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RESEARCH ARTICLE

Structure and emplacement of the Nandurbar–Dhule mafic dyke swarm, Deccan Traps, and the tectonomagmatic evolution of flood basalts

Ranjini Ray · Hetu C. Sheth · Jyotirmoy Mallik

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Abstract Flood basalts, such as the Deccan Traps of India, represent huge, typically fissure-fed volcanic provinces. We discuss the structural attributes and emplacement mechanics of a large, linear, tholeiitic dyke swarm exposed in the Nandurbar–Dhule area of the Deccan province. The swarm contains 210 dykes of dolerite and basalt >1 km in length, exposed over an area of 14,500 km^2. The dykes intrude an exclusively basaltic lava pile, largely composed of highly weathered and zeolitized compound pahoehoe flows. The dykes range in length from <1 km to 79 km, and in thickness from 3 to 62 m. Almost all dykes are vertical, with the others nearly so. They show a strong preferred orientation, with a mean strike of N88°. Because they are not emplaced along faults or fractures, they indicate the regional minimum horizontal compressive stress (σ_3) to have been aligned ~N–S during swarm emplacement. The dykes have a negative power law length distribution but an irregular thickness distribution; the latter is uncommon among the other dyke swarms described worldwide. Dyke length is not correlated with dyke width. Using the aspect ratios (length/thickness) of several dykes, we calculate magmatic overpressures required for dyke emplacement, and depths to source magma chambers that are consistent with results of previous petrological and gravity modelling. The anomalously high source depths calculated for a few dykes may be an artifact of underestimated aspect ratios due to incomplete along-strike exposure. However, thermal erosion is a mechanism that can also explain this. Whereas several of the Nandurbar–Dhule dykes may be vertically injected dykes from shallow magma chambers, others, particularly the long ones, must have been formed by lateral injection from such chambers. The larger dykes could well have fed substantial (≥1,000 km^3) and quickly emplaced (a few years) flood basalt lava flows. This work highlights some interesting and significant similarities, and contrasts, between the Nandurbar–Dhule dyke swarm and regional tholeiitic dyke swarms in Iceland, Sudan, and elsewhere.

Keywords Volcanism · Flood basalt · Deccan · Magma · Dyke swarm · Rifting · India

Introduction

Continental flood basalt provinces (CFBs) are products of fissure eruptions on a grand scale. The plumbing systems of these vast lava fields can be both extensive and complex (e.g., Walker 1999; Elliot and Fleming 2004), and dyke–sill networks are important parts of these. CFBs that are eroded exhibit dense swarms of mafic dykes that arguably represent congealed magma-filled fissures through which these lavas poured out. Mafic dyke swarms are of great current international interest, because of their value in understanding mantle-crust evolution and dynamics (e.g., Halls and Fahrig 1987; Parker et al. 1990; Baer and Heimann 1995; Ernst et al. 1995, 2001; McHone et al. 2005).

The ~65-million-year-old Deccan CFB of India (with a present-day areal extent of 500,000 km^2; Fig. 1) has been extensively studied in terms of geochemistry, palaeomagnetism, and stratigraphy. The flood basalts are best exposed in the Western Ghats (Sahyadri) region, where they reach a stratigraphic thickness of 3 km. Three regional-scale dyke swarms outcrop in the province (Auden 1949; Deshmukh

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R. Ray · H. C. Sheth (✉) · J. Mallik
Department of Earth Sciences,
Indian Institute of Technology (IIT) Bombay,
Powai, Mumbai (Bombay) 400076, India
e-mail: hcsheth@iitb.ac.in

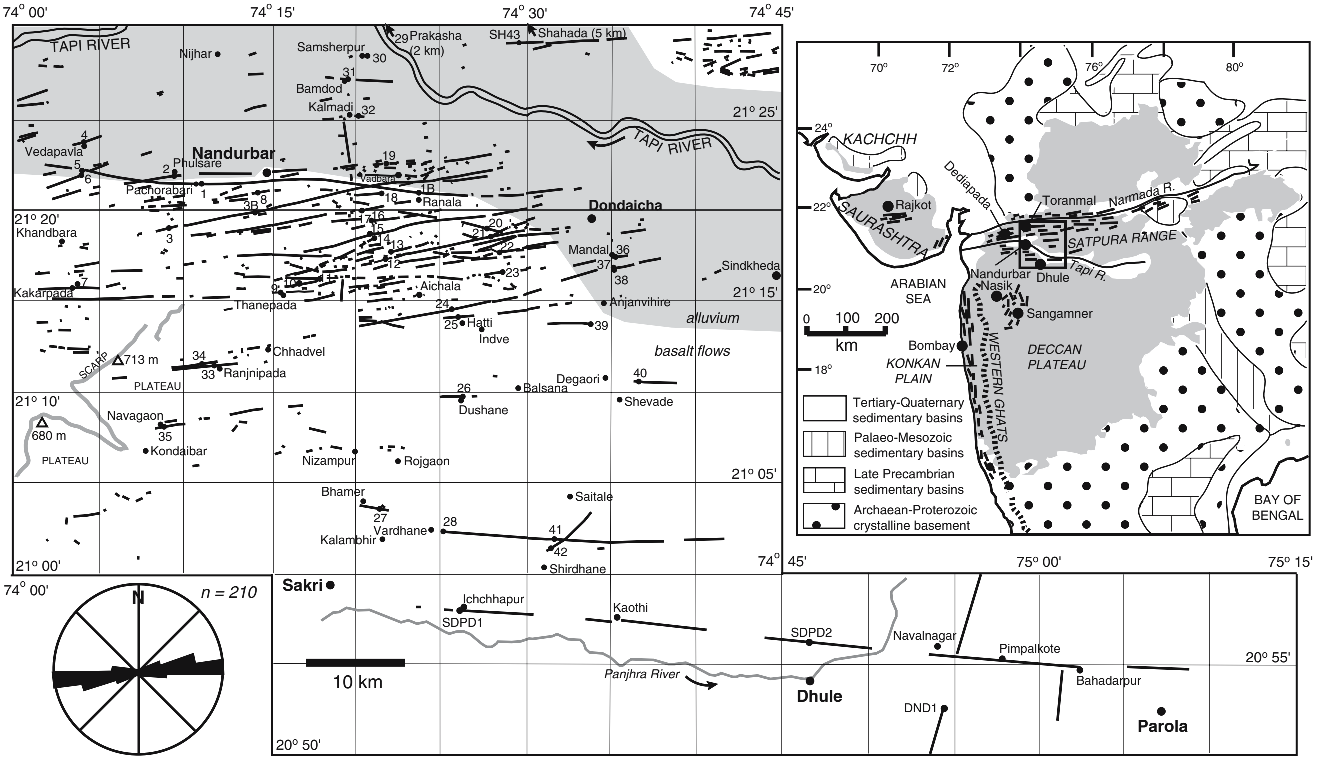

Fig. 1 Map of the Nandurbar–Dhule dyke swarm showing the major physiographic and geological features, the dykes, and sampling locations. All numbers have the prefix NBD (not shown). The alluvium belt along the Tapi River is shaded. At right is a key map showing the Deccan flood basalt province (*shaded*), its principal dyke swarms, and important localities. *Box* shows the location of the area of this study covering twenty toposheets of 1:50,000 scale. The toposheet nos. are: 46 K/2, 3, 4, 6, 7, 8, 10, 11, 12, 14, 15, 16; 46 L/1, 5, 9, 13; 46 O/2, 3, 4; 46 P/1. A rose diagram of the trends of 210 dykes (>1 km) measured over this region is shown at bottom left. The Nandurbar–Dhule dykes are shown on the map with uniform thickness so that the structural trends can be easily recognized and appreciated; the dykes are by no means of the same thickness or equally pronounced (see text)

and Sehgal 1988; Bondre et al. 2006; Fig. 1). The Narmada–Satpura–Tapi swarm is a linear, ENE–WSW-trending, giant dyke swarm (Sant and Karanth 1990; Ernst et al. 1995), apparently continuing westward into the Saurashtra peninsula. The NNW–SSE-trending Konkan or west coast dyke swarm (e.g., Dessai and Viegas 1995) is exposed on the Konkan plain, between the Arabian Sea and the Western Ghats escarpment to the east. Both these swarms contain profuse dykes of tholeiites as well as ultramafic, silicic, alkalic and carbonatitic rocks, plus larger intrusions. The third important dyke swarm in the province is the Western Ghats swarm northeast of Bombay, exclusively tholeiitic in composition (Beane et al. 1986; Vanderkluysen et al. 2004; Bondre et al. 2006).

Here, we discuss the geology, structural attributes and emplacement mechanics of a large tholeiitic dyke swarm, part of the Narmada–Satpura–Tapi giant dyke swarm, that outcrops in the Nandurbar–Dhule region of the central Deccan CFB (Fig. 1). Our study has the following objectives: (1) To provide field and structural data on this dyke swarm, (2) to estimate palaeostresses using these structural data, (3) to calculate the magmatic overpressures and source depths for the dykes and understand their emplacement mechanics, and (4) to discuss the broader implications of the data for the tectonomagmatic evolution of the Deccan Traps, and for flood basalts in general.

Regional geology

Much of the Nandurbar–Dhule area is flat, at a general elevation of ~200 m above mean sea level, and exposes highly weathered, zeolitized basalt lava flows of the compound pahoehoe type. In the Satpura Range to the north, thick basalt sequences such as the 870-m-thick Toranmal sequence (Fig. 1) are dominated by columnar-jointed "simple" flows. Geochemical–isotopic data for some of the basalt lavas and dykes (e.g., Sheth et al. 1997, 2004; Chandrasekharam et al. 1999; Mahoney et al. 2000) show broad to strong similarities with lava flows exposed in the Western Ghats. No felsic lavas or tuffs are seen, and red beds (altered tuffaceous materials or palaeo-weathering profiles) are very few and localized (a few tens of metres in lateral extent). Along the Tapi River, Tertiary and

Quaternary alluvium, 30-km-wide and 200–400 m thick, caps the basalt pile. The base of the lava pile is not exposed, and the lava pile may be a few hundred metres thick. Whereas the lavas are horizontal around Dhule and Dondaicha, they show distinct, gentle (5–10°) northward dips around places like Shahada and Kondaibar (Fig. 1). The Nandurbar–Dhule tholeiitic dyke swarm cuts the basalt flows. Being much more erosion-resistant than the lavas, the dykes form linear, often-prominent ridges that run for many kilometres. Duraiswami (2005) has discussed how the dykes control the local groundwater table in the Sakri area.

Published petrographic, mineral chemical and whole-rock geochemical data for many dykes in the Nandurbar–Dhule area (Melluso et al. 1999) suggest magma evolution in relatively shallow magma chambers. The magmas are evolved (MgO=3.30–6.00 wt.%, n=48) tholeiitic basalts and basaltic andesites, and low-pressure equilibration and fractional crystallization (especially of olivine) are evident. The Deccan lava pile in the Western Ghats and much of the Satpura region is also made up almost exclusively of such evolved subalkalic basalts and basaltic andesites (Sheth 2005), and the Nandurbar–Dhule dykes may well have supplied upper levels of the regional lava stratigraphy now lost to erosion, but likely preserved in sections elsewhere in the province, including the Western Ghats. Singh (1998), based on gravity modelling, postulated an igneous layer, 8–24 km thick, under the entire Narmada–Satpura–Tapi region, with its base at the Moho. Bhattacharji et al. (2004) carried out further gravity modelling and postulated shallow-level (7–8 km) magma chambers in this general region, consistent with Melluso et al.'s (1999) conclusions.

The dykes are very abundant just to the south of Nandurbar, but become fewer and more widely spaced farther away. Fig. 1 shows the part of our study area where the dykes are the most profuse, and covers six Survey of India topographic sheets of 1:50,000 scale (Nos. 46K/3, 7, 11, 4, 8, 12), with parts of others to the southeast. We have not represented our entire study area (covering twenty toposheets and an area of 14,500 km^2) in Fig. 1, as this would render the smallest dykes (here, 1 km long) invisible at the scale of the figure. This larger area is bounded by latitudes 20° 45′ N and 21° 45′ N and longitudes 74° 00′ E and 75° 15′ E.

Methodology

The first step in our study was to locate the dykes on the twenty toposheets. The sheets are commercially available from the Survey of India, and have a contour interval of 20 m. They beautifully depict the dykes as linear ridges many kilometres or tens of kilometres long, each with equal slopes on either side of the crest. Many dykes rise at least one contour interval above the lava flows, and dykes that are not so high are also well shown by dotted contours. A single dyke certainly does not always form a single continuous ridge over all its length, though two long dykes (~35 and 54 km) just south of Nandurbar indeed do so for much of their length (Fig. 1). Most dykes are made up of several linear segments that lie nearly on a straight line in most cases, with a spacing between the segments usually about 10% or so of the segment length, leaving little doubt as to a dyke's continuity. In some cases the dykes do not form continuous ridges, but can be identified by strongly aligned spot heights over long distances.

We were primarily interested in the strike, dip, length and thickness parameters for the dykes and their statistical distributions. Statistical treatment of structural data on high-density dyke swarms, made up of hundreds or thousands of dykes, is both valuable and essential in structural–tectonic interpretations (e.g., Klausen and Larsen 2002; Mandal et al 2006). The strike and length were noted for each individually discernible dyke on the toposheets. Many of the smallest dykes are offshoots of the larger ones (see also Melluso et al. 1999). Some of these were stubby in plan (low length/width ratios), and their exact trends were in fact difficult to determine. We have therefore excluded from our statistical analysis all dykes shorter than 1 km. We measured 210 dykes longer than 1 km; many are several kilometres long, some several tens of kilometres long, and the longest is 79 km long.

The toposheet measurements were followed by field work to examine and sample the dykes and their host rocks, and particularly to measure dyke widths. Previous experience shows that dyke thicknesses measured from a topographic map (or an aerial photograph) are usually significant over-estimates because the dyke ridges always include screens of the host basalts on either side, and no simple relationship exists between ridge width and actual dyke width.

Field observations

The dykes are all typical dolerites and basalts, quite fresh and undeformed, and almost all appear aphyric in hand sample, though thin sections show common microphenocrysts of plagioclase, clinopyroxene or olivine, in a groundmass largely of the same minerals with Fe–Ti oxides. No felsic dykes or composite dykes were found. No dykes passing into lava flows were observed, and no shallow-dipping sheets, sills, or plugs were observed either. No dyke tips were seen in vertical or lateral sections. The dyke ridges often rise sharply over the surrounding basalt lavas, and run for many kilometres (Fig. 2a, b). Almost all dykes are vertical, with a very few that are very steeply dipping (85°, Fig. 2b, c). A few thick dykes (e.g., Fig. 2c) show multiple cooling layers with horizontal columnar jointing, and may be the products of several magma injections over hundreds or thousands of years as inferred by Gudmundsson (1995a) for Tertiary dykes in Iceland. Many thick dykes show large-scale jointing that divides the dyke rock into roughly cubic blocks, and some other dykes are represented only by bouldery mounds. We did not come across any dyke forming low ground relative to the lavas, though one dyke forms a notch at the summit of a butte of the compound lavas (Fig. 2d). Thus, our methodology of locating dykes on toposheets followed by field work is likely to have located most dykes.

By no means are all dykes shown in Fig. 1 equally prominent. Dykes at high angles to the general ENE–WSW trend are often inconspicuous. Some are not even 5 m high, and yet easily identifiable on the toposheets from dotted

Fig. 2 The Nandurbar–Dhule dykes in the field. See Fig. 1 for locations. (**a**) Large ridge formed by dyke NBD1, at Pachorabari village, ~5 km W of Nandurbar. Dyke trends N85°, is vertical, 5.4 m wide and 54.3 km long. Field party for scale. (**b**) Dyke NBD25 in roadcut, near Hatti. Dyke strikes N83°, dips 85°, is 15.9 km long and 7 m wide, and shows platy jointing. (**c**) Dyke NBD9 near Thanepada, viewed along strike (N75°). Dyke dips steeply north (*right*), is >23 m thick, and shows some ten columnar-jointed rows, each ~2 m wide. (**d**) Dyke NBD27 (exactly behind the person) in a conspicuous lava butte near Bhamer, N of Sakri. The dyke trends N85°, is vertical, 5.2 km long and 3.5–4 m wide. (**e**) Intersecting dykes. Dyke NBD2 (*foreground*) is vertical, and slightly curved in plan but with an overall N75° trend. It is almost totally soil-covered and therefore of unknown width. Photo at Chikani Dagadi village, 1 km S of Phulsare. In the distance (*westwards*), the dyke meets the larger N85°-trending dyke NBD1, but cross-cutting relationships are ambiguous. (**f**) E–W-trending dyke NBD41 in roadcut S of Saitale, with two very clear margins (exactly behind students). Dyke is 23.3 km long and 7 m wide. (**g**) Dyke NBD40 NE of Shevade. Dyke trends E–W, is vertical, 5 km long, 13 m wide, well-jointed and bouldery, with very clear contact with compound flow of basalt (*lower ground*). (**h**) The 79-km-long Sakri–Dhule–Parola dyke forming a spine on a hill of compound flows, near Ichchhapur

contours. For example, a thin, >5-km-long dyke striking N10°W meets an ~E–W dyke just south of Kalmadi village (northeast of Nandurbar, Fig. 1). The N10°W dyke is so subdued, however (relief ~1–2 m) and so completely weathered and soil-covered that we were unable to determine which of the two intrudes the other. Similar is the situation with dykes NBD2 and NBD1 south of Phulsare, west of Nandurbar (Fig. 1, 2e). The contacts of the dykes with the country rock (where the dykes usually display finer grain size and small-scale blocky jointing) are sometimes very clearcut (Fig. 2f, g), making width measurement easy, but often one or both margins of the dyke are not visible because of weathering and soil cover.

The longest, 79-km-long, dyke (Fig. 2h) runs roughly E–W from near Sakri, through just north of Dhule, to Parola (SDPD in Fig. 1). It is only 7 to 6.5 m wide throughout its length. The thickest dykes (two) in the area are 62 m wide. Two long (54.3 and 35.8 km) dykes just south of Nandurbar show considerable thickness variation along strike; one of them also has a gentle but distinct curvature. The depth of the present-day exposure level beneath the initial top of the lava pile is not known, but from comparisons to the thicker basalt sections in the province, we estimate it to be ~1–1.5 km.

Structural attributes of the dykes

Dyke trends and palaeostresses

Most dykes strike roughly ENE–WSW or E–W. No faults or pre-existing fractures, along which dykes might have been emplaced, were noticed. Fig. 1 contains a rose diagram of the 210 dyke trends showing their strong preferred orientation. Fig. 3a shows the strike frequency histogram for the dykes, with a normal (Gaussian) distribution, and the mean strike is N88°. Undeformed dykes are very useful palaeostress indicators, because most dykes propagate as magma-driven extension fractures (mode I cracks) akin to hydraulic fractures that form perpendicular to the minimum principal compressive stress (e.g., Pollard 1987; Valko and Economides 1995; Ida 1999; Ernst et al. 2001; Gudmundsson and Marinoni 2002). The maximum (σ_1) and intermediate (σ_2) principal compressive stress directions lie normal to one another within the plane of the dyke, whereas the minimum principal compressive stress (σ_3) is perpendicular to the plane of the dyke. Our data suggest that the regional minimum principal compressive stress (i.e., maximum tensile stress, σ_3) was aligned ~N–S during dyke swarm emplacement. σ_3 was also horizontal, as the perfectly vertical (and rarely, very steep-dipping) dykes require. The spread in dyke strike may reflect fluctuations in the direction of σ_3 about a time-averaged mean direction. Gudmundsson (1995b) has made essentially similar observations in northern Iceland.

The few dykes at high angles to the general trend (Fig. 1) are similar to those often observed in regions of crustal extension and rifting, such as Iceland, and must indicate a temporary rotation of the three mutually perpendicular stress directions (Gudmundsson 1990, 1995a,b). Many E–W-trending dykes may, for example, be emplaced under a situation involving a N–S-oriented σ_3 direction and E–W-oriented σ_1, but the pressurization associated with the emplacement of these dykes may temporarily increase the compressive stress in the crust enough to make the σ_1 direction N–S and the σ_3 direction E–W. New dykes emplaced under these conditions acquire a N–S preferred orientation. With continued crustal extension and rifting, and compressive stresses generated by the N–S oriented dykes, the temporary stress field can rotate to the original with a N–S σ_3. New dykes emplaced in it would again acquire E–W preferred orientations. Thus, large numbers of parallel dykes that largely define the average direction of the swarm indicate the time-averaged, regional σ_3, whereas dykes that are at high angles to the general swarm trend indicate temporary (and sometimes spatially localized) rotation of the stress field (Babiker and Gudmundsson 2004).

Dyke lengths

The dykes show a great range in exposed length, from <1 km to 79 km. No dyke terminated laterally in such a way that we could be sure it did not continue further, so all measured lengths are minimum values. The swarm contains many dykes tens of kilometres long, and such dykes are also known from other areas in the province, such as central Saurashtra where the Sardhar dyke southeast of Rajkot (Fig. 1) runs for 55 km (Auden 1949). The 79-km-long dyke that runs from near Sakri through Dhule to Parola is probably the longest documented dyke in the province. It does not form a continuous ridge along this entire length, but consists of many segments. Keshav et al. (1998) mapped this dyke between Dhule and Parola and noted strike-perpendicular separations of several hundred metres between adjacent segments, much larger than the dyke thickness of ~7 m. They found no obvious connections (such as thin igneous veins) between consecutive segments, though such may exist at depth. Segmentation is an inherent and universal feature of dykes, owing to common lateral variations in crustal stresses that affect magmatic overpressures (dyke driving pressures), and discontinuities and layering in rocks (e.g., Delaney and Pollard 1981; Baer and Beyth 1990; Gudmundsson 1990, 1995a, 2002, 2003, 2005, 2006).

Length distributions of many dyke swarms show a power law relationship (e.g., Gudmundsson, 1995a,b; Mege and Korme 2004). Figure 3b shows the length size

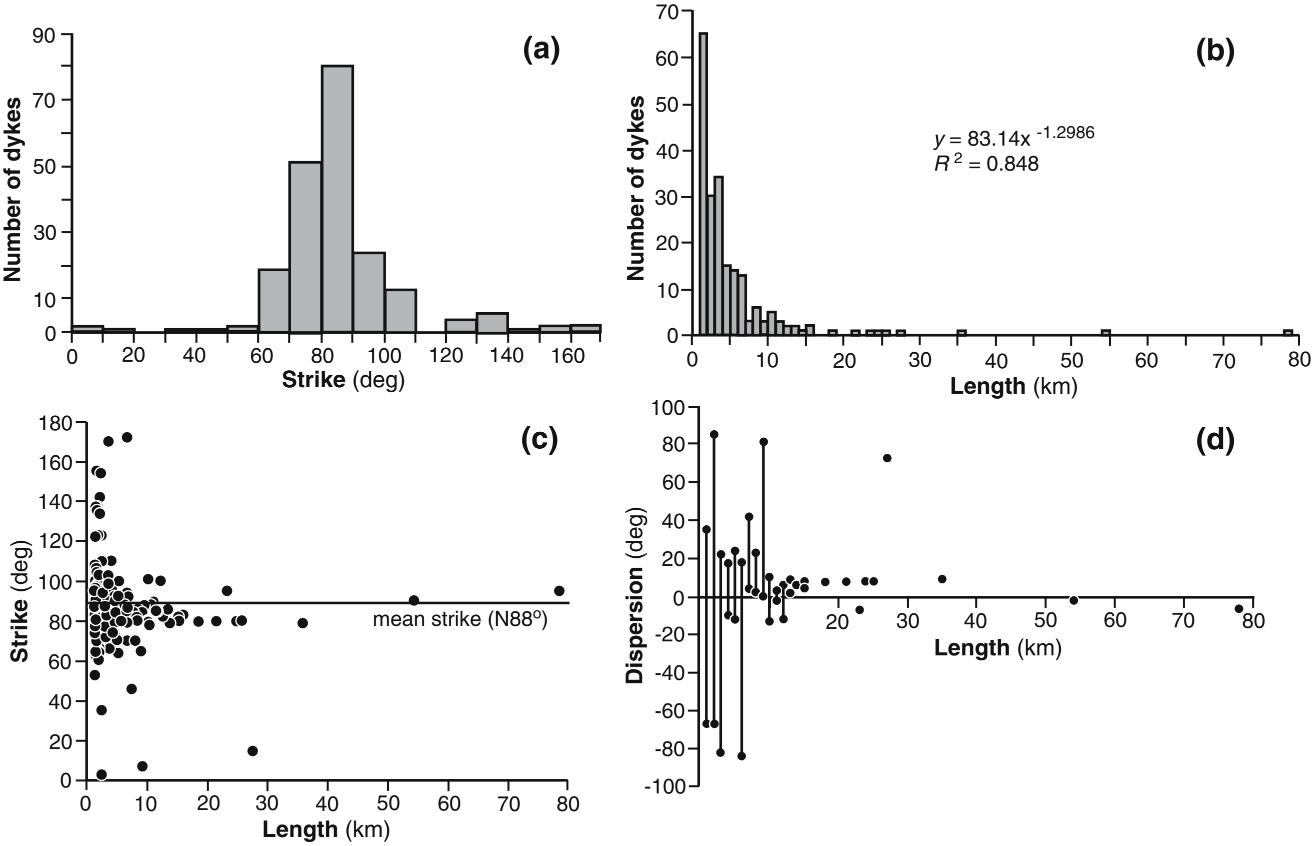

Fig. 3 (**a**) Histogram showing the distribution of 210 dyke trends measured. (**b**) Plot of the 210 dykes showing a typical power law distribution (of the general form $y=ax^k$). The exponent k is negative (−1.2986) and a, the constant of proportionality, is 83.14. Correlation coefficient R^2=0.848. (**c**) The variation in length as a function of dyke trend indicating that mostly the E–W-trending dykes achieve lengths >30 km. (**d**) Dispersion from mean trend as a function of length. *Vertical lines* connect the maximum and minimum dispersion (*black circles*) observed for a particular length, and thus define the range of dispersion observed in all dykes of a given length. *Single black circles* indicate only one dyke of that particular length

distribution of the Nandurbar–Dhule dykes, which is also described by a power law with a negative exponent. The mean length (5.4 km) differs from the mode (2 km). Because outliers affect the mean, the median (3.3 km) is a representative average length for these dykes. A plot of dyke strike vs. length (Fig. 3c) shows that it is mostly the E–W-trending dykes that are >30 km long. The dispersion from the mean trend is much greater for the smaller dykes than for the larger dykes (Fig. 3d), and the larger dykes thus better represent the direction of the time-averaged σ_3.

Dyke thicknesses

The thicknesses of twenty-seven dykes could be measured at their sampling sites with a tape (Fig. 2f), without any ambiguity. For the others, no margin or only one margin was distinct owing to weathering and soil cover. The measured thicknesses range from 3 to 62 m with a mean of 17 m and median of 10 m. Dyke swarms typically display thickness size distributions that are power law (e.g., Gudmundsson 1995a,b; Babiker and Gudmundsson 2004) or log-normal (e.g., Walker et al. 1995). The thickness size distribution for the Nandurbar–Dhule dykes is neither (Fig. 4a). We are not sure if this is an artifact of having few thickness measurements. Figure 4b shows that it is again the E–W-trending dykes that reach considerable thicknesses.

The two long dykes south of Nandurbar (Fig. 1) show considerable thickness variation along strike. One of these (54.3 km long) is 5.4 m thick where sample NBD1 was taken, but 24 m thick some 23 km to the east (sample NBD1B). The other dyke is ≥10 m thick where sample NBD3 was taken (only one visible margin), but 42 m thick 10 km to the east (sample NBD3B) (Table 1).

Aspect ratios

The aspect ratios (length/thickness) of the twenty-seven dykes are given in Table 1. Typically, longer dykes in regional dyke swarms are also thicker, as they are in the Tertiary dyke swarms in Iceland (Gudmundsson 1983, 1984). However, thickness and length show absolutely no correlation for the Nandurbar–Dhule dykes (Fig. 4c). The 79-km-long Sakri–

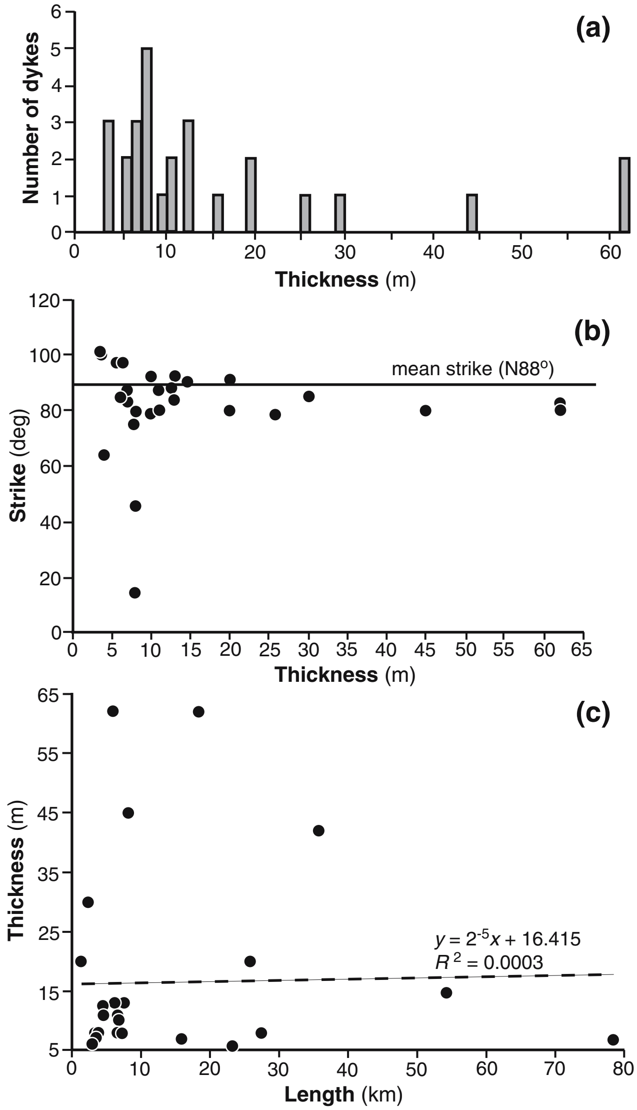

Fig. 4 (**a**) The thickness distribution for 27 dykes (mean thickness used where multiple measurements exist, in all three panels). (**b**) Thickness–strike plot. (**c**) Thickness vs. length plot, showing a complete absence of correlation (R^2=0.0003)

Dhule–Parola dyke has a thickness throughout its great length of only 6.5–7 m, and therefore a very high aspect ratio of 11,630:1, whereas the lowest aspect ratio is 70:1. This is a large range, with a mean aspect ratio of 1493:1 and a high standard deviation of 2326.7.

Crustal dilation

Marinoni (2001) has reviewed algebraic and trigonometric methods of calculating the crustal dilation produced or accommodated by sheet intrusions such as dykes and inclined sheets. A commonly used formula for percentage dilation (Walker 1959; Gautneb et al. 1989) is to divide the aggregate thickness of dykes or sheets (×100) by the length of the strip measured approximately perpendicular to the trend of the dyke swarm. However, this underestimates the dilation, and a more realistic formula (Marinoni 2001) is:

$$\%\ dilation = (aggregate\ \ dyke\ thickness)/ \\ (length\ of\ traverse - aggregate\ dyke\ thickness)$$

This simple formula is valid when the traverse along which dilation is measured is perpendicular to the dyke swarm and the dykes are vertical or nearly vertical (so that the width of outcrop equals thickness). Where the traverse is at a low angle to the trend of the swarm, or when the dykes or sheets are shallow-dipping, corrections indicated by Marinoni (2001) should be applied. These are unnecessary here, and we calculate the local percentage dilation in a small 5-km-long strip between the dykes NBD1 (5.4 m thick), NBD8 (62 m) and NBD3B (42 m), to be 3.8%. We cannot calculate the dilation along a longer strip over the densest part of the swarm because the thicknesses of many dykes could not be measured. Nevertheless, using ridge widths of fourteen dykes in a 12.5-km-long NNW–SSE traverse between Vadbara (east of Nandurbar) and Aichala, we calculate a percentage dilation of 15.8%, which must be an overestimate of unknown magnitude because of the previously indicated lack of any apparent relationship between ridge width and measured dyke width. We consider that a quite conservative estimate of the percentage dilation accomodated by the Nandurbar–Dhule swarm in its densest part is 5%, and this is considerable (but see below).

To the northwest of Nandurbar, the strongly ENE-oriented tholeiitic dyke swarm of Dediapada was studied by Krishnamacharlu (1972) who reported some 71 dykes with an aggregate thickness of 5,000 feet in a ~NE–SW, 18-mile profile and a crustal dilation of 4%. 5000 feet in 18 miles translates to crustal dilation of 5.6%, using the formula above, and Krishmacharlu's (1972) profile was at quite a small angle to the swarm trend. It is not clear how the value of 4% was arrived at, but it seems roughly correct. In Iceland, crustal dilation due to Tertiary and Pleistocene regional dyke swarms is highly variable, from 1–2% to as high as 28% along partial profiles, and the average dilation is 5–6% (Gudmundsson 1995b).

Dyke initiation, magmatic overpressures, and source depths

Gudmundsson (1983) used dyke aspect ratios to calculate magmatic overpressures and thereby depths of dyke origin in eastern Iceland, the latter consistent with seismic and electrical resistivity data. Babiker and Gudmundsson (2004) used aspect ratios of mafic dykes in Sudan to calculate magmatic overpressures. Taking a value of ~8 km for the depth to the source magma chambers of the Nandurbar–

Table 1 Dyke parameters and calculated magmatic overpressures (P_o) and source depths (z)

Sr. no.	Dyke no.	Trend (Nxy^{o})	Length (km)	Thickness (m)*	Aspect ratio (L/T)	P_o (MPa) for E=5 GPa	P_o (MPa) for E =10 Gpa	Depth z (km) for E=5 GPa	Depth z (km) for E=10 GPa
1	NBD1-1B	90	54.3	14.7	3,694				
2	NBD3B	79	35.8	42	852				
3	NBD8	82	6	62	97	28.0	56.1	*28.6*	*57.2*
4	NBD10	80	4.6	11	418	6.49	13.0	6.62	13.2
5	NBD11	87	6.7	11	609	4.45	8.91	4.54	9.09
6	NBD12	80	25.8	20	1,290				
7	NBD13	75	3.9	8	488	5.56	11.1	5.68	11.4
8	NBD14	64	5.2	4	1,300	2.09	4.17	2.13	4.26
9	NBD18	85	2.9	6	483	5.61	11.2	5.73	11.4
10	NBD19	87	3.5	7	500	5.43	10.8	5.54	11.1
11	NBD20	101	10.1	3.5	2,886				
12	NBD24	80	18.4	62	297				
13	NBD25	83	15.9	7	2,271				
14	NBD27	100	5.2	3.7	1,405	1.93	3.86	1.97	3.94
15	NBD28-41	95	23.3	5.75	4,052				
16	NBD30	85	2.4	30	80	33.9	67.8	*34.6*	*69.2*
17	NBD31	92	6.85	10	685	3.96	7.92	4.04	8.08
18	NBD32	91	1.4	20	70	38.8	77.5	*39.5*	*79.1*
19	NBD33	84	7.6	13	585	4.64	9.28	4.73	9.47
20	NBD34	80	8.2	45	182	14.9	29.8	*15.2*	*30.4*
21	NBD35	80	3.4	8	425	6.38	12.8	6.51	13.0
22	NBD39	88	4.5	12.5	360	7.54	15.1	7.69	15.4
23	NBD40	92	6.2	13	477	5.69	11.4	5.80	11.6
24	NBD42	46	7.4	8	925	2.93	5.87	2.99	5.98
25	NBD36	79	6.6	8	825	3.29	6.58	3.36	6.71
26	DND1	15	27.5	8	3,438				
27	SDPD1-2	95	78.5	6.75	11,630				
	Mean				1,493	10.1	20.2		
	s.d.				2,326.7	11.32	22.64		

Notes: * denotes mean thickness for dykes with multiple thickness measurements along strike, as recommended by Gudmundsson (1983). This is not possible for NBD3-3B. Other values are single measurements. Overpressures and source depths are calculated only for the dykes with a strike dimension smaller than or equal to the dip dimension (height above magma chamber, taken here as ~8 km). Anomalously large values of source depths are shown in italics. Note that dyke NBD9 (Fig. 2c), apparently the product of multiple magma injections, does not feature here, as only one margin of it was exposed. *s.d.* =standard deviation.

Dhule dykes, based on previous petrological and gravity modelling, we can calculate the magmatic overpressures in the same way. We assumed, as did Gudmundsson (1983) and Babiker and Gudmundsson (2004) for dykes in Iceland and Sudan, respectively, that those Nandurbar–Dhule dykes that have a strike dimension (trace length) shorter than the dip dimension (dyke height above magma chamber, ~8 km) were emplaced essentially vertically. There is, of course, no a priori reason why these dykes cannot have formed in part by lateral injection, but vertical injection from shallow magma chambers is a plausible assumption for these select dykes.

In general, dykes initiate when a magma chamber or reservoir ruptures, and this happens when the following condition is met (Gudmundsson 1995a):

$$P_T = \sigma_3 + T_O \tag{1}$$

where P_T is the total magmatic pressure in the reservoir, and σ_3 and T_o are the minimum principal stress and the in situ tensile strength, respectively, in the roof rocks of the source reservoir.

If P_L is the lithostatic stress, then the magmatic excess pressure

$$pe = P_T - P_L \tag{2}$$

Equation (1) can then be rewritten as

$$\left(P_L + pe = \sigma_3 + T_O\right) \tag{3}$$

The magmatic excess pressure p_e in the source magma chamber, buoyancy effects, and the state of stress in the host rock together determine the magmatic overpressure P_o (also called net pressure or driving pressure). P_o is the pressure available at any particular point to drive open the walls of a dyke-fracture. A long-lived magma chamber is in lithostatic equilibrium with the host rocks, and then $P_L=\sigma_3(=\sigma_1)$. New magma entering the chamber, or a reduction in σ_3 because of extension in the roof, temporarily makes $p_e>T_o$, and a dyke is initiated. Possible stress concentration effects due to the irregular shape of the magma chamber are included in the local magnitude of σ_3 (Gudmundsson 2002).

Dykes that never reached the surface can be modelled as circular interior cracks. Volcanic fissures (feeder dykes), and probable feeder dykes exposed at shallow depths in rift zones (such as here) can be modelled as two-dimensional through-the-thickness cracks between two free surfaces, one the Earth's surface and the other the surface of the magma chamber (Babiker and Gudmundsson 2004). The strike dimension (trace length, L) for such dykes is smaller than the dip dimension (height above the chamber), which is treated as being effectively infinite (Gudmundsson 2005). The magmatic overpressure P_o can be calculated using the equation (Sneddon and Lowengrub 1969):

$$P_O = (b_{max}E)/2L(1-v^2) \tag{4}$$

where b_{max} is the maximum dyke thickness, and E and v are the Young's modulus and Poisson's ratio respectively, of the host rock. b_{max} is directly proportional to overpressure but inversely proportional to the Young's modulus E of the host rock, a measure of stiffness. Stiffness increases with confining pressure (depth) but decreases with increasing rock porosity, water content, and temperature, and most importantly fractures. Because of fractures and discontinuities with different frequencies (Priest 1993), values of E for common in situ rocks can be 20–65% of values based on small-sample laboratory measurements. Laboratory measurements on basalts and gabbros yield stiffnesses as high as 110–130 GPa; volcanic tuffs, on the other hand, have laboratory values as low as 0.05–0.1 GPa (Afrouz 1992; Bell 2000). Static laboratory stiffnesses vary between 0.5 GPa and 8 GPa for most young hyaloclastites in Iceland, and between 10 GPa and 35 GPa for near-surface Holocene and Pleistocene basaltic lava flows in Iceland (Oddson 1984; Egilsson et al. 1989; Gudmundsson 2006). The stiffnesses of these rocks generally increase with age and depth of burial. Corresponding contrasts in Poisson's ratio in a multilayered sequence are much more limited. Appropriate values of Poisson's ratio are 0.25 for granitic crust, 0.28 for basaltic crust, and 0.30 and higher for ultramafic rocks (Babiker and Gudmundsson 2004; Mohan and Ravi Kumar 2004).

Babiker and Gudmundsson (2004) calculated magmatic overpressures of early Cretaceous and late Proterozoic dykes in Sudan, emplaced in much older (and cooler) granitic basement. They used values of E for the granitic basement of 10 and 30 GPa, values that are appropriate considering the antiquity of the basement relative to the dykes. In contrast, the Nandurbar–Dhule dykes were emplaced at shallow levels (presumably 1–1.5 km) in a basaltic lava pile that was itself forming and was thus young, warm, and with low stiffness. Almost the whole pile is made up of compound pahoehoe lava flows, and such flows are composed of hundreds of small (metre-scale) pahoehoe flow units, lobes and toes (Bondre et al. 2004a,b; Sheth 2006), which again means low stiffness.

Considering these factors, in situ E values of 5–10 GPa are most appropriate for the basaltic lava pile (A. Gudmundsson, pers. comm.). Using these values, and a corresponding Poisson's ratio of 0.28, we calculated the magmatic overpressures of the Nandurbar–Dhule dykes (Table 1). The range of calculated magmatic overpressures is from 1.93 to 38.8 MPa (for E=5 GPa), and 3.86 to 77.5 MPa (for E=10 GPa). Most of the calculated P_o values seem very reasonable, and are within the range obtained by Babiker and Gudmundsson (2004) for the Sudanese dykes (though the latter were emplaced in granitic rocks).

We used the overpressures to calculate the depths to source magma chambers as done by Gudmundsson (1983) for some regional Icelandic dykes, using the equation:

$$z = P_O/(\rho_r - \rho_m)g \tag{5}$$

where ρ_r is the average crustal density (assumed to be 2,800 kg/m^3), ρ_m is magma density (2,700 kg/m^3, Pinel and Jaupart 2004), and g the acceleration due to gravity. The calculated depths to magma chambers (Table 1) are low (a few kilometres) for fourteen of the dykes, consistent with the petrological and gravity modelling. For these dykes, therefore, the assumption of vertical injection from shallow magma chambers and the use of Eq. (4) are valid. Four dykes, however, have anomalously large values of source depths, and these are notably the stubbier dykes with low aspect ratios: NBD34 (182:1), NBD8 (97:1), NBD30 (80:1), and NBD32 (70:1). The latter three dykes are particularly short for their width. In comparison, the Sudanese dykes have aspect ratios between 243:1 and 2330:1. As noted, all length estimates here are lower bounds, and so all overpressure values are upper bounds, as they are in the study of Babiker and Gudmundsson (2004). A distinct possibility exists that these stubbier dykes are actually longer but not exposed throughout their length at the present level of exposure, and their aspect ratios have therefore been underestimated — perhaps significantly. Notably, the dykes NBD30 (2.4 km long, 30 m wide) and NBD32 (1.40 km long, 20 m wide) are exposed in the alluvium of the Tapi River, and probably do run for considerable distances under the alluvium. However, whereas incomplete along-strike exposure can be invoked to explain the low aspect ratios and therefore the relatively high calculated magmatic overpressures and source depths these few Nandurbar–Dhule dykes, thermal erosion (Fialko and Rubin 1999) must also be considered as a mechanism that can create the same effect.

Discussion

Thermal erosion

Thermal erosion of wall rocks by magma flowing in a dyke is a non-dilational mechanism of dyke widening, i.e., if thermal erosion occurred, the measured dyke thickness would not represent the crustal dilation associated with fracture opening and dyke emplacement (Fialko and Rubin 1999). Fialko and Rubin (1999) found that thermal erosion is most significant in wide dykes (~7 m and upwards) with turbulent magma flow and wall rocks of granitic composition. Some of the Nandurbar–Dhule dykes (Fig. 1) are tens of metres thick, and the median thickness is 10 m. We did not observe any obvious evidence of thermal erosion (such as xenoliths) in any of the dykes, including the thicker ones. A few of these apparently formed by repeated magma injections in the same fracture, as shown by many columnar cooling layers (Fig. 2c). Gudmundsson and Marinoni (2002) and Babiker and Gudmundsson (2004) described such dykes from Iceland and Sudan respectively, and argued that their multiple nature suggested insignificant thermal erosion. Kristjansson (1985) found from magnetic studies that a typical 4-m-thick Tertiary dyke in Iceland was able to reset the remanence in the adjacent lava flows (at ~500°C) out to a distance only about 10% of the dyke width. However, our dykes are much thicker than this, and turbulent flow as opposed to laminar flow is an important factor (Huppert and Sparks 1985; Fialko and Rubin 1999). A dolerite dyke described from this region by Chandrasekharam et al. (1999) has chemical and isotopic characteristics reflecting significant bulk assimilation of granitic crust, which the authors postulated occurred during turbulent flow during ascent through the crust (cf. Huppert and Sparks 1985). The dyke, 15 m thick at the level of exposure, notably has the highest initial $^{87}Sr/^{86}Sr$ ratio (0.72315) of any Deccan rock analyzed to date, and the lowest initial εNd value (−20.2) as well.

Fialko and Rubin (1999) showed that thermal erosion of basaltic wall rocks (fusion temperature 1,150°C, Bruce and Huppert 1990) by mafic dyke magma (say, at 1,250°C) may be as low as a few percent, though dyke width and turbulent flow are important, and *mechanical* erosion of wall rocks can also occur. In any case, the chilled dyke margins with fine jointing that we have seen are not evidence against thermal erosion. Though chilled margins have been thought to indicate that the wall rocks were effectively sealed off from the flowing magma, Fialko and Rubin (1999) present a scenario of repeated chipping-off of chilled margins due to magma turbulence, so that the chilled margins seen today are only the final surviving ones. Overall, for the few dykes in our study which are abnormally thick for their length, we consider thermal erosion as likely an explanation as incomplete along-strike exposure. This is, of course, not to say that thermal erosion has not occurred in the other dykes, because if these dykes fed substantial lava flows at higher levels (which we consider probable), then hot, mafic magma flowed for several years past any single point within the dyke fracture and may have caused some thermal erosion. Thermal erosion can explain not only the anomalously low aspect ratios of these few dykes, but also the unusual thickness distribution for the dykes and the absolute lack of correlation between dyke length and width.

If thermal erosion did occur on a large scale in a large number of Nandurbar–Dhule dykes, our estimate of the average crustal dilation would clearly be an overestimate, though it would be difficult to assess its magnitude. Thermal erosion is not a *required* mechanism for most of the Nandurbar–Dhule dykes, but it cannot be ruled out as a possible cause of the very low aspect ratios of some of the dykes.

Lateral dyke propagation and magma flow

As seen, vertical injection from a magma chamber is a reasonable assumption for dykes with a strike dimension smaller than the dip dimension (where the latter is independently known) (Table 1). Lateral injection must be considered for the rest. Several workers have studied the dynamics of lateral magma transport in dykes (e.g., Lister and Kerr 1991; Rubin 1995; Ernst et al. 1995; Fialko and Rubin 1999). In continental giant dyke swarms, such as the 2,000-km-long Mackenzie dyke swarm in Canada, magma flow was predominantly vertical in the central area of the topographic uplift and changed to horizontal farther away, as inferred from measurements of anisotropy of magnetic susceptibility (AMS), dyke fabrics, and dyke wall structures (Greenough and Hodych 1990; Ernst and Baragar 1992). Doubts have been raised recently on the usefulness of AMS and magnetic fabrics to infer magma flow directions, because in several cases these characteristics appear to have been affected or even decided by late-stage crystal settling of magnetite grains around plagioclase laths, and similar mechanisms unrelated to magma flow itself (McHone et al. 2005).

Gudmundsson (1990, 1995a,b) argued that linear, regional dyke swarms in Iceland form by essentially vertical injection from regional magma reservoirs located below the crust (Fig. 5), because crustal magma chambers that can drive lateral dykes are absent in many areas. In the Narmada–Satpura–Tapi region, magma chambers at shal-

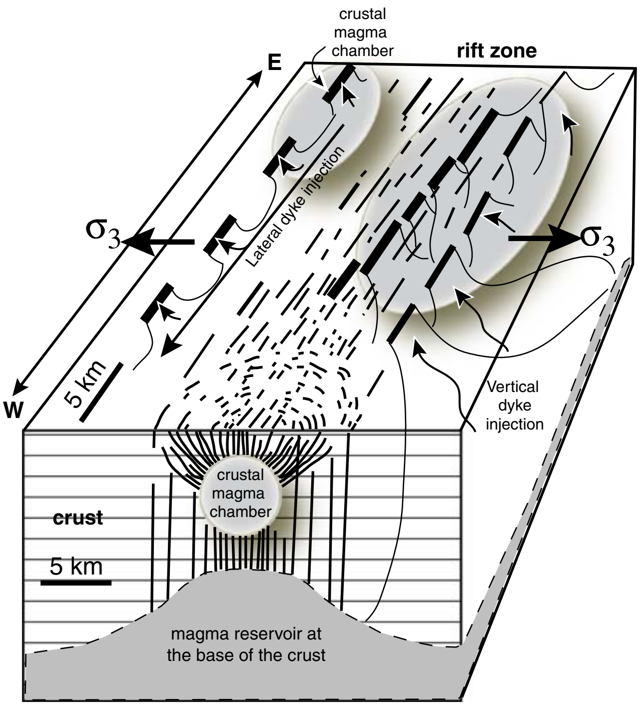

Fig. 5 Schematic block diagram that integrates the features of the Nandurbar–Dhule dykes with those of regional dykes in Iceland. The latter dykes become longer and thinner (not shown) with increasing depth, and are emplaced essentially by vertical injection from a large magma reservoir below the crust. A spherical magma chamber within the crust produces dyke and sheet swarms of highly variable orientations around it, but the rest of the rift zone experiences the regional stress, and hence the consistent orientations of the regional dykes. Such local dyke/sheet swarms do not exist in the Nandurbar–Dhule area, though roughly ellipsoidal shallow magma chambers are inferred within the crust. Both vertically and laterally propagating dykes are injected from these magma chambers, and the consistently oriented dykes reflect the regional stress. The large magma reservoir shown represents the reservoir at the base of the crust under Iceland, and also the large igneous layer postulated within the crust under the Narmada–Satpura–Tapi region, as explained in the text

low depths have been proposed, and the consistent regional orientations of the dykes then reflect very homogeneous regional stress conditions, under which both vertical and long-distance lateral dyke injection could occur. The longer of the Nandurbar–Dhule dykes, such as the two long dykes just south of Nandurbar, must have involved lateral dyke propagation. One of these, dyke NBD1-1B, shows distinct curvature in plan, probably a consequence of several laterally propagating and coalescing fracture segments as modelled by Mandal et al. (2006).

Many regional dykes in Iceland and Britain (Macdonald et al. 1988) and elsewhere are discontinuous in lateral sections, and commonly offset by large distances relative to their thickness. Such dykes are usually longer at depth than nearer the surface, and also become thinner with depth, with a roughly Y-shaped geometry (Gudmundsson 1990; Ernst et al. 1995; Fig. 5). Gudmundsson (1990) argued that the direction of magma flow in such regional dykes made up of offset segments is more likely to have been vertical than lateral. Constant thickness along strike, on the other hand, may be more consistent with lateral magma flow. The Sakri–Dhule–Parola dyke maintains a near-constant thickness of 7 to 6.5 m throughout its 79 km length, and like many laterally injected dykes worldwide, it is segmented. In such dykes, systematic compositional changes along strike may be expected. The laterally injected Jurassic dykes of eastern North America (Greenough and Hodych 1990), and the Mackenzie giant dykes (Baragar et al. 1996) show more contamination downstream than upstream. Two samples of a segmented regional dyke just outside the map area in Fig. 1, collected ~35 km apart, showed somewhat different elemental and Nd–Sr–Pb isotopic compositions (Sheth et al. 1997). The initial $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratios are 0.70481 (±0.00002) and 0.70474, initial εNd values are +1.4 (±0.2) and +1.5, and present-day $^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$ ratios are 17.483 (±0.012) and 17.578. This dyke may be a laterally injected dyke, though the observed chemical variation is perhaps not inconsistent with vertical magma flow from a large and incompletely homogenized magma chamber. Future geochemical and isotopic studies of the Nandurbar–Dhule dykes will throw light on these issues. We believe that whereas several of these dykes may have formed as essentially vertical injections from shallow magma chambers, others must have been injected laterally.

Broader dynamical implications

Our study offers the first insights into the structure and emplacement of a regional, linear, tholeiitic dyke swarm in the Deccan Traps. It also enables comparisons, especially to regional tholeiitic dyke swarms in Iceland. Those swarms are some 50 km long, 5–10 km wide, and contain several hundred dykes, with the average dyke thickness being ~4 m (Gudmundsson 1990). In their great lengths, regionally consistent orientations, verticality, and power law length distribution, the Nandurbar–Dhule dykes mimic the Icelandic regional dykes. On the other hand, the Nandurbar–Dhule dykes show characteristics such as an irregular thickness distribution and a total lack of correlation between dyke length and thickness that contrast with those of the Icelandic regional dykes. Incomplete along-strike exposure can probably explain these results. Thermal erosion of the wall rocks by dyke magmas, due to turbulent flow in wide dykes, also explains these results well. Interestingly, the same mechanism has been considered insignificant in Iceland (Gudmundsson and Marinoni 2002) and Sudan (Babiker and Gudmundsson 2004), where the dyke swarms do show regular (power law or log-normal) thickness distributions and good correlations between dyke length and width. Clearly, much work remains to be done on the Nandurbar–Dhule and other dyke swarms in the Deccan province, but the following broader dynamical interpretations can be considered reasonably robust.

Magma reservoirs and magma chambers

Gudmundsson's (1990, 1995a,b) thesis that the regional dykes in Iceland are emplaced directly from large, sub-crustal magma reservoirs (Fig. 5) was essentially based on the absence of crustal magma chambers in many parts of the rift zones, and also supported by the primitive (MgO-rich) compositions of many lavas and regional dykes. The roughly spherical magma chambers that do develop under central volcanoes in Icelandic rift zones produce their own stress patterns and dyke-sheet swarm configurations that overprint the regional rift- and plate-scale ones (Fig. 5). Dykes and sheets in such central volcanic swarms have highly variable strike, and average dips of (45–60°), usually towards the centre of the associated central volcano. They are also much thinner (1 m thick on the average) than the regional dykes (Gudmundsson 1990). It is of interest that the Saurashtra–Kachchh region, northwestern Deccan province, abounds in plugs and plutons with radial and arcuate dykes (e.g., Auden 1949). The shallowly emplaced dykes in our study area have a clear and strong E–W-preferred orientation, suggesting that shallow magma chambers were unable to overprint the regional stress during dyke emplacement, probably due to significant crustal extension. Based on gravity modelling, Bhattacharji et al. (2004) postulate up to eight of these shallow, disconnected fossil magma chambers (with the average density of 2.96 g/cm^3), which were apparently sourced from a larger, deeper reservoir represented by a dense body at ~25 km depth. The fossil magma chambers are 23.8±2.4 km in length, 15.9±1.5 km wide and 12.4±1.2 km thick on average, and thus roughly prolate ellipsoids in shape. Their roofs are at an average depth of 6.5±0.6 km below the Earth's surface (Fig. 5).

Previously, Singh (1998) postulated, based on gravity modelling, a large, thick mafic igneous layer (of density 3.02 g/cm^3) under much of the extent of the Narmada–Satpura–Tapi zone. This igneous layer has been intruded into the crust, which he determined to be of normal crustal thickness (38 km), with the base of the layer at the Moho. The layer is as much as 24 km thick under the west coast, west of our study area, and ~16 km thick under Nandurbar–Dhule, thinning to 8 km towards the east. This means that the top of the igneous layer under the Nandurbar–Dhule region is at a depth of ~22 km. This layer is in many ways similar to the regional magma reservoir that exists under the Icelandic crust, and some of our dykes may have been derived directly from it. We look forward to acquiring and modelling geochemical and isotopic data on these dykes.

Ponding, crustal extension, and magma drainage

A provocative idea proposed recently (McHone et al. 2005, Silver et al. 2006) is that the stupendous flood basalt events are not the result of catastrophic *melting* events in mantle plumes, but catastrophic *drainage* events. These authors postulate that CFB melts form and accumulate to form vast ponds or reservoirs beneath the lithosphere, over long time periods (several million years). When lithospheric extension allows magma ascent, a huge number of lithospheric dykes form that drain the melt rapidly from the magma reservoirs to the surface, with or without crustal magma chambers.

The Nandurbar–Dhule dyke swarm was evidently associated with significant crustal extension. A role for pre-volcanic or syn-volcanic crustal extension in flood basalts has not been acknowledged by all workers however. For example, Hooper (1990) stated that crustal extension succeeded the Deccan eruptions and did not precede it. He argued that the feeder dykes of the Western Ghats lava pile were a group of somewhat randomly oriented tholeiitic dykes in the same region (Beane et al. 1986), and that the alkalic compositions of many dykes in the Narmada–Satpura–Tapi region meant that they could not have fed the uniformly tholeiitic Western Ghats sequence. His argument essentially was that the Narmada–Satpura–Tapi dykes (including the huge tholeiitic ones) did show strong preferred orientations, were intrusive into the lava pile, and therefore indicated extension to have succeeded volcanism, whereas in the Western Ghats, the randomly oriented feeder dykes indicated the lack of pre-volcanic extension.

Sheth (2000) analyzed Hooper's (1990) thesis and pointed out that the fact that many dykes in the Narmada–Satpura–Tapi and west coast regions were intrusive into the lava pile (e.g., Auden 1949) did not preclude the possibility that these dykes produced lava flows at higher levels, now lost to erosion but likely preserved in sections elsewhere. Sheth (2000) pointed out that most of these dykes were truncated at the present ground level. The Nandurbar–Dhule dykes are exactly so (Fig. 2). It is important that not a single case of a dyke tip ending vertically in the lava pile has been reported. As regards the alkalic dykes, we do agree with Hooper (1990) that they could not have supplied the tholeiitic lava pile-but the large tholeiitic dykes did, in all probability.

Interestingly, the new data of Vanderkluysen et al. (2004) and Bondre et al. (2006) on dykes from Sangamner (Fig. 1) and other areas of the Western Ghats show that the orientations of the potential feeder dykes are not as random as they have been thought to be previously (Beane et al. 1986; Hooper 1990), and whereas several of these dykes may well have fed substantial lava flows that make up the local stratigraphy, some other dykes that show close chemical similarities to the lava flows show significant differences in their isotopic compositions. Several lava flows in the Western Ghats may have been locally erupted, whereas others probably extended to long distances of up to several hundred kilometres from massive tholeiitic feeder dykes located in the Narmada–Satpura–Tapi and west coast regions. Thick lava sections (>1 km) in the Satpura mountain range were arguably formed similarly, with some lavas being locally derived and others covering long distances (Mahoney et al. 2000). If flood lavas could cover distances of 500 km or more after eruption in the Columbia River basalt province (Hooper 1997), they could have done so in the Deccan.

Eruption rates and time scales

For the huge Roza Member of the Columbia River CFB of northwestern U.S.A., Thordarson and Self (1998) calculated an eruption rate of 4,000 m^3/s, using a total emplacement time of 10 years, and an exposed linear eruptive vent–fissure system 150 km long. This rate is the same as the peak eruption rate of the 1783–84 Laki eruption in Iceland, the world's largest historic eruption (Thordarson et al. 1996). Individual segments in the 27-km-long Laki fissure remained active one after another over several months. Several large compound pahoehoe flows in the Deccan have volumes of 1,000 km^3 and larger, though how much larger cannot be answered because individual flow fields have not been systematically mapped. Even if the eruption rates for the lava flows were only of the order of 1 m^3/s per metre of feeder dyke length (the average for Kilauea, Self et al. 1997), then a 5-km-long segment of a 50-km-long feeder dyke, active at any one time, would produce 5,000 m^3/s of lava, or ~105 km^3 over eight months. Then eruptive activity could shift to another 5-km-long segment by lateral magma migration, and thus the 50-km-long fissure would produce 1,050 km^3 of lava over 80 months, or ~6.66 years. This is directly comparable to the figures for the Columbia River basalts obtained by Self et al. (1997) and Petcovic and Dufek (2005), and, the eruption rate per metre length of fissure (1 m^3/s) is no greater than that for modern Kilauea eruptions. If larger dyke segments or entire dykes were active throughout their length, however, a large, 1,000 km^3 lava flow may well have been emplaced in a couple of years — or much less.

Conclusions

The large tholeiitic dyke swarm around Nandurbar and Dhule in the central Deccan flood basalt province, mapped over an area of 14,500 km^2, exposes 210 dykes >1 km in length. The dykes intrude highly weathered basalt flows, mostly compound pahoehoe. The longest dyke is 79 km and several are tens of kilometres long. All are vertical or almost so, and from 3 to 62 m thick. The dykes show strong preferred orientations, with an average trend of N88°. Because the dykes are not emplaced along faults or pre-existing fractures, the data indicate that the regional minimum horizontal compressive stress (σ_3) was aligned approximately N–S during the emplacement of the swarm. The length distribution of the dykes is described by a power law with a negative exponent, as are dyke lengths within many swarms worldwide, but the thickness distribution is irregular. Dyke length and width show no correlation. Using the aspect ratios (length/thickness) of the dykes, we calculate very reasonable values of magmatic overpressures and shallow depths (a few kilometres) to source magma chambers, consistent with previous petrological and gravity modelling studies. Relatively high overpressures and source depths calculated for a few dykes, on the other hand, may be an artifact of systematically underestimated aspect ratios due to insufficient along-strike exposure of the dykes. However, thermal erosion can also explain the anomalous results. Whereas many of the dykes may be vertical injections from shallow magma chambers, others, especially the long ones, must have been formed by lateral injection from such chambers. The larger of the Nandurbar–Dhule dykes could have produced substantial volumes of Deccan lavas; at low, Kilauea-like eruption rates of 1 m^3 per metre length of fissure, a 50-km-long dyke in the region with consecutively active 5-km-long segments could produce a lava flow >1,000 km^3 in volume, in <7 years. Given long-enough feeder dykes, huge Deccan lava flows could erupt and extend to considerable distances within years. Future systematic mapping and geochemical characterization of individual large Deccan lava flows and flow fields, as well as of regional dykes, should provide fundamental insights into the volcanological, stratigraphic, and tectonic evolution of flood basalt provinces.

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