Palaeomagnetic Studies on the Dykes of Mumbai Region, West Coast of Deccan Volcanic Province: Implications on Age and Span of the Deccan Eruptions

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Abstract: Through detailed AF and thermal demagnetizations of 35 samples (161 specimens) collected from 6 dykes located at Murud region, south of Mumbai, we report the first mean characteristic remanent magnetization direction as D=341°; I= -42°(μ95=5.7; N=6 dykes) for the dykes intruded into the West Coast zone of the Deccan Volcanic Province. The virtual geomagnetic pole (VGP) position (44°N; 83°W; A95=5.8°; N=6 dykes) calculated from this study is compared with those of the Narmada-Tapti zone dykes and with the Deccan Super Pole, proposed by Vandamme *et al*. (1991). Based on the concordance of these poles and recently reported $^{40}Ar/^{39}Ar$ and $^{87}Rb/^{86}Sr$ dates on the dykes of the studied region (Murud), it is proposed that the entire Deccan flows and the associated dykes were erupted in a short interval close to the Cretaceous-Tertiary Boundary at 65.5 Ma. Thermal demagnetization spectra along with isothermal remanent magnetizations and L-F test experiments indicated that the SD type titano-magnetite was the major ChRM carrying magnetic mineral in the samples. Out of the 6 studied dykes, one dolerite dyke showing the "reverse magnetic polarity", could have acted as a feeder dyke to the Poladpur Formation flows, which host the dykes in the studied area. The remaining four dolerite dykes and one lamprophyre dyke, yielding "normal polarity" directions, might have fed to the youngest formations of Wai Subgroup flows, viz., Panhala Formation and Desur Formation, which were eroded in the studied region.

INTRODUCTION

It is a widely accepted view that the Deccan flood basalts of Indian sub-continent, covering at present an area of 500,000 sq.km., is the result of outburst of immense magma material from the Reunion Hot spot source that impinged on the northerly drifting Indian lithosphere in the Late Cretaceous (Morgan, 1981). The Deccan Province is traversed by three major rift zones, namely the Narmada-Tapti-Son rift, the Cambay rift and the West Coast rift, which form a triple junction at the CambayBasin (Sheth and Chandrashekharam, 1997). Over the last 30 years the Deccan Traps have attained the attention of geochronologists, palaeomagnetists, geochemists and petrologists alike with its impressive horizontal lava piles, enormous size and volume along with its rapid eruptions at the K/T boundary coinciding with the much debated mass extinctions (Sen, 2001; Subbarao, 1999a and 1999b). Palaeomagnetic investigations on the Deccan Traps have been successful in strengthening the plate-tectonic theory as well as establishing the magnetostratigraphy of the flow sequence permitting constraints on the ages and span of eruption of the flows. From the compilation of the available good quality palaeomagnetic data on the flows, Vandamme *et al*. (1991) proposed a normal-reverse-normal polarity sequence that correspond to the chrons 30 N-29 R-29 N; a major part of the eruptions is limited to the chron 29 R. From detailed geochronological studies on the 2.5 km thick lava pile in the 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 long has been proposed for the Deccan Traps. Recent $^{40}Ar/^{39}Ar$ dating of mineral separates and whole rocks from the Western Ghats lava pile, has reinforced these views by (Hofmann *et al*., 2000). In contrast, Venkatesan *et al*. (1993, 1994) suggested the flow duration to be not less than 3 Ma with eruption pre-dating the KTB by at least 1.0 Ma. Dhandapani and Subbarao (1992) had also favored a longer duration of more than 6 Ma for the Deccan flows by identifying normal polarity in the lowermost Deccan flow coinciding with the Cretaceous Long Normal Superchron.

Most of the rock magnetic and palaeomagnetic studies till date have focused on measurements from different lava flows. In order to have a better understanding of the Deccan volcanic episode, in particular, the precise age, span and mechanism of eruption as well as the original extent of the Deccan Province, it is desirable to extend palaeomagnetic studies to the associated intrusive phases. There are only three published palaeomagnetic reports on the Deccan traps dykes -- (i) Mandaleshwar dykes in the south of Narmada river (Subbarao *et al*., 1988), (ii) Dhadgaon and Nandurbar dykes respectively from the south of Narmada and Tapti rivers (Prasad *et al*., 1996) and (iii) Goa dykes, which exist around 70 km beyond the present day southern margin of the Deccan Province, along the west coast of India (Patil and Rao, 2002). Besides these three reports, Radhakrishna *et al*. (1994) have studied the central Kerala dykes, based on palaeomagnetic and $^{40}Ar/^{39}$ Ar ages (69±1 Ma), as the feeders to the Deccan volcanic sequences and suggested that the Deccan eruptions were widespread and extended southward into Central Kerala. The most prominent region of Deccan Traps Province, the Western Ghat Section, where flows yielded good quality palaeomagnetic, isotopic dates and geochemical data sets, is lacking in detailed palaeomagnetic studies on the intrusive bodies. Only one report by Subbarao *et al*. (1992) identifying the dyke polarities is available to the best of authors" knowledge. However, at present palaeomagnetic and geochemical investigations along with geochronological studies are initiated on the dykes and recently Sahu *et al*. (2003) have presented ^{87}Rb/^{86}Sr ages and Sr isotopic composition of alkaline dykes near Mumbai. In this present article, we have reported new palaeomagnetic results from the dykes along the West Coast, south of Mumbai (Bombay), and compared the results with those of the previous studies for constraining the age and duration of the Deccan trap flows and also discussed their genetic relation with the flows.

GEOLOGY OF THE STUDY AREA

Mafic dykes are concentrated in clusters and swarms in the two tectonic belts paralleling the N-S trending West Coast and Sahyadri Mountains and E-W trending Narmada-Tapti-Satpura lineament zones in the Deccan volcanic province (Figure 1). According to Deshmukh and Sehgal (1988) 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 and they occupy dilatory tensional fractures, which are formed due to tectonic movements in the two tectonic belts.

The Murud region, the present study area (Figure 2), lies in the Konkan Coastal belt of the Western Ghat Section, and is predominantly covered by flows of Poladpur and Ambenalli Formations of Wai Subgroup of the Deccan Basalts (Subbarao and Hooper, 1988). Powar and Vadetwar (1995) identify these flows as simple and compound types that range in thickness from about 5m to 40m or more. The "Panvel Flexure" is the most prominent tectonic feature in this region (Auden, 1949). In this area tholeiitic to mildly alkaline flows of Deccan basalts are intruded by a number of basic (dolerite) dykes associated with plugs of gabbro-diorite. The dykes of this region are mostly oriented N-S, parallel to the "Panvel lineament". According to Powar and Vadetwar (1995), over 32% of the dykes occur in the azimuth range N 0-9° and nearly 60% in the range N 0- 30°. The dykes show sharp contacts with the basalts and have chilled margins. The dykes are vertical or steeply inclined up to 70°. Based on their field characteristics, Dessai and Viegas (1995) distinguished these dykes into four generations. Powar and Vadetwar (1995) observed close similarity in the mineralogy and chemistry of basalts and dolerite dykes of this region and suggested that both dykes and flows represent the Poladpur magma-type. They also opined that the dykes were emplaced immediately after the outpouring of basalts of Poladpur Formation, but are not the feeders to the flows.

SAMPLING AND MEASUREMENTS

35 oriented block samples were collected from 5 dolerite dykes (4 dykes, RID 1 to 4, belong to south of Rat Island, 1 dyke (TBD-1) from north-west of Borlai (Figure2- b) and 1 lamprophyre dyke (ELD-1) from Beacon Hill region (Figure 2-c). It has been taken care that minimum 5 samples from each dyke was collected. Rat Island dykes trend N10°W and their widths range from 1 to 2 m. Borlai dyke trends N50°W and has the width of around 2.5 m, whereas, Beacon Hill lamprophyre dyke trends NNE- SSW direction with a width of 3 m. From the collected 35 samples around 160 standard cylindrical specimens of size 2.2 cm height and 2.5 cm diameter were prepared in the laboratory.

The Natural Remanent Magnetization (NRM) intensities of all the prepared specimens were measured with JR-5A Spinner magnetometer (M/S Agico, Czech Republic) having the sensitivity of 3 pT. NRM intensities of dolerite dyke specimens were in the range of 0.22 to 3.31 A/m, whereas, lamprophyre dyke specimens were in the range of 0.60 to 1.19 A/m. The magnetic susceptibilities were measured by MS-2B Bartington susceptibility meter. The magnetic susceptibilities of dolerite and lamprophyre dyke specimens were in the ranges of (1599 – 5932) x 10-5 SI and (11610 – 12220) x10-5 SI respectively. Koenigsberger (Qn) ratios were calculated and it was noticed that the dolerite specimens had relatively higher values (mean=0.68) than those of lamprophyre dykes specimens (mean=0.20). Both the alternating field (AF) and thermal demagnetization methods were used to isolate the characteristic remanent magnetization (ChRM) directions from the specimens. For the AF demagnetizations M/S. Molspin AF demagnetizer was used and for the thermal demagnetizations, MAVACS system manufactured by Geofyzica, Brono, was used. Initially 36 specimens representing 6 dykes were selected for detailed demagnetizations (pilot studies). A total 18 specimens were subjected to eleven steps of peak AF fields at 2.5, 5.0, 7.5, 10.0, 15.0, 20.0, 30.0, 40.0, 60.0, 80.0 and 100.0 mT; and another 18 specimens were demagnetized in 10 temperature steps at 100, 200, 300, 350, 400, 450, 500, 560, 585 and 600°C.

RESULTS AND ANALYSIS

Both the AF and thermal demagnetizations were found equally effective in isolating the ChRM directions from the dolerite dyke specimens. In the case of Rat Island dykes (RID-1 to RID-4), a very weak low coercivity component was removed by the application of 5 mT – 10 mT AF peak fields and good grouping in the directions showing normal polarities were noted in steps between 10 mT to 40 mT fields. The NRM intensity was reduced to 3 to 5% by the application of 40 mT; and at above the fields, the directions were randomized. With the thermal demagnetizations on these dykes, viscous component could be erased by the application of 100°C step and the primary directions of "normal polarities" were obtained between 200°C to 450°C heating steps. At 450°C the NRM intensity was reduced to less than 2% in many

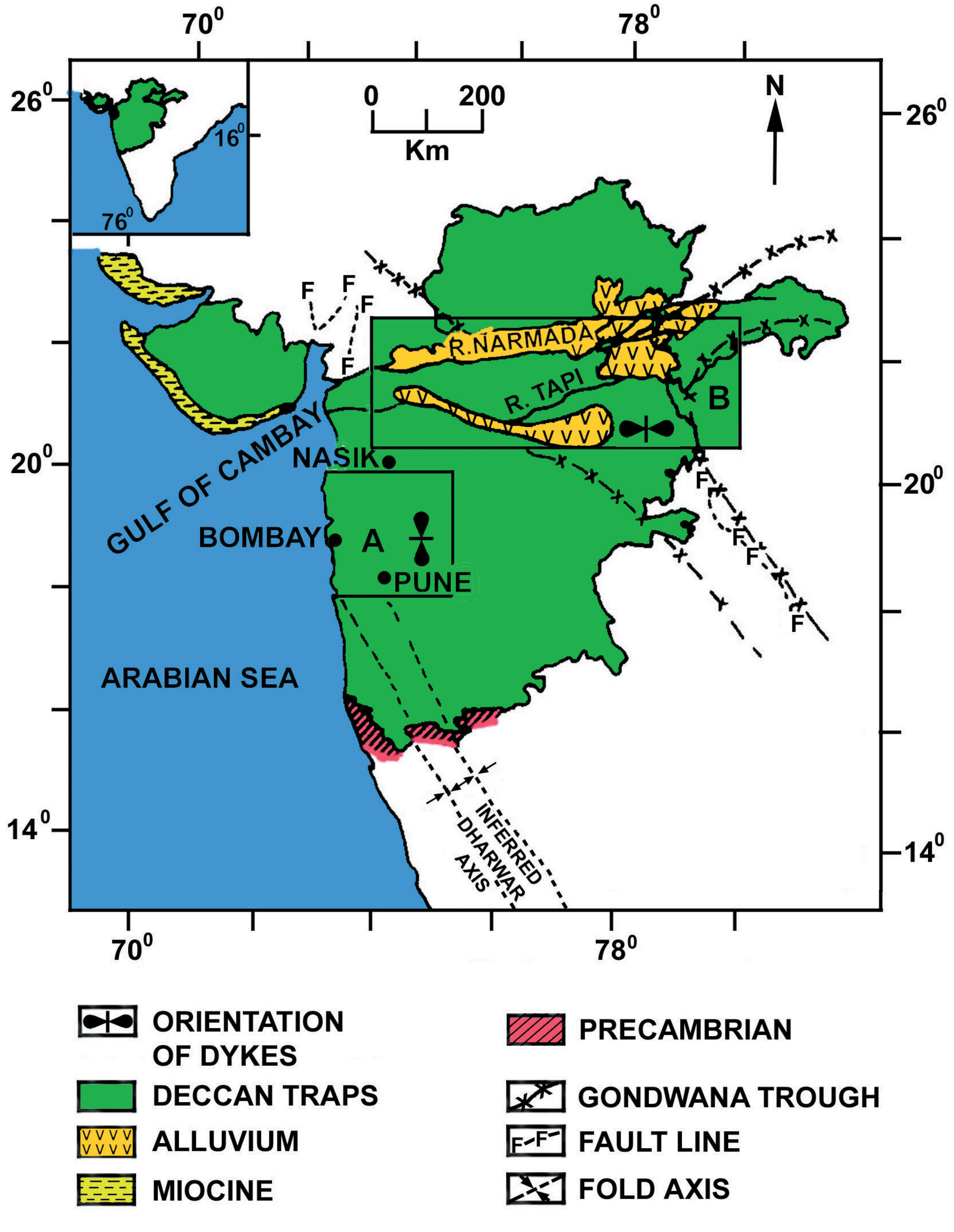

Figure 1. Generalized geology and important tectonic features of the Deccan Volcanic Province. Areas enclosed by rectangles A, B indicate the dyke swarm belts of the West Coast and the Narmada-Tapti lineaments respectively (modified after Deshmukh and Sehgal, 1988; and Prasad *et al.*, 1996).

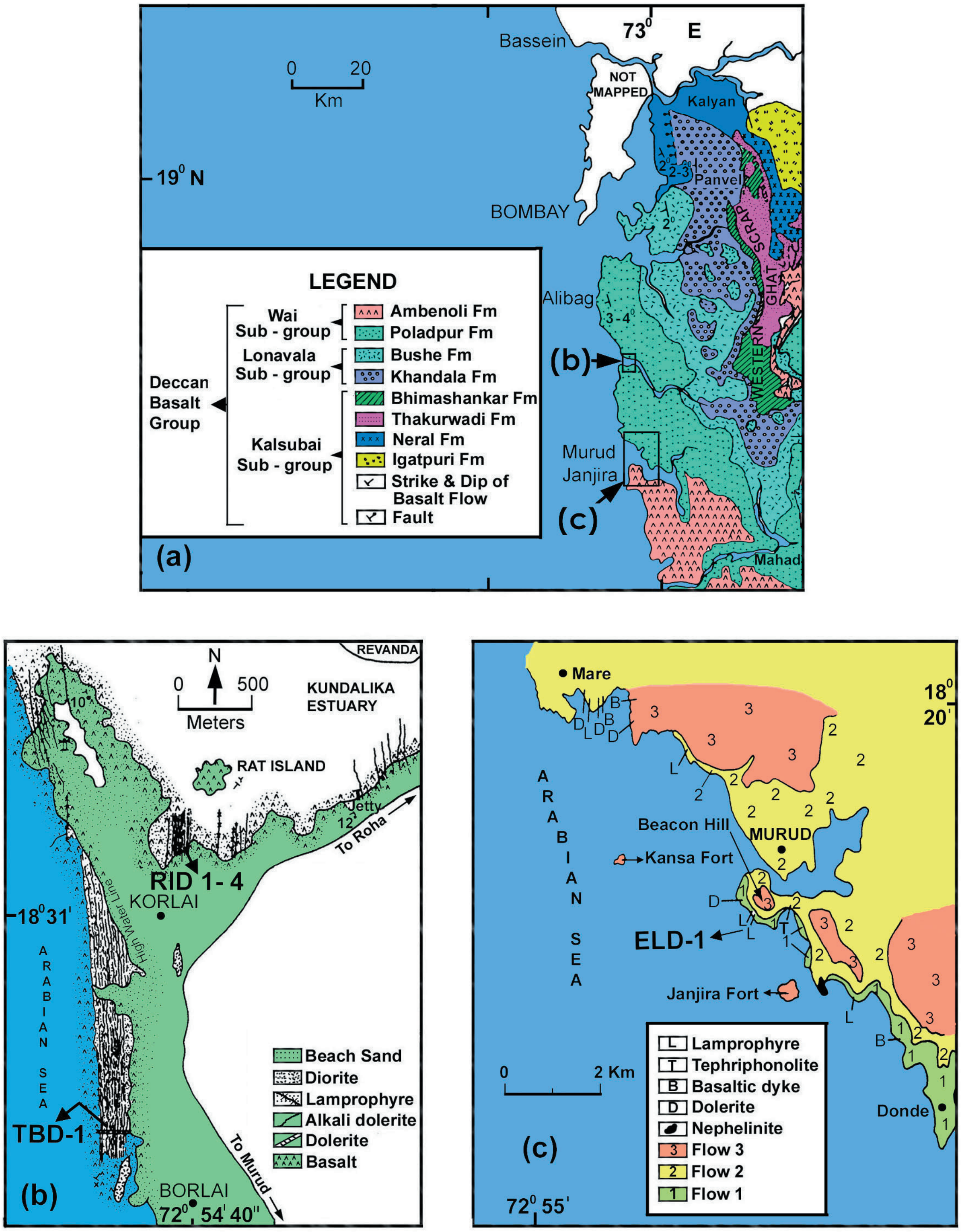

Figure 2. Location map. (a) Geology of the Western part of the Deccan Province (Subbarao and Hooper, 1988). (b) Geological map showing the location of Rat Island dolerite dykes, RID-1 to RID-4 and Borlai dolerite dyke, TBD-1 (after Dessai and Viegas, 1995). (c) Geological map showing the location of Beacon Hill lamprophyre dyke, ELD-1 (after Bodas *et al*., 1988).

of the specimens. Figure 3 shows the typical AF and thermal demagnetizations behaviors of these specimens. Unlike the Rat Island dykes, Borlai dyke (TBD-1) showed characteristic direction of “reverse polarity” having southeast declinations along with the positive intermediate inclinations. A minor viscous component was erased by 5 mT AF field or 100°C thermal cleanings. Figure 4 represents the AF and thermal demagnetizations response of the Borlai dyke samples. As in the Rat Island dykes, in this dyke also, the primary component was recovered in the 10 mT to 40 mT AF fields and 2S.K. Patil1, B.R. Arora2 thermal steps. The lamprophyre dyke (ELD-1) behaved differently to the progressive AF demagnetization steps. A strong present earth”s field (PEF) component did not vanish even at the AF fields of 100 mT, the highest field to which specimens were subjected, though the NRM

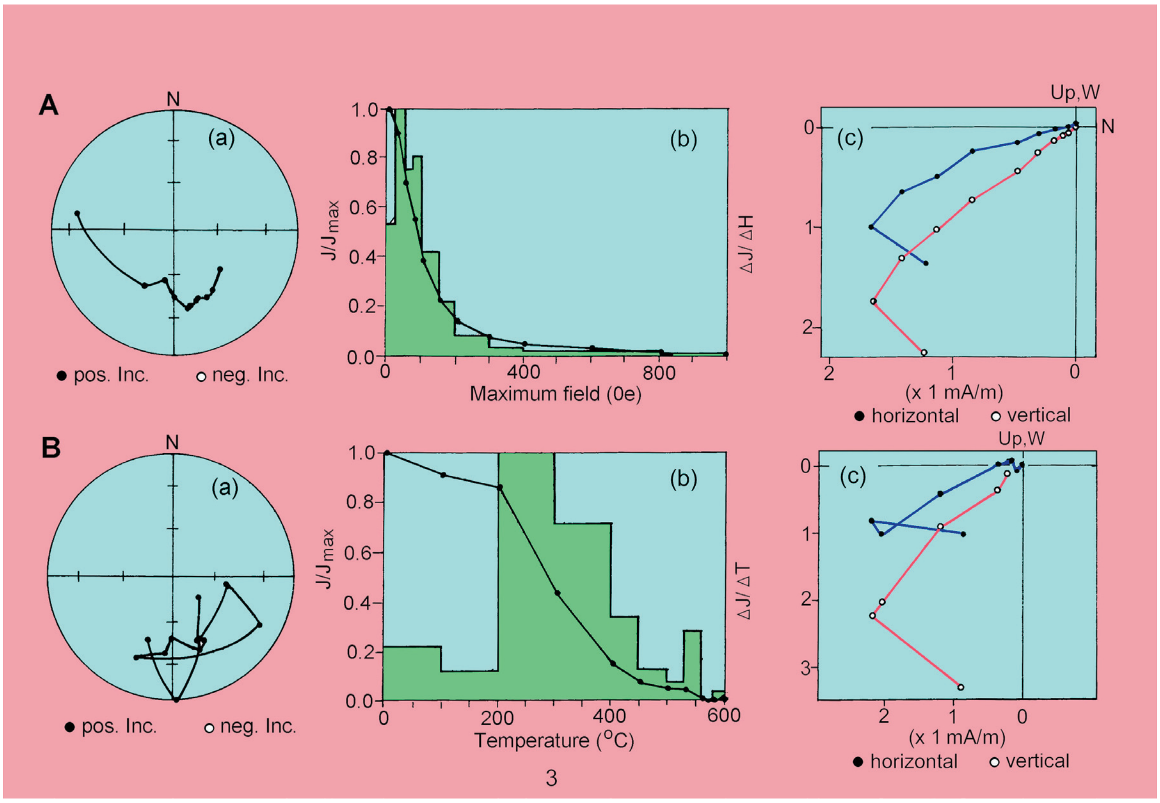

Figure 3. (A) and (B) represent AF and thermal demagnetization results of the specimens from the Rat Island (RID 1-4) dykes respectively in stereographic projection, (b) Normalized Intensity decay (J/Jmax) along with PTRM (hatched histograms, DJ/DH for AF demagnetizations and DJ/DT for thermal demagnetizations) and (c) Zijderveld diagram.

intensity decreased regularly with increasing AF fields. But, thermal demagnetization was effective in yielding the "normal polarity" ChRM directions in 8 specimens belonging to 2 block samples, although total 18 specimens (5 block samples) were analyzed. Figure 5 shows the characteristic behavior of thermal demagnetization on representative specimen of ELD-1 dyke. From thermal demagnetization spectra on these representative specimens, as the NRM intensity drops to 3-4% by the application of 400°C thermal step, it was inferred that titano-magnetite was the major remanence carrying magnetic mineral in the samples.

ROCK MAGNETIC INVESTIGATIONS

To understand the ChRM carrying magnetic mineral and its domain state, isothermal remanent magnetizations (IRM) and the Lowrie-Fuller (1971) test were performed on the representative specimens. For this purpose, 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 of IRM was measured after each step. Figure 7-A shows the IRM spectra on the representative specimens. The IRM curves saturating at fields 200 mT indicate titano-magnetite as the major magnetic mineral, which was carrying the ChRM in the samples. For the L-F test experiments, the 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 and the AF demagnetizations were repeated in the similar steps as those in the NRM demagnetizations. Figure 7-B shows response of L-F test on the representative specimens. The NRM demagnetizations were found harder than those of SIRM demagnetizations, indicating the SD type magnetic minerals in the samples.

DISCUSSIONS AND CONCLUSIONS

The mean magnetization direction in the dykes of Murad region, isolated from detailed AF and thermal demagnetizations on statistically significant number of samples, is considered as primary. Subbarao *et al*. (1992) identified normal and reverse polarity dykes in this region but did not report the ChRM directions; and so the magnetization direction derived in this study (D= 341°; I= -42°) is the first result for the West Coast dykes. The palaeo pole (44°N; 83°W; A95 = 5.8°) deduced from this study is compared with those of the poles obtained for the dykes from south of Narmada-Tapti region viz., Mandaleshwar (Subbarao *et al*., 1988) and Dhadgaon (Prasad *et al*. 1996) and also with the Deccan Super Pole (37°N; 79°W; A95 =2.4°) estimated from the existing high quality palaeomagnetic data (Table – 2 and Figure 8) representing all geographical provinces of Deccan Basalts (Vandamme *et al*., 1991). As the VGPs of the Murud dykes,West Coast as well as for the Mandaleshwar and Dhadgaon dykes of Narmada region match well with the Deccan Super Pole, the same

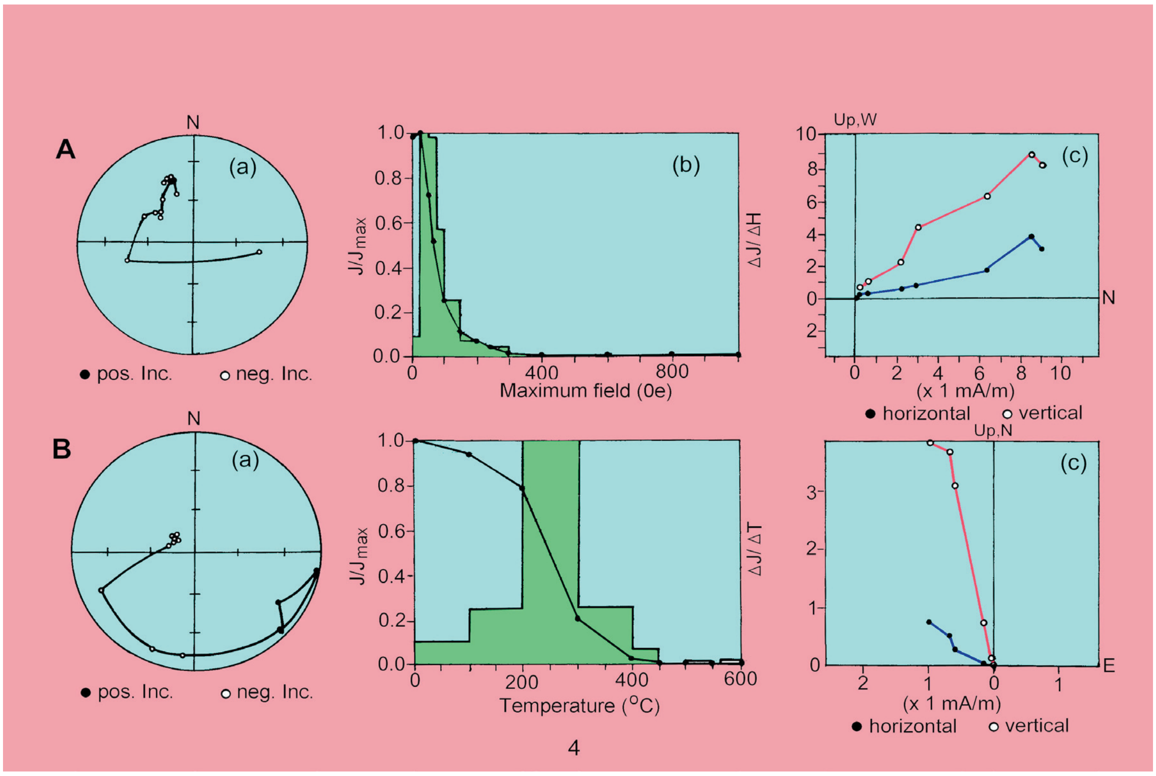

Figure 4. (A) and (B) represent AF and thermal demagnetization results of the specimens from Borali (TBD-1) dyke respectively. (a), (b) and (c); same as listed in the Figure3.

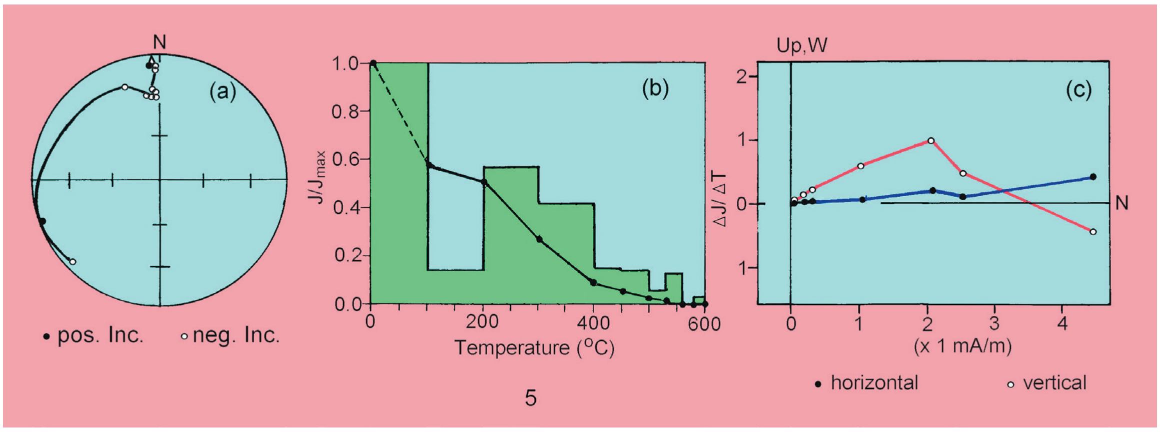

Figure 5. Thermal demagnetization result of Beacon Hill lamprophyre (ELD-1) dyke. (a), (b) and (c) as listed in the Figure3.

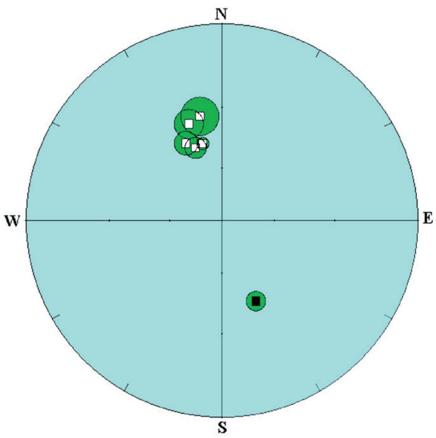

Figure 6. Characteristic mean directions along with their corresponding a95 circles. Open (full) squares indicate projections in the upper (lower) hemisphere.

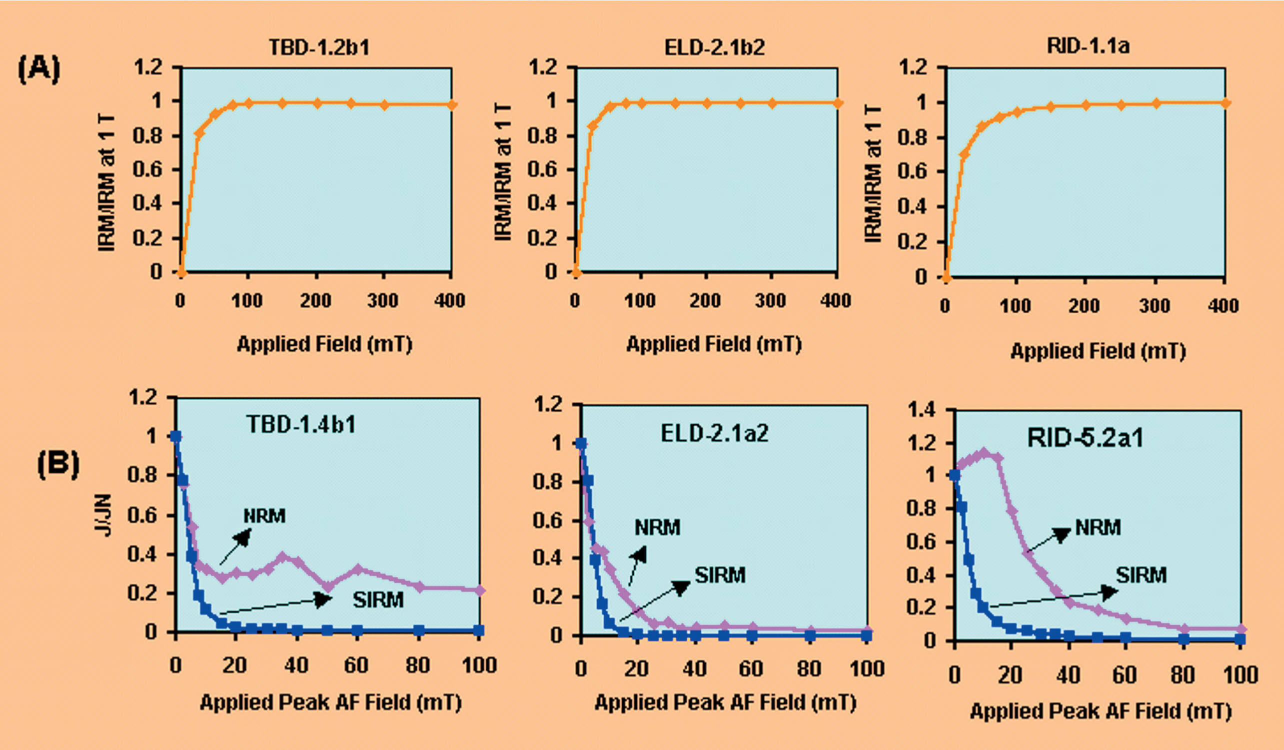

Figure 7. (A) IRM acquisition and (B) L-F test curves for the representative specimens.

Table 1: Palaeomagnetic results of Murud dykes

Dyke	Mean Directions (AF)					Mean Directions (Thermal)					Mean Directions (AF+Thermal)					VGP			
No.	Dm	Im	k	μ_{95}	N(n)	Dm	Im	k	μ_{95}	N(n)	Dm	Im	k	μ_{95}	N	Lat.(°N)	Long.(°W)	dp	dm
RID – 1	340	-40	22	7.2	8(15)	343	-28	38	6.6	8(12)	341	-35	51.4	6.7	8	48	80	4.7	7.9
RID – 2	325	-48	28	8.6	5(12)	346	-36	32	5.2	5(12)	335	-43	102.2	5.8	5	40	77	4.0	6.4
RID – 3	342	-44	37	12.1	5(14)	350	-48	96	4.1	5(16)	346	-46	116.8	3.1	5	42	90	3.3	5.2
RID – 4	344	-47	30	9.5	6(15)	335	-48	33	8.5	6(15)	340	-47	100.3	5.4	6	39	84	4.0	6.2
TBD –1	153	41	98	5.6	7(22)	160	43	110	4.8	7(20)	157	42	115.1	4.8	7	42	79	3.6	5.9
ELD –1	-	-	-	-	-	348	-33	85	8.6	2(8)	348	-33	85.2	8.6	2	52	91	5.5	9.8
Over all Mean											341	-42	136.9	5.7	6	44	83	(A_{95} =5.8°)	

Notes: 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 meank: Fisher"s precision parameter; μ_{95}= Circle of confidence at 95% probability leveldp, dm: Semi-axes of the oval of 95% confidence for the VGP

magnetization age is proposed for the flows and the dykes over the entire Deccan Province, including the West Coast and Narmada- Tapti regions. Our preliminary palaeomagnetic results on the dykes intruded in Bhuj area, Western Gujarat) also indicated the pole concordant with the Deccan Super Pole (Lakshminarasimhan *et al*., 2003).

There is a considerable debate over the isotopic ages of the Deccan traps. Geochronological results on the dykes are few when compared to those on the traps. Earlier isotopic investigations dealing with K/Ar datings by Agrawal and Rama (1976) and Balasubrahmanyan and Snelling (1981) have yielded west coast dykes ages ranging from 81 Ma to 34 Ma and the reliability of these dates are questionable (Vandamme *et al*. 1991). However, ^{40}Ar/^{39} Ar and ^{87} Rb/^{86} Sr age estimations on the dykes are very scanty. Hoffmann *et al*. (2000) yielded ^{40}Ar/^{39} Ar age for one dyke, situated south of Mumbai (could be the present study area), as 65.2±0.4 Ma. Knight *et al*. (2000) reported ^{40}Ar/^{39} Ar plateau ages ranging from 70.77±0.12 to 69.71±0.14 Ma for mica separates; and biotite-whole rock Rb/Sr ages as 63-64 Ma, for the lamprophyre dykes of the Murud region (present study area). To verify these age models, recently Sahu *et al*. (2003) attempted a ^{87} Rb/^{86} Sr internal isochron approach on the lamprophyre dyke and worked out an age of 64.9±0.8 Ma. Based on these new dates of the dykes and the ages proposed for the Deccan Province lavas (Vandamme *et al*. 1991), it can be inferred that the entire traps and associated dykes were erupted in a short interval close to the Cretaceous-Tertiary boundary at 65.5 Ma.

The other point for discussion is regarding the genetic link between the flows and dykes, ie., whether the

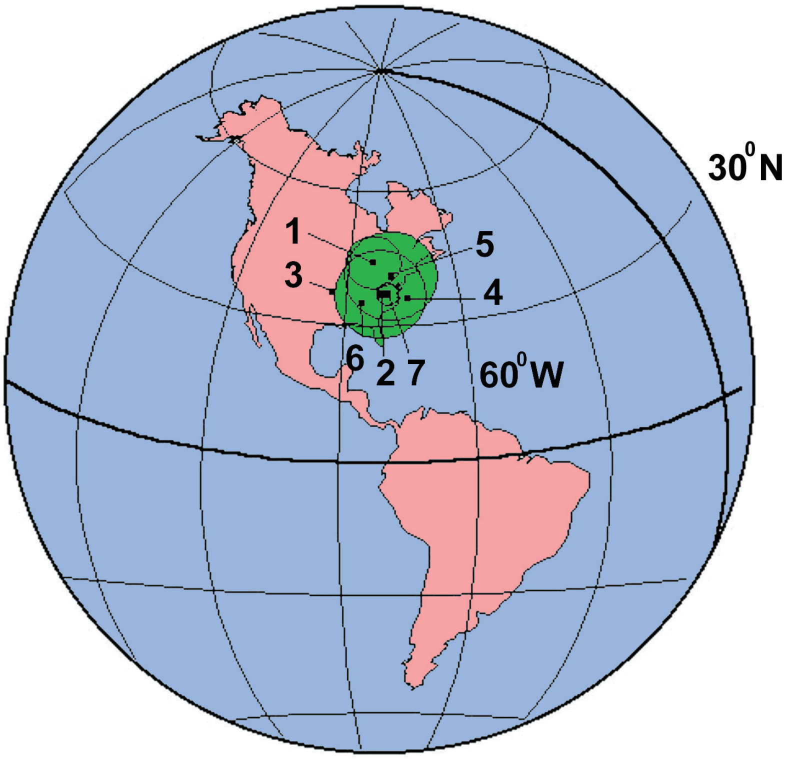

Figure 8. Mean VGP for the Murud dykes along with the poles listed in the Table 2.

Table 2: Palaeomagnetic pole positions of the Deccan Traps related dykes and the Deccan Super Pole

Pole No.	Locality	N	Age (Ma)	Magnetic Directions			VGP				Palaeo	Reference
				Dm	Im	a_{95}	Lat. (°N)	Long. (°W)	dp	dm	Lat. (°S)	
1	Murud	6		341	-42	5.7	44	83	(A_{95} =5.8)		24	This study
2	Dhadgaon	11		338	-44	9.4	37	81	(A_{95} =9.7)		26	Prasad et al. (1996)
3	Mandaleswar	5		350	-50	5.0	37	94	4.6	6.8	32	Subbarao et al.(1988)
4	Mandaleshwar	3		153	44	16.6	36	74	13	20.8	27	Subbarao et al.(1988)
5	Goa	9	62.8±0.2(Ar/Ar)	156	47	9.9	41	78	(A_{95} = 9.81)		28	Patil and Rao (2002)
6	North Kerala	6	69±1 (Ar/Ar)	163	61	10.1	35	86			32	Radhakrishna (1994)
7	Deccan Super Pole	163	65.5±2.5 (Ar/Ar)				36.9	78.7	(A_{95} = 2.4°)			Vandamme et al.(1991)

Symbols are in the Table-1
For the Deccan Super Pole, "N" indicates the number of flows

dykes are feeders to the overlying flows or hypabyssal intrusives. Before discussing this point, it is proper to note the stratigraphy of the West Coast flows. Subbarao *et al.* (2000) classified Western Ghats flow sequences into three subgroups and eleven formations based on geochemical indicators. Magnetostratigraphy on these flows define a simple Reverse-Normal (R-N) sequence (Table- 3). From this table, it can be noted that seven relatively older formations of Kalsubai and Lonawala Subgroups and also two formations of the younger Wai Subgroup were marked with the "reverse polarity" and were overlain by three "normal polarity" formations viz., Mahabaleshwar, Panhala and Desur Formations. On the joint consideration of geochemistry and palaeomagnetic directions on the Mandaleshwasr dykes of South Narmada region, Subbarao *et al.* (1988) concluded that the dykes of normal and reverse polarities acted as feeders to the respective polarity lava flows of the Narmada-Tapti region. A study by Bhattacharji *et al.* (1994) provided new evidence that the mafic dykes along the Narmada-Tapti belt acted as primary feeders to the flows, based on marked similarities in major, trace, REE composition and isotope ages of the flows and associated dykes. In the West Coast, randomly oriented dykes, particularly in the area of Nasik-Kalsubai region, having similar chemical characteristics with those of overlying flows, were described as feeders to the later (Subbarao *et al.* 1992).

In contrast, in the present study area, N-S and NE - SW trending dykes of tholeiitic, acidic and lamprophyric compositions, were suggested as hypabyssal intrusives (Powar and Vadetwar, 1995). All the 6 dykes investigated here, intruded into the "reverse polarity" Poladpur Formation flow of Wai Subgroup and therefore the dykes should be younger than the Poladpur Formation and should be hypabyssal intrusives. On the other hand, if it is considered that the dykes act as feeders to the flows, as in the case of the Mandaleshwar dykes, then the argument could be as follows: The reverse polarity dyke (TBD-1) might be the feeder to the Poladpur Formation, whereas, the normal polarity dykes, might have acted as feeders to the upper "normal polarity" flows like Panhala or Desur Formations. As these flows can not be seen in the studied region, it can be opined that these upper flows might have been eroded from this region. Palaeomagnetism alone can not distinguish the feeder dykes from the simple intrusive bodies. Field evidences and other geological characteristics can be used to distinguish them from intrusive bodies, palaeomagnetic studies on the dykes will then compliment the geochemical and petrographical investigations to relate the dykes with the overlying flows, based on the magnetic polarity.

It is concluded from the present palaeomagnetic investigation that the six studied dykes successfully yielded ChRM directions that were carried by the titano-magnetite of single domain grain sizes. The pole position derived from the present study is considered as the first palaeo pole for the dykes of the West Coast zone of the Deccan Province. On the basis of comparison of the present pole with those of the Narmada dykes and with the Deccan Super Pole, and by taking into consideration the recent isotopic ages, it is inferred that the entire Deccan flows and the associated dykes of Narmada-Tapti and West Coast zones were erupted in a short interval straddling the Cretaceous-Tertiary Boundary at 65.5 Ma. If the dykes are considered as feeders, the reverse polarity dyke (TBD-1) might have acted as the feeder to the Poladpur Formation flow and the normal polarity dykes might have fed to the Panhala and Desur Formations, which were weathered out in the studied region. Field investigations are suggested to distinguish the feeder dykes from the simple intrusive bodies. Further, detailed palaeomagnetic studies along with $^{40}Ar/^{39}Ar$ and $^{87}Rb/^{86}Sr$ isotopic ages are recommended for the dykes intruded in to the entire Deccan province, to understand the complete picture of the Deccan basaltic episode.

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Table 3: Stratigraphy of the Deccan Basalt Group, Western Ghats, India

Group	Subgroup	Formation	Polarity
Deccan Basalt	WAI	Desur	N
		Panhala	N
		Mahabaleshwar	N
		Ambenali	R
		Poladpur	R
	LONAWALA	Bushe	R
		Khandala	R
	KALSUBAI	Bhimashankar	R
		Thakurvadi	R
		Neral	R
		Igatpuri	R
		Jawhar	R

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