in the Late Cretaceous (Morgan, 1971, 1981). Based on good quality Palaeomagnetic, palaentological and radiochronological data Courtillot et al. (1986) suggested that the Deccan eruptions took place in a short interval of <1 Ma, straddling the cretaceous-tertiary boundary, spanning a sequence of three magnetic chrons, 29N–29R–30N. Even though, the present day Deccan traps occupy an area of approximately 500,000 km^2 of west central India, the original extent was in excess of 1,500,000 km^2 (Krishnan, 1982) and 2,600,000 km^2 (Pascoe, 1964) extending north as far as Sind (Pakistan) and Lalitpur (Uttar Pradesh) and those lying off the western coast (Cochin, Ratnagiri, Bombay) and on the south-eastern coast (Krishna–Godavari basin), prior to the erosion and their continuation beneath the Arabian Sea. The signatures of these eroded Deccan flows can be expected in the form of dykes and sills. Also, dykes of Phanerozoic ages in the Peninsular Shield are not uncommon. Murthy (1985) has reported the dykes which are in close geographic association with flows of the Deccan and Rajmahal provinces to be of Mesozoic age. Hasnain and Qureshy (1971) related the Mysore and Chitradurga dykes (Karnataka state) with the Deccan traps on the basis of their Palaeomagnetic and geochemical signatures. Palaeomagnetic, geochemical and geochronological (K-Ar ages 69–84 Ma) studies of Huliyadurga dykes (in Karnataka) showed strong coherence with the Deccan basalts (Kumar et al., 1988). Radhakrishna et al. (1994) described the central Kerala dolerite dykes ($^{40}Ar/^{39}Ar$ age 69 ± 1 Ma), as feeders to the Deccan volcanic sequences and suggested that the eruptions were widespread and extended southward into central Kerala.

Widdowson et al. (2000) have stated that along the length of the Deccan coastal plains of the Konkan region including the Goa coast, the eastward recession of the Western Ghats scarp removed any original basalt flows that might have existed. Accordingly, we can see in the present times, the Precambrian rocks as the host rocks for the dykes and the ages are only speculative in the absence of Palaeomagnetic and geochronological constraints. On the basis of geochemical characteristics and field markers, Subbarao and Hooper (1988) classified the Western Ghats sequences into three subgroups and 11 formations (Table 4). Palaeomagnetic studies on these formations indicate a thick pile of lavas with reversed polarity overlain by normal polarity flows viz. Mahabaleshwar, Panhala and Desur formations of the youngest Wai subgroup (Wensink et al., 1977; Khadri et al., 1988; Subbarao et al., 2000). The formations of the Wai subgroup are geographically widespread throughout the southern and eastern traps and extend towards the Narmada rift, while Kalsubai subgroup formations are restricted to the northwestern region of the Deccan province.

Table 4
Stratigraphy of the Deccan basalt group, Western Ghats, India (Subbarao et al., 2000)

Group	Subgroup	Formation	Polarity
Deccan basalts	Wai	Desur	N
		Pannala	N
		Mahabaleshwar	N
		Ambenali	R
		Poladpur	R
	Lonawala	Bushe	R
		Khandala	R
	Kalsubai	Bhirnashankar	R
		Thakurvadi	R
		Neral	R
		Igatpuri	R
		Jawhar	R

N: normal polarity; R: reverse polarity.

Palaeomagnetic studies undertaken here on the Goan dykes have yielded primary directions and thereby proved to be contemporaneous to the Deccan traps. In consideration of these Palaeomagnetic results with the geological, geochemical and $^{40}Ar/^{39}Ar$ age data support (Widdowson et al., 2000), these reverse and normal polarity—exhibiting intrusive bodies could be interpreted as the feeders for the uppermost Wai subgroup, the Ambenali (reverse polarity) and Mahabaleswar (normal polarity) formations of the Deccan basalt group of Western Ghats. Alternatively, these intrusives may be related to post-trappean tectonics related to the peak magnetic activity observed at 63 Ma in the Seychelles (Courtillot et al., 1986), which probably corresponded to the end of Deccan volcanism and/or to the initiation of rifting of the Arabian Sea. Joint Palaeomagnetic and geochronological investigations along with geochemical studies arc desirable on many dykes intruded in the Precambrian Shield, to distinguish the phanerozoic dykes from the Precambrian dykes and to understand the phanerozoic magnetic activity in the southern Indian peninsula.

Acknowledgements

The authors are thankful to the Department of Science and Technology (DST), Government of India, for the award of the project and financial help under which the present study was carried out. Thanks are due to Professor B.R. Arora, for his keen interest and encouragement throughout the course of this work. Professor A.G. Dessai of Goa University guided us in the sample collection and the same is acknowledged. We are grateful to Professor G.S. Lakhina, Director, Indian Institute of Geomagnetism, Mumbai, for his continued interest and permission to publish this paper.

References

Cisowski, S., 1981. Interacting vs. non-interacting single domain behavior in natural and synthetic samples. Phys. Earth Planet. Int. 26, 56–62.

Courtillot, V., Besse, J., Vandamme, D., Montigny, R., Jaeger, J.J., Cappetta, H., 1986. Deccan flood basalts at the cretaceous/tertiary boundary? Earth Planet. Sci. Lett. 80, 361–374.

Dankers, P., 1981. Relationship between medium destructive field and remanent coercive forces for dispersed natural magnetite. Geophys. J. Roy. Astron. Soc. 64, 447–461.

Dunlop D.J., Ozdemir, O., 1997. Rock Magnetism: Fundamentals and Frontiers. Cambridge University Press, Cambridge, 573 pp.

Fisher R.A., 1953. Dispersion on a sphere. Proc. Roy. Soc. London Ser. A. 217, 295–305.

Hasnain, I., Qureshy, M.N., 1971. Palaeomagnetism and geochemistry of some dykes in Mysore state, India. J. Geophys. Res. 76, 4786–4795.

Iyer S.D., Wagle. B.G., D'Cruz, E.E., 1990. Dyke swarms along the Goa coast. In: Proceedings of the National Seminar on Recent Researches in Geology of western India. M.S. University of Baroda, Vadodara, p. 14.

Khadri, S.F.R., Subbarao, K.V., Bodas, M.S., 1988. Magnetic studies on a thick pile of Deccan traps at kalsubai. Geol. Soc. India Memoir 10, 163–179.

Kirshvink, J.L., 1980. The least-squares line and plane and the analysis of Palaeomagnetic data. Geophys. J. Roy. Astronom. Soc. 62, 699–718.

Krishnan, M.S., 1982. Geology of India and Burma, 6th ed. CBS Publishers, Delhi.

Kumar, A., Bhaskara Rao, Y.J., Padma Kumari, V.M., Dayal, A.M., Gopalan, K., 1988. Late cretaceous mafic dykes in the Dharwar craton. Proc. Indian Acad. Sci. Earth Planet. Sci. 97 (1), 107–114.

Lowrie, W., Fuller, M., 1971. On the alternating field demagnetization characteristics of multi-domain thermoremanent magnetization in magnetite. J. Geophys. Res. 76, 6339–6349.

Morgan, W.J., 1971. Convection plumes in the lower mantle. Nature 230, 42–43.

Morgan W.J., 1981. Hotspot tracks and the opening of the Atlantic and Indian Oceans. In: Emiliani., C. (Ed.), The Sea, vol. 7. Wiley, New York, pp. 443–475.

Murthy N.G.K., 1985. Mafic dyke swarms in India. In: Proceedings of the International Conference on Mafic Dyke Swarms. Toronto, Canada (abstracts).

Murthy N.G.K., 1995. Proterozoic mafic dykes in southern peninsular India: a review. In: Devaraju T.C. (Ed.), Dyke Swarms of Peninsular India. Mem. Geol. Soc. India, No. 33, pp. 81–98.

Pascoe E.H., 1964. A Manual of the Geology of India and Burma, 3rd ed. Government of India Press, Calcutta.

Radhakrishna, T., Dallmeyer, R.D., Mathew, J., 1994. Palaeomagnetism and $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ isotope correlation ages of dyke swarms in central Kerala, India: tectonic implications. Earth Planet Sci. Lett. 121, 227–244.

Radhakrishnamurthy, C., 1985. Identification of titanomagnetites by simple magnetic techniques and application to basalt studies. J. Geol. Soc. India 26, 640–651.

Sharma P.V., 1994. Late Palaeocene geomagnetic polarity transition in the vestmanna core of the lower basalt sequence on the Faeroc islands. In: Subbarao, K.V. (Ed.), Magnetism: Rocks to Superconductors Mem. Geol. Soc. India, No. 10 (supplement).

Subbarao K.V., Bodas M.S., Khadri S.F.R., Beane, J.E., 2000. Penrose Deccan 2000. In: Proceedings of the Field Excursion Guide to the western Deccan basalt province, 19–25 March 2000, 241 pp.

Subbarao, K.V., Hooper, P.R., 1988. Reconnaissance map of the Deccan basalt group in the Western Ghat, India. Mem. Geol. Soc. India, No. 29, pp. 117–135.

Wensink, H., Boelrijk, N.A.I.M., Hebeda, E.H., Priem, H.N.A., Verdurmen, E.A.T., Verschure, R.H., 1977. Paleomagnetism and radiometric age determinations of the Deccan traps, India. In: Laskar B., Raja Rao C.S., (Eds.), Proceedings of the 4th International Gondwana Symposium, Calcutta, pp. 832–849.

Widdowson, M., Pringle, M.S., Fernandez, O.A., 2000. A post *K–T* boundary (early Palaeocene) age for Deccan-type feeder dykes, Goa, India. J. Petrol. 41 (7), 1177–1194.

Vandamme, D., Courtillot, V., Besse, J., Montigny, R., 1991. Palaeomagnetism and age determination of the Deccan traps (India): results of a Nagpur–Bombay traverse and review of earlier work. Rev. Geophys. 29, 159–190.

Zijderveld J.D.A., 1967. ac demagnetization of rocks. In: D.W. Collinson, Creer K.M., Runcorn S.K. (Eds.), Methods in Palaeomagnetism. Elsevier, New York, pp. 256–286.