Evidence of the deformation of dykes from the Central Deccan Volcanic Province, Aurangabad, Maharashtra, India

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Abstract: The Deccan Volcanic Province (DVP) covers an area of more than 500 000 km^2. There are three major dyke swarms in this province, viz. the Narmada-Tapi, the Western Coast and the Pune-Nasik. In addition, the Nandurbar-Dhule and Pachmari dykes have also been studied. However, the Central Deccan Volcanic Province (CDVP), including parts of Aurangabad (Maharashtra, India), has received less attention than the SW, northern and NE parts of the Deccan Trap. We report on deformed/offset dykes in and around Aurangabad, in the CDVP. These dykes intrude the stratified host basaltic lava flows composed of weathered porphyritic and amygdaloidal basalt. This rheological contrast locally affected the emplacement of dykes, producing offset, the formation of sills, the curvature of dyke walls and finger-like intrusions. The offset of dykes is presumably caused by variations in local stress. The dyke swarm from the CDVP is reported for the first time. The range in the length and width of the dykes is 2.4–26.2 and 1–27 m, respectively. The dykes trend NE, which matches that of the Narmada-Tapi dyke swarm. The present study indicates that the feeder dyke(s) may have fed the basaltic lava flows of the Aurangabad region. The bent pipe vesicles indicate that the lava flowed towards the SE.

Continental flood basalt provinces are produced by fissure eruption (Ray *et al.* 2007). The Deccan flood basalt erupted at approximately 65 Ma in the Indian peninsula and currently covers more than 500 000 km^2 (e.g. Watts & Cox 1989). These are best developed in the Western Ghat escarpment in the SW part of the province (Sheth *et al.* 2013) where they are 1.7–2.0 km thick (Kaila *et al.* 1981). They thin out gradually towards the east. Dykes, sills and plugs are important components of the magmatic plumbing system of the Deccan Trap.

The Seychelles microcontinent separated from India at approximately 64–62 Ma, with prolific volcanism affecting India and the Seychelles during the Late Cretaceous–Early Paleocene. This volcanism is described as Deccan Traps (Misra *et al.* 2015; Mukherjee *et al*. 2016 and references therein). Dyke swarms are reported from various parts of the Deccan Trap (Misra 2008). Misra *et al.* (2014) recently described in detail the dykes and brittle shear zones from the Deccan Trap in and around the Mumbai region (also see Misra & Mukherjee 2015*a*, *b*; Misra *et al.* 2015). These dykes are brittle sheared. North-trending dyke swarms on the Konkan plain between the Arabian Sea and the Western Ghats escarpment (West Coast dyke swarm) (e.g. Viswanathan & Chandrasekharam 1976; Widdowson *et al.* 2000; Hooper *et al.* 2010), and the Nasik-Pune dyke swarm NE of Mumbai and partly on the Konkan plain have a weak NNE trend (Beane *et al.* 1986; Bondre *et al.* 2006; Vanderkluysen *et al.* 2011).

There are three major dyke swarms in the Deccan Trap (Auden 1949; Deshmukh & Sehgal 1988; Vanderkluysen *et al.* 2011): one of them is the ENE-trending Narmada-Tapi dyke swarm (e.g. Bhattacharji *et al.* 1996; Melluso *et al.* 1999; Ray *et al.* 2007); and other two are the north-trending Western coast dyke swarm and the NNE-trending Pune-Nasik dyke swarm.

Kaplay & Wesanekar (2014) reported 'mini-dyke swarms' and small 'feeder dykes' from the SE Deccan Volcanic Province (SEDVP) of the Nanded region. However, the Central Deccan Volcanic Province (CDVP: Aurangabad region) is less studied than the SW, northern and NE parts of the Deccan Trap (Sheth *et al.* 2013). The dykes from the CDVP were briefly described by Karmarkar & Muley

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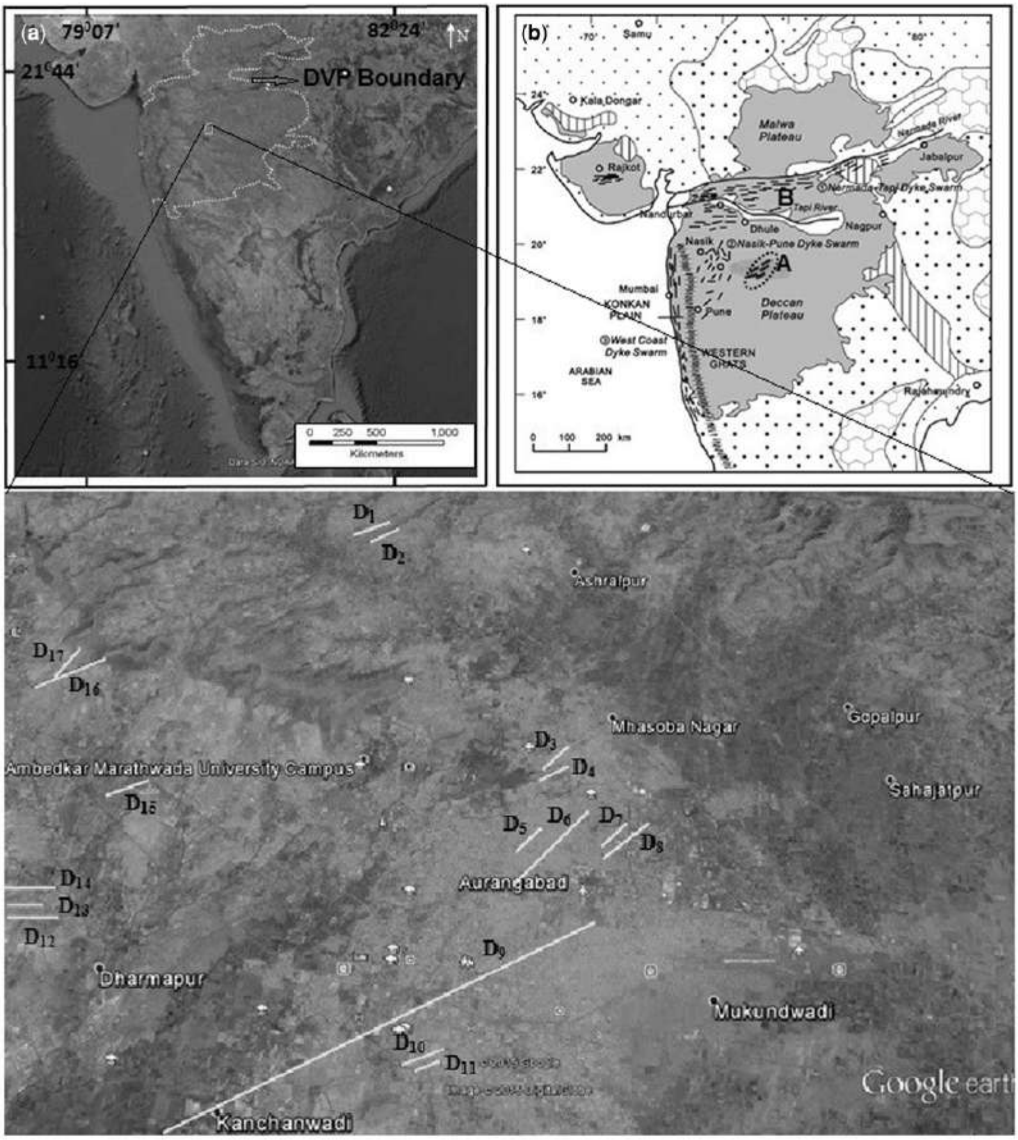

Fig. 1. Orientations of the dykes from the Aurangabad dyke swarm. The map is compiled with inputs from Chande (1985) and the present work. Inset (**a**) shows a Google Earth image of the location of the study area. Inset (**b**) is a map showing three major dyke swarms in the Deccan Volcanic Province (DVP) (Deshmukh & Sehgal 1988). The dotted ellipse indicates the 'Aurangabad dyke swarm'. The trend (NE–SW) of the Aurangabad dyke swarm (A) corroborates with the trend of the Narmada-Tapi dyke swarm and the Pachmari dykes (B).

(1977, 1978). Chande (1985) reported as many as 17 dykes from the Aurangabad district, most of which trend NE. We report on the 'feeder dykes' from the CDVP of the Aurangabad region. In addition, deformation features, both primary and secondary, have also been studied. The primary structures include offsets developed at the time of dyke propagation along a surface of rheological contrast, and the secondary structures include kinking and offset.

Study area

The study was carried out in and around Aurangabad. The dykes, referred to here as the 'Aurangabad dyke swarm', have been mapped in the field. However, construction and excavation have rendered most of the dykes unsuitable for field measurements. Figure 1 shows the spatial distribution of the dykes.

Dyke lineaments

A lineament was defined by O'Leary *et al.* (1976, p. 1463) as:

> a mappable simple or composite linear feature of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differs distinctly from the patterns of adjacent features and presumably reflects a subsurface phenomenon.

The definition that was re-coined as:

> A lineament is a regional scale linear or curvilinear feature, pattern or change in pattern that can be identified in a data set and attributed to a geologic formation or structure (Qureshy & Hinze 1989, p. 5).

In the topographical domain, geological lineaments are associated with geomorphological features (e.g. linear valleys, ridgelines, escarpments and slope breaks). Many structural features (e.g. faults, fractures, joints, veins and dykes) may be expressed as 'lineaments' in remote sensing images (Masoud & Koike 2006). Spectral signatures of dykes in the images are characterized by dark tones. Fine textures exhibit a linear to curvilinear ridge-like (elevated) topography with a discordant intrusive relationship with country rock (Veeraiah *et al.* 2006). Dyke lineaments can thus be identified in satellite images by their conspicuous narrow ridge-like features. Prior to fieldwork, the dykes were identified on toposheets and Google Earth images. The dykes are compact basalts, more resistant than the amygdaloidal/porphyritic basalt as the host rock. Therefore, the dykes appear as 'narrow ridges'.

Field characters of dykes

Most of the dykes are exposed as ridges of high relief. However, as the dyke rock is compact, it is used as a building material, and, hence, these dykes are excavated and are now exposed as linear depressions flanked by the host rock. In places, only remnants of these dykes are exposed (Fig. 2). The horizontal columnar joints and sharp dyke–host rock contact enable these intrusions to be identified more easily in the field. Almost all of the dykes are single intrusions. Terminations of the dykes into the horizontal basaltic lava flows were not observed, however.

The dykes are discontinuous and trend NW. In places, they exhibit an 'en echelon' pattern (Chande 1985). Some of these dykes run parallel to each other for approximately 2–3 km.

Types of dykes

Based on composition and cross-cutting relationships, two types of dykes were recognized. The first type of dyke is a compact basalt that shows horizontal columnar joints. The other type of the dyke is the 'feeder dyke' and is an 'amygdaloidal basalt type'. In addition, small intrusions have also been reported. Dykes are devoid of 'xenoliths' and show an equigranular texture. However, in some instances, the grain size is finer at the contact than in the centre (Chande 1985). Such a disparity in grain size indicates a high cooling rate at the margin owing to the temperature difference between the dyke and the host rock.

The disposition of these dyke lineaments is shown in Figure 1. Of the 17 dykes shown, 14 trend NE, whereas the rest trend east. The length and thickness of the dykes varies from 2.4 to 26.20 km and from 1.0 to 27 m, respectively. The thickest dyke (27 m) intrusion is reported from D_6 (Fig. 1). The thickness of the dykes, except for a few, does not vary along the trend. Table 1 presents the field measurements of the length and width of the dykes.

The host rock for both the Majnu Hill dyke and the Satara dyke is porphyritic basalt (Fig. 3). However, phenocrysts are larger for the latter and, hence, it is referred to as the Giant Porphyritic Basalt. The country rock for the Jatwada dyke is highly weathered basalt.

The dykes usually share a sharp contact with their host rocks (Fig. 3). However, in places, the contact is wavy, possibly characterized by calcrete deposition. Thin, chilled contacts were also found (Fig. 4a).

Off-shoot and vein intrusion

Some of the dykes show small, sub-parallel 5–14 cm-thick off-shoot or finger-like projections (Fig. 4a), which, in places, maintain a sharp contact with the host rock (Fig. 4b). A few of them are as thick (1.5 m) as the main dyke (Chande 1985). Occasionally, thin quartz and zeolite veins also occur within the dykes (e.g. the Majnu Hill dyke: referred to here as D_4).

Joints in the dykes

All of the compact basalt dykes show typical 'horizontal columnar joints'. The columns are four- to six-sided (Fig. 5). The cooling surfaces are vertical.

Columnar joints in basalt form perpendicular to the cooling front (Spry 1962). In a basaltic flow, the cooling front is horizontal and, therefore, the

Fig. 2. (**a**) Low-lying ridge as the surface expression of dykes at Jatwada. (**b**) The aerial view of the Majnu Hill dyke, with the locations of outcrop exposures at points A, B, C and D. (**c**) Remnants of dykes (marked as arrows) along the almost totally excavated dyke at Satara (D_{10}) and (**d**) Mitmita dyke (D_{15}).

columns are vertical (Simon & Conrad 2008); while horizontal columns are developed in dykes with a vertical cooling front (Juang & Chen 2004). However, the orientations of the basaltic columns from the D_4 dyke change from almost horizontal (1°) to vertical (78°) within a narrow zone (Fig. 6) that possibly also indicates a shift in the orientation of the cooling front, which, in turn, may be attributed to a local temperature sink (Fig. 6).

The tensional stresses set up during contraction may produce regular joint sets perpendicular to the cooling surfaces. The joint columns propagate inwards from the cooling surfaces as the 'cooling front' advances (Grossenbacher & McDuffie 1995; Cas & Wright 1996; Robert & Allen 1997; Simon & Conrad 2008).

The dykes also show vertical sets of joints that cut through the horizontal columns. The spacing between the vertical joints increases from the boundary towards the central part of the dyke. This could be attributed to the lowering of the cooling rate inwards from the boundaries. Closely spaced vertical joints were found to occur only on one side of the Satara dyke (D_{10}), while there were none on the other side (Fig. 7). The field evidence suggests that all of these joints are cooling joints.

Discussion

'Basaltic dykes', also referred to as the 'Aurangabad dyke swarm', have intruded the CDVP in the study area. Almost 80% of the dykes trend NE and the rest trend east (Fig. 8). Most of the dykes are almost straight, and a few dykes are curved.

The length distribution of the dykes is shown in Figure 9. Mean, mode and median lengths of the dykes are 9.29, 5.1 and 6.0 km, respectively. The length distribution does not follow a negative power law (Gudmundsson 1995).

Table 1. *Location and disposition of the dykes*

S.N.	Locality	Trend	Orientation	Length exposed (km)	Thickness (m)
D_1	Rahatpati Laman Tanda, Jatwada	N55° E–S55° W	Vertical	4.2	4.20
D_2	Ovur village	N45° E–S45° W	Vertical	4.0	4.70
D_3	Harsul	N55° E–S55° W	Vertical	8.3	8.00
D_4	Majnu Hill	N85° E–S85° W	Vertical	12	4.75
D_5	Rama International Hotel	N55° E–S55° W	Vertical	4.40	5.50
D_6	Between Satara Hill and Hotel Ajanta Ambassador	N50° E–S50° W	Vertical	10.8	27.00
D_7	Prabhu Industries, Chikhalthana	N50° E–S50° W	Vertical	3.80	6.00
D_8	Chikhalthana	N50° E–S50° W	Vertical	5.40	1.00
D_9	Satara	N70° E–S70° W	Vertical	26.20	16.00
D_{10}	Satara Hill	N65° E–S65° W	Dipping 78° due north	5.4	13.5
D_{11}	Satara Hill	N65° E–S65° W	Dipping 78° due north	3.2	13.5
D_{12}	Tisgav Hill	East–west	Vertical	3.6	6.5
D_{13}	Tisgav Hill	East–west	Vertical	2.6	6.0
D_{14}	Tisgav Hill	East–west	Vertical	3.6	4.9
D_{15}	Padegaon village	N65° E–S65° W	Vertical	2.4	8.0
D_{16}	Aurangabad–Chalisgaon Road	N50° E–S50° W	Vertical	7.6	7.1
D_{17}	Aurangabad–Chalisgaon Road	N35° E–S35° W	Vertical	3.4	7.0

Orientation and thickness values are taken from Chande (1985).

Primary structures

Offset in dykes. The present study revealed a number of primary structures: for example, offset, finger-like intrusions, feeder dykes and bent vesicles.

Offset in the D_4 dyke has been reported previously by Hanamgnod *et al.* (2011). They, in their preliminary study, reported the displacement of this dyke and attributed it to localized tectonic disturbance or deformation. The dyke is exposed at four different points (Figs 10, 11, 12, 13 & 14).

Offsets are developed at the time of dyke propagation along a surface of rheological contrast. Hence, these features are not related to any tectonic deformation.

We found feeder dykes along the same section, where dyke displacement has been reported by Hanamgnod *et al.* (2011) near Majnu Hill (Fig. 11). These dykes are made up of amygdaloidal basalt, which cuts through the porphyritic basalt flow, thus developing a horizontal contact of the lower porphyritic basalt with the upper amygdaloidal basalt. The compact basalt dyke cuts through these two flows. In the feeder dyke, walls are curved parallel surfaces.

The nature of non-planar dyke walls may be attributed to contrasting mechanical (rheological) properties of the host rock (Maria *et al.* 2012). The compact basalt dyke near Majnu Hill (with horizontal columnar joints) shows non-planar dyke walls towards the upper part of the dyke (Fig. 11), which could be due to the contrasting rheological properties of the porphyritic and amygdaloidal basalt.

The D_4 dyke near Majnu Hill, that was reported on by Hanamgnod *et al.* (2011), trends almost east–west (N85° E–S85° W). The basaltic dyke shows typical horizontal columnar joints. The dyke is exposed at four points, viz. A, B, C and D, towards the SW (Fig. 2).

At A, the dyke is 4.75 m wide and is offset by 5 cm in a north–south direction (Fig. 10).

However, the dyke at B is 4.75 m wide and exhibits a larger offset (1.3 m) than that at A. The distance between the dykes at A and B is 5 m (Fig. 15). The sense of offset is ‘dextral’ (Fig. 11). The lower part of the dyke is displaced towards the south, while the upper part is displaced towards the north.

Dyke offset across layers of contrasting rheological (mechanical) properties is a common

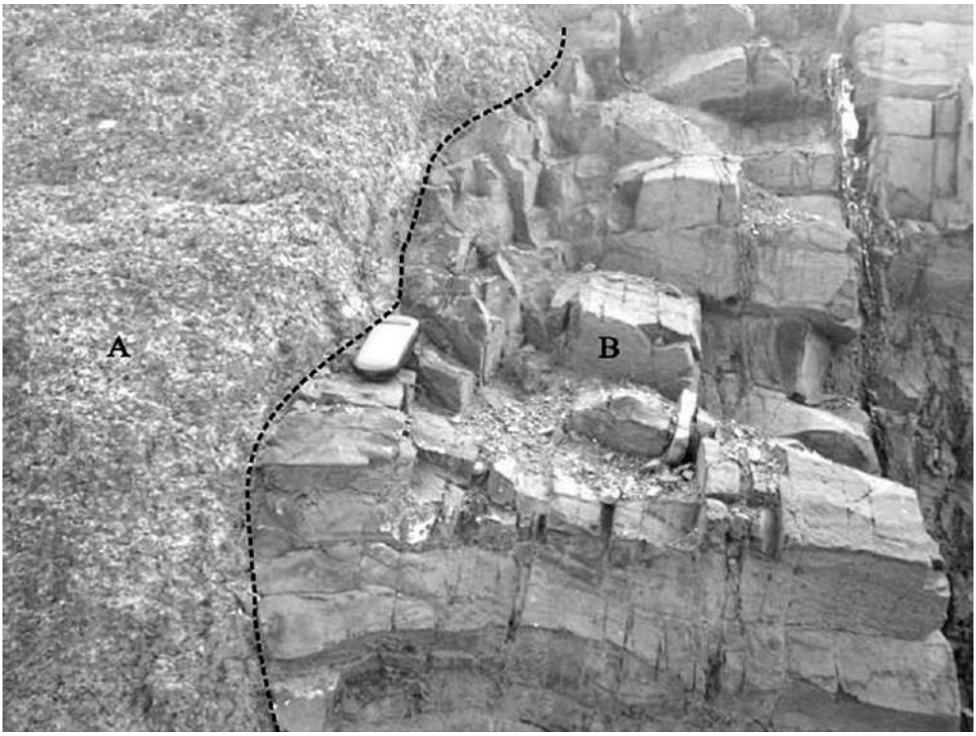

Fig. 3. Sharp contact of the porphyritic host rock (A) with the compact basalt dyke rock (D_4).

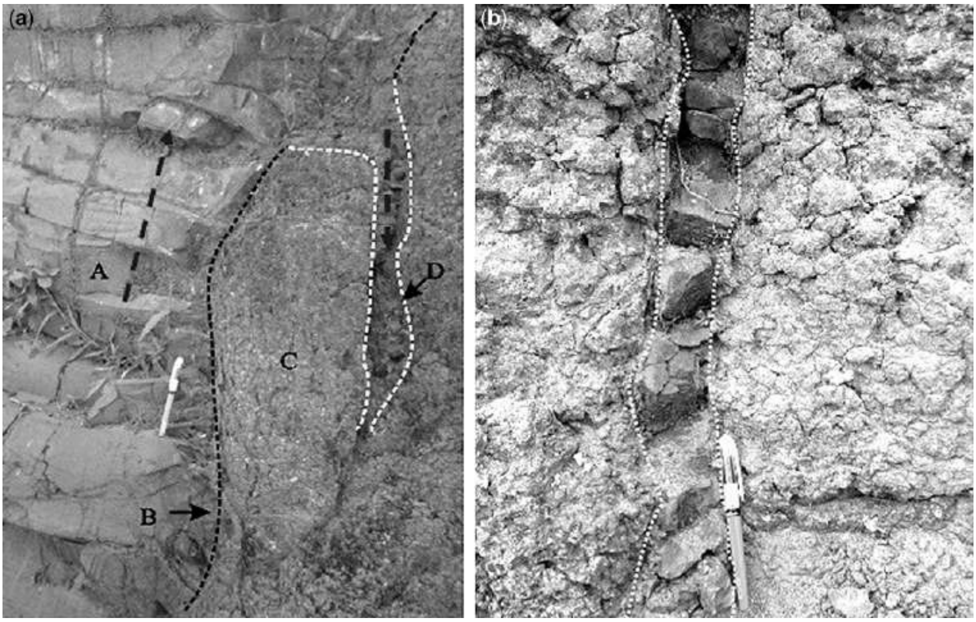

Fig. 4. (**a**) A, Majnu Hill dyke rock (D_4); B, a thin chilled margin; C, porphyritic host rock; D, small off-shoot (finger-like projection) along the Majnu Hill dyke (marked as E in Fig. 10). The dashed arrows indicate the flow directions of the dyke and off-shoot. (**b**) Small intrusion along the Jatwada dyke (D_1).

Fig. 5. Typical cross-section of a horizontal columnar joint of dykes with four- to six-sided columns (D_1).

phenomenon (Gudmundsson & Brenner 2004), which also illustrates the pronounced effect of rheological variations in the host rock on dyke propagation. Such offsets may also be partly related to mechanical weaknesses along the contact. A similar feature was encountered near Majnu Hill (Fig. 11): here the dyke has apparently been displaced along the vicinity of the stratigraphic joint. This may be attributed to a stress barrier related to the abrupt difference in stiffness between the porphyritic basalt and the amygdaloidal basalt.

A dyke may follow the contact as a sill for some distance (Gudmundsson *et al.* 2002). In Figure 11, the lower part of the dyke is offset towards the south along the contact of two different rocks (marked as B in Fig. 11; a magnified view of the same is shown in Fig. 12).

A block model view of the structures (Fig. 15) illustrates the variation in the offset magnitude, which rises from A (5 cm) (Fig. 10) to B (1.3 m) (Fig. 11) and then again decreases at C (30 cm) (Fig. 13). No offset was discernible at D (Fig. 14). Local stress variations, which also seem to be the case here, are unfavourable for dyke propagation and may arrest the dyke (Gudmundsson & Brenner 2004). However, dyke arrest is not observed in the Aurangabad region.

Finger-like intrusions. Some of the dykes (e.g. D_4 and D_1) generated thin, irregular finger-like intrusions (Fig. 4), which follow an oblique trend but are concordant to the main dyke. In D_4, the finger-like projection is in the opposite direction to the propagation of the main dyke. This intrusion

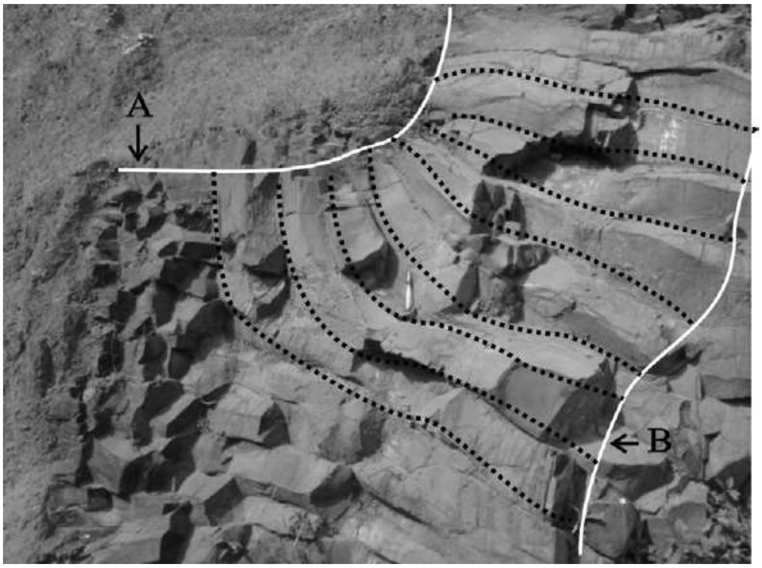

Fig. 6. Dyke showing the change in the orientation of the cooling front (D_4). A, horizontal cooling front; B, subvertical cooling front.

has clearly come from the main body of the dyke magma

Feeder dykes. Feeder dykes are reported from different parts of the DVP. Arguably, the Deccan lava flows were largely fed by dykes in swarms (e.g. Swanson *et al.* 1975). The Narmada-Tapi dyke swarm might be linked genetically with the lower- and middle-level stratigraphic formations of the Western Ghats sequence some distance from the Narmada-Tapi region. The Coastal and Nasik-Pune swarms contain many feeders to the Western Ghat (Widdowson *et al.* 2000; Bondre *et al.* 2006; Hooper *et al.* 2010; Vanderkluysen *et al.* 2011). Deccan

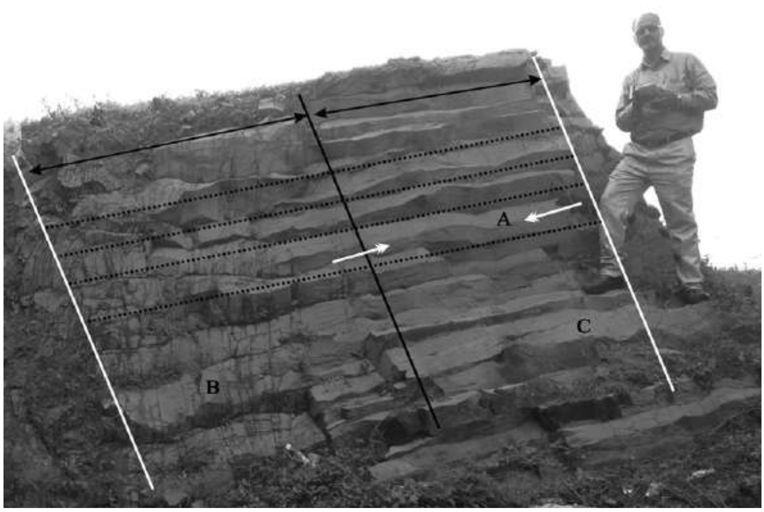

Fig. 7. Remnant of the Satara dyke (D_{10}, dipping towards the north at 79°) with 'deformed columns' at A; B, vertical sets of joints restricted only on one side of the dyke; the other side, C, is devoid of the vertical set of joints. The dotted lines indicate the orientation of columns in the dyke; the solid line indicates the cooling front; and arrows indicate the direction of compression (north–south).

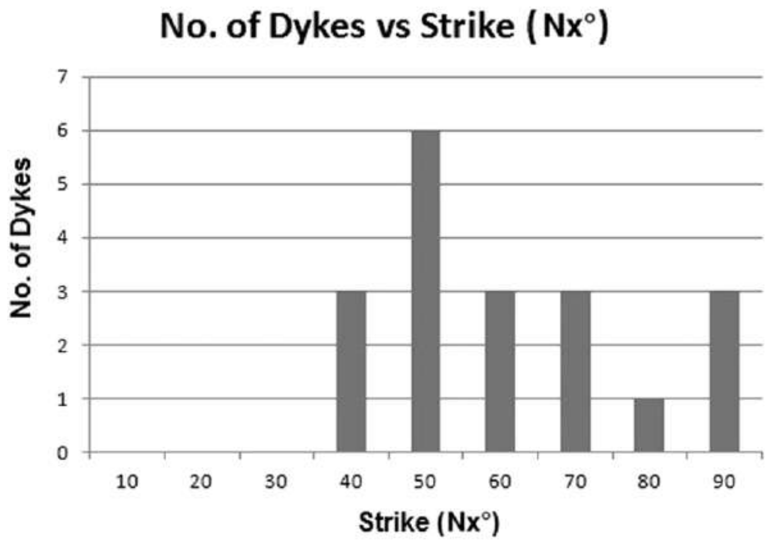

Fig. 8. Strike frequency histogram of the Aurangabad dyke swarm.

lavas seem to have migrated quite long distances (see also Self *et al.* 2008).

The present study reveals the exposure of a ‘feeder dyke’ near Majnu Hill (Fig. 16). Compositionally, the dyke is amygdaloidal basalt, pouring into the top horizontal basaltic flow. Perhaps, the Aurangabad region was also one of the eruptive centres for the formation of the Deccan Trap.

Deformed vesicles. Deformed vesicles indicate the lava-flow direction (Philpotts & Ague 2009 in Misra 2014). The pipe amygdaloidal basaltic flow near Majnu Hill is inclined towards the west at 39°. The pipe vesicles in this flow are deformed and are bent towards the SE (the dashed black lines in Fig. 17).

Secondary deformation structures

Kinking. The evidence of deformation is observed from the remnant part of the Satara dyke (marked as B in Fig. 2c). Horizontal columnar joints are common in the dykes of basaltic composition. The columns from this dyke (D_{10}) undulate in a narrow

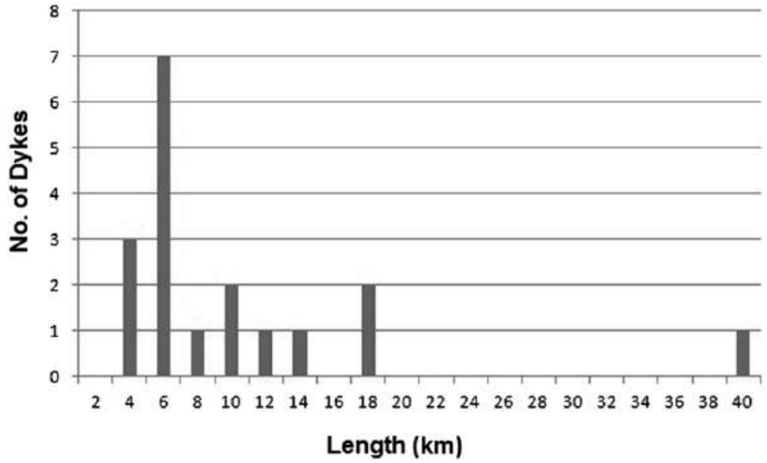

Fig. 9. Length distribution of the dykes.

Fig. 10. The cross-section view of A from Figure 2b: the compact basalt dyke showa an offset of 5 cm (dyke D_4). E, small offshoot.

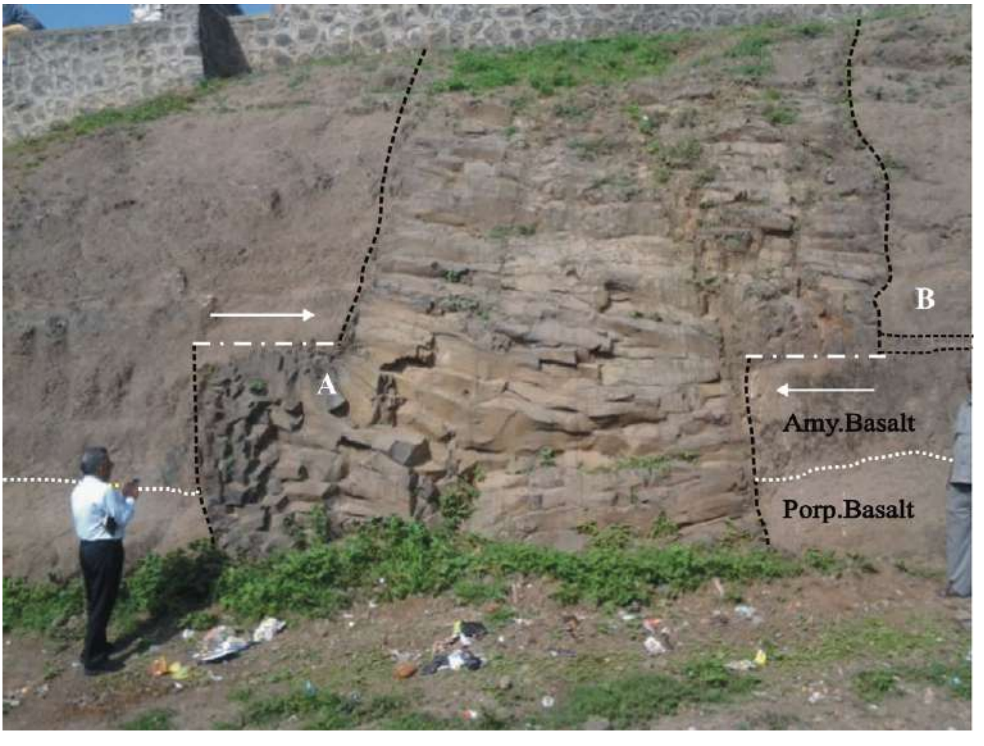

Fig. 11. A dyke (D_4) showing deformation (offset) near Majnu Hills in Aurangabad City. Amy. Basalt, amygdaloidal basalt; Prop. Basalt, porphyritic basalt. A, columnar joints become vertical here, in the rest of the dyke the columns are horizontal. B, sill following the contact of two rocks.

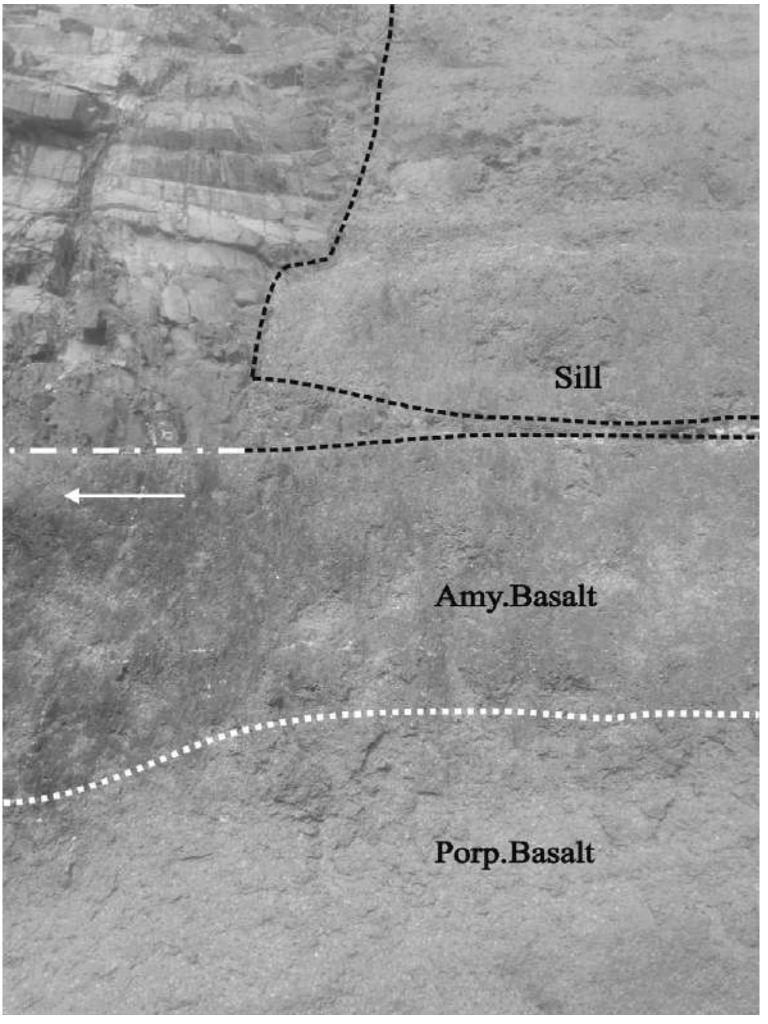

Fig. 12. Magnified view of B (D_4) in Figure 11. This part of the dyke (marked as B in Fig. 11) follows the horizontal contact for a while (1.3 m) in a direction towards the north, which is exactly opposite to the direction of offset (which is towards the south) shown by the dyke. Amy. Basalt, amygdaloidal basalt; Prop. Basalt, porphyritic basalt.

zone. The dip direction of a few of these varies from NNE to south. These zones are interpreted to be 'kink hinges' (Fig. 18), although not tight kinks. These columns are either horizontal or dip uniformly towards the south at 15°–22°. This structure may be attributed to north–south-directed compression. However, these are absent in other dykes.

Offset. Offsets are also observed from another remnant part of the Satara dyke (marked as A in Fig. 2c). A subvertical intrusion within this part shows an offset of 15 cm (Fig. 19). The orientation of the displacement is north–south.

The kinking towards the west (marked as B in Fig. 2c) suggests that it underwent north–south compression. Moreover, the offset towards the east (marked as A in Fig. 2c) also suggests similar deformation, leading to the displacement of the intrusion.

Kinking (Fig. 16) and offset along the fracture (Fig. 17) may be attributed to 'tectonic deformation'.

All of the dykes from the study area are subvertical and display regular, almost straight, boundaries with the host rocks. Thus, they define 'n-type' flanking structures (Mukherjee & Koyi 2009; Mukherjee 2013, 2014*a*, *b*, 2015). The dominant

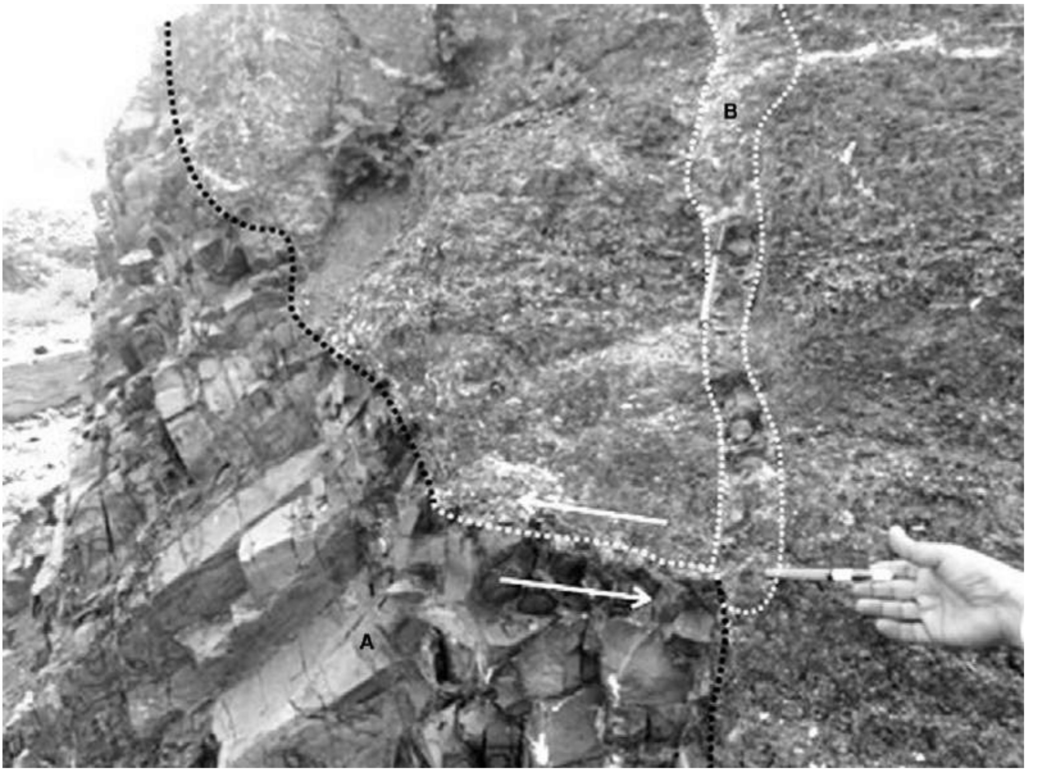

Fig. 13. Remnant of a dyke (D_4) showing an offset to the main dyke A, and B is the (finger-like projection) off-shoot of the main dyke.

Fig. 14. Exposure of the Majnu Hill dyke (D_4) showing no displacement.

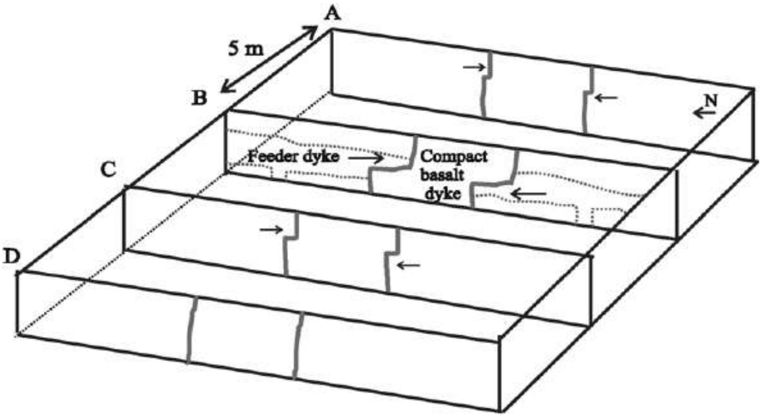

Fig. 15. 3D model (not to the scale) depicting the increase in the offset from A to B and then a decrease in offset from B to C in the Majnu Hill dyke (D_4).

trend is NE, which matches with that of those observed near the Narmada-Tapi dyke swarm. However, this trend does not corroborate with the north-trending West Coast dyke swarm and the dyke swarm from the Nashik-Pune region (Fig. 1). Most of these are en echelon dyke segments.

Conclusions

The 'Aurangabad dyke swarm' consists of 17 vertical and sub-parallel dyke segments emplaced in the CDVP. The morphological features, the regional en echelon distribution of some dykes and the NE–SW orientation pattern suggest that the 'Aurangabad dykes' were injected along pre-existing fractures. The general trend of these dykes matches with that of the 'Narmada-Tapi dyke swarm'.

Aurangabad dykes also show primary deformation structures, viz. offset, feeder dykes and deformed vesicles, as well as secondary ones. The offset of the dyke along the vicinity of the stratigraphic joint is the major one. This offset possibly developed due to stress barriers related to abrupt variations in rheological properties between porphyritic basalt and amygdaloidal basalt. Feeder dykes was another prominent primary structure. The evidence of feeder dykes pouring into the lava flow above suggests that Aurangabad was also an eruptive centre and the dyke fed the lava flow at Aurangabad. Geochemical and isotopic studies are required in order to draw a meaningful

Fig. 16. (**a**) 'A' – Feeder dyke (Amyduloidal Basalt), 'B' – Host rock (porphyritic basalt) and 'C' – Compact Basalt Dyke (D4). (**b**) Magnified view of Feeder Dyke (D4). 'A' – Feeder dyke (Amyduloidal Basalt), 'B' – Host rock (porphyritic basalt).

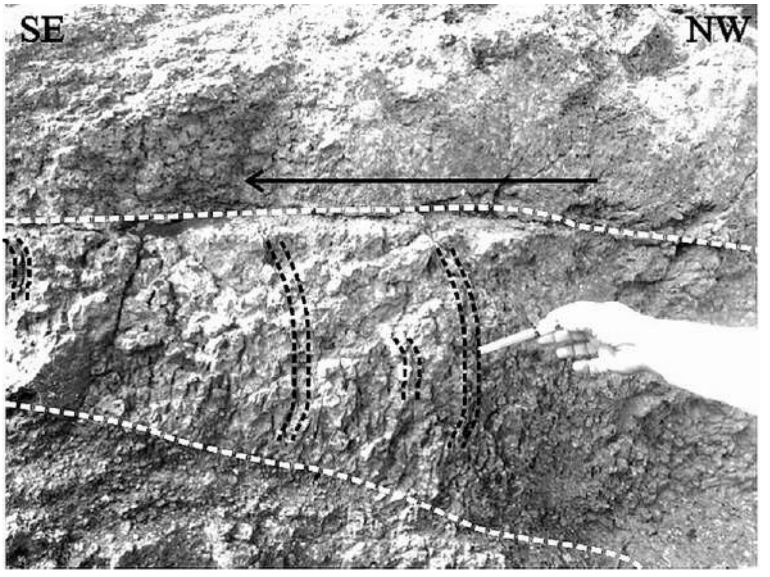

Fig. 17. Pipe amygdaloidal Basalt flow (marked as dashed white lines) showing bent pipe vesicles (dashed black lines) near Majnu Hill Dyke (D_{10}). Arrow indicates the flow direction.

correlation between the Aurangabad dyke swarm and those from other parts of the Deccan Volcanic Province. The direction of flow of the basalts near Majnu hill was deduced from the 'deformed vesicles'. Most of the joints, including the columnar joints, formed due to cooling and, hence, are not considered to be secondary deformation features.

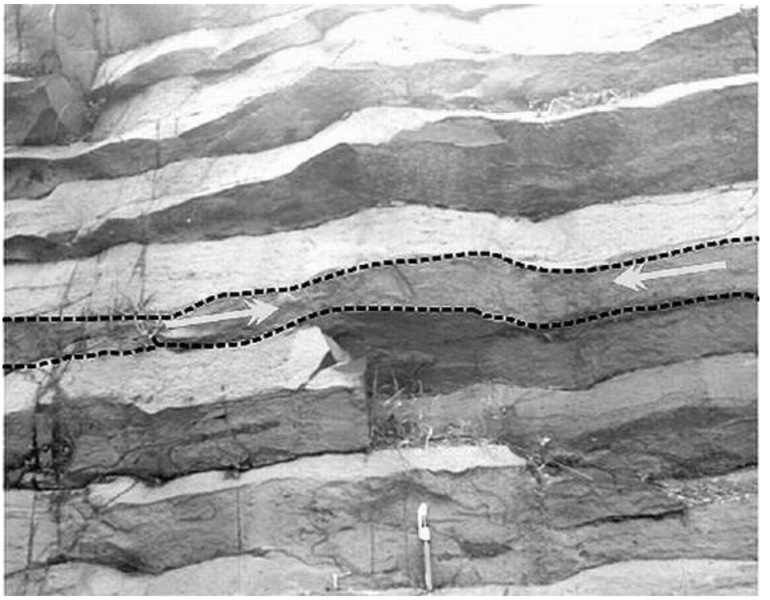

Fig. 18. Magnified view of Figure 7 (dyke D_{10}) showing a 'kink fold' with a sudden change in the dip of the columnar joint from horizontal to inclined and then back to a horizontal nature over a narrow span. The white arrow indicates the direction of compression (north–south).

Fig. 19. Displacement of an intrusion in the Satara dyke (D_{10}).

Secondary structures, such as kinking and offset along fractures, are the results of tectonic deformation, and suggest that the Satara dyke from the Aurangabad region experienced an episode of north–south compression. Nevertheless, a detailed structural analysis of these dykes seems necessary.

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