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The "Panvel Flexure" along the Western Indian continental margin: an extensional fault structure related to Deccan magmatism

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Abstract

On the basis of field observations aided by remote sensing data a new model for the Western Indian "Panvel Flexure" is proposed. The model involves normal motion on east-dipping faults and westward tilting of fault blocks. The "flexuring" occurred by attenuation and foundering of continental crust due to crustal thinning and loading by a dyke-swarm, following a period of massive magmatic discharge accompanying the continental break-up and opening of Indian Ocean during early Tertiary times.

1. Introduction

The continental margin "Panvel Flexure" in the Deccan Traps flood basalt province along the west coast of India was originally described by Auden (1949). Much work has since been carried out, mainly on the petrostratigraphy of the Deccan Traps (Beane et al., 1986; Devey and Lightfoot, 1986; Mitchell and Widdowson, 1991) and new models (Devey and Lightfoot, 1986; Cox, 1988; Watts and Cox, 1989) have been suggested for the origin of the dip of this flexure. These models, however, do not deviate much from the one proposed by Auden (1949) which involves simple monoclinal bending of the lava pile. Devey and Lightfoot (1986) suggested that "flexuring" is the result of warping of the crust in response to rifting. Watts and Cox (1989) ascribed the "flexuring" to the uplift of the Western Ghats and consequent subsidence of the continental margin. The above models are not in agreement with our field observations and therefore cannot explain the origin and the variation of dip in the Deccan Traps. In their description of the coast-parallel flexure of East Greenland, Nielsen and Brooks (1981) suggested that the Panvel, as well as other flexures, could be compared structurally to the East Greenland flexure. This and recent field studies along the coast around Bombay and neighbouring areas have necessitated a reinterpretation of the mechanism of rotation.

2. Deccan volcanism

The Deccan Traps flood basalt province in west-central India (Fig. 1a) covers an area of

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800,000 km^2 (Watts and Cox, 1989), attains a maximum thickness of 1.5–2 km along the Western Ghats escarpment (Holmes, 1965; Kaila et al., 1981) and thins eastward. To the west of the escarpment is the flat narrow Konkan coastal plain.

The Deccan basalts are believed to have been generated during the Cretaceous–Tertiary transition as the Indian plate migrated northwards over the Reunion hot-spot (Morgan, 1981) which subsequently gave rise to the Chagos–Laccadive and Mascarene ridges and is at present responsible for the volcanic activity on Reunion Island (Duncan, 1981; Morgan, 1981). On the basis of this model, Cox (1983) suggested that the Deccan Traps should be characterised by older lavas in the north with progressive overstepping of lava units and younging towards the south. This was later substantiated by geochemical work on the southern part of the Deccan Province (Beane et

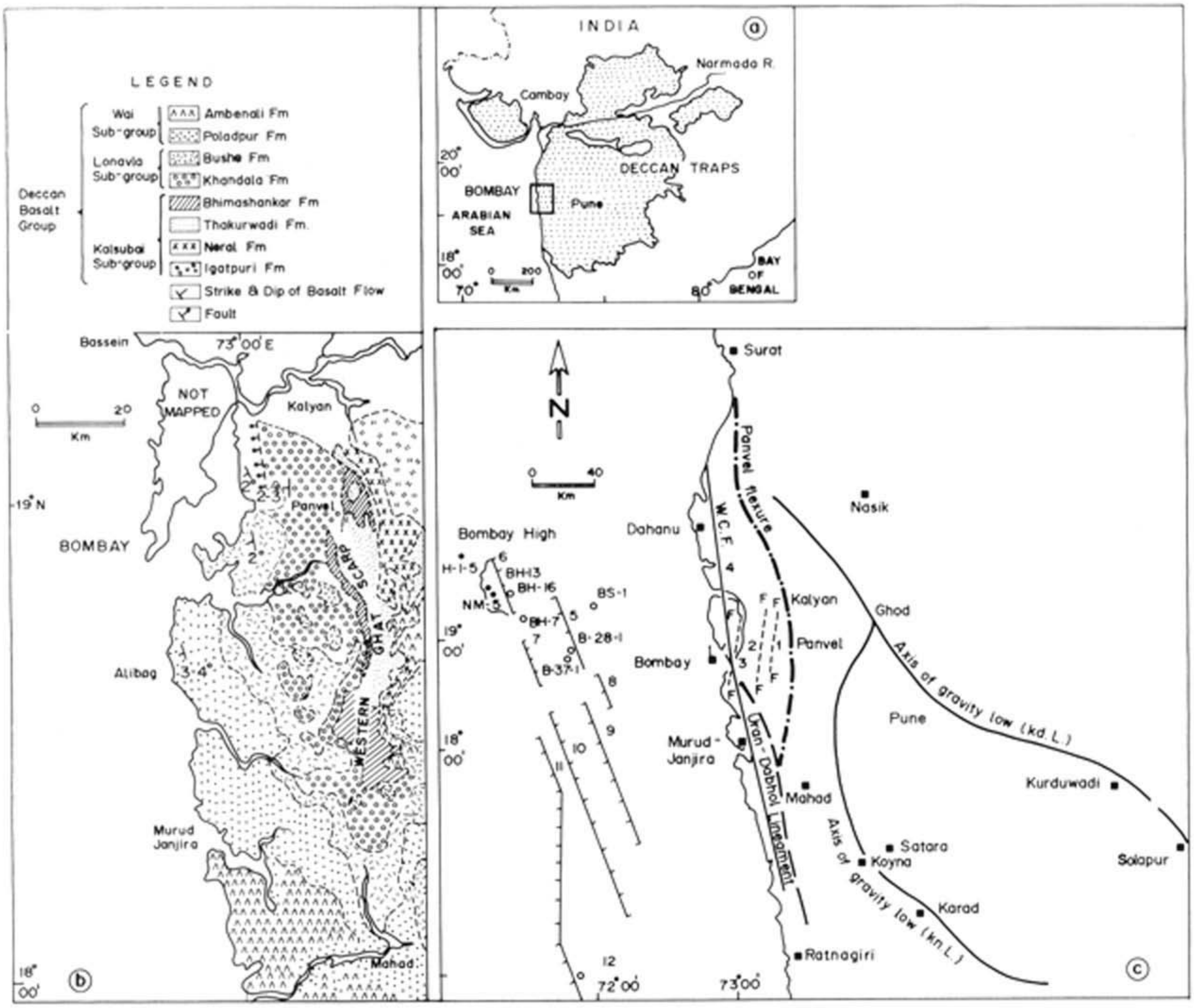

Fig. 1. Location map. (a) Regional context. (b) Geology of the area (after Subbarao and Hooper, 1988). (c) Major lineaments: Biswas, 1982; Qureshy, 1981; Krishna Brahmam and Negi, 1973). Faults: *1* = Belpada, *2* = Sheva, *3* = Alibag-Uran, *4* = West Coast; (*4–12* after Biswas, 1982; *kn-L* and *kd-L* after Krishna Brahmam and Negi, 1973). Drill wells: circle-well ended in Deccan Traps; dot-well ended in Precambrian basement without encountering Deccan Traps].

al., 1986; Devey and Lightfoot, 1986; Mitchell and Cox, 1988; Mitchell and Widdowson, 1991).

Recent radiometric datings indicate that the basaltic volcanism occurred within a narrow time span between 65 and 69 Ma (Courtillot et al., 1988; Duncan and Pyle, 1988) straddling the Cretaceous–Tertiary boundary. An epoch of reversed magnetic polarity, chron 29R, ascribed to this volcanic event (Courtillot and Cisowski, 1987; Gallet et al., 1989) and paleontological data (Jagger et al., 1989) suggest an even shorter time span (less than 1 Ma).

3. Geology of the area

The area extending from Dahanu in the north to Mahad in the south, between latitude 18 and 20°N (Fig. 1) along the west coast where the "flexure" is best exposed, has been investigated using satellite imagery, aerial photographs and field work. The area is predominantly covered by the Deccan flood basalts which have been traditionally classified as Upper Traps (Pascoe, 1964). In more recent petrostratigraphic work (Beane et al., 1986; Devey and Lightfoot, 1986; Mitchell and Cox, 1988)) these rocks have been assigned to Bushe and Khandala Formations of the Lonavla Sub-group and to Poladpur and Ambenali Formations of the youngest Wai Sub-group (Fig. 1b) of the Deccan Basalt Group (Subbarao and Hooper, 1988).

Wynne (1886) observed that the lavas along the coast show a tilt towards the west. Blanford (1867) suggested that the dip in the lava flows is due to "monoclinal flexure" which was named the "Panvel Flexure" by Auden (1949). In this paper the "flexure" is described as an extensional fault structure. However, the term "flexure" has been retained "by tradition" as aptly put by Nielsen and Brooks (1981).

4. Tectono-magmatic evolution of the western continental margin of India

In the plate tectonic model, Deccan magmatism has been attributed to fragmentation of Gondwanaland during the Late Cretaceous (Le Pichon and Heirtzler, 1968; Dietz and Holden, 1970; Wensink, 1973; Verma and Mittal, 1974) and rifting of the western Indian platform. Tensional faulting along ancient basement trends led to submergence of parts of the platform with possible volcanism. Volcanism started in the mid- to Late Cretaceous (Wensink and Klootwijk, 1971; Sclater and Fischer, 1974) when Greater India (India together with Seychelles and the Mascarene Plateau) separated from Madagascar about 80 Ma ago (Norton and Sclater, 1979). The major outburst of this volcanic activity, however, coincided with the separation of India from the Seychelles and the Mascarene plateau about 65 Ma ago (Norton and Sclater, 1979) and its movement over the Reunion hot-spot.

During the early Tertiary, the Western Indian margin witnessed a major faulting event forming the West Coast Fault (W.C.F.) along Precambrian basement trends (NNW–SSE system of fractures) preceding the separation of India from Seychelles (Crawford, 1971; Mahoney, 1988). This fracture system has also been associated with a mantle high off Bombay (Narain et al., 1968) where the crustal thickness is only 18 km (Kaila, 1988). The mantle upwarp (Burke and Dewey, 1973) is inferred from a positive gravity anomaly (Glennie, 1951; Kailasam et al., 1972), a negative magnetic anomaly (Agarwal et al., 1986), and high heat flow values (Verma, 1970; Bose, 1972). The "Panvel Flexure" development is associated with the West Coast Fault which parallels the edge of the continental shelf (Surendar Kumar, 1975a,b; Cox, 1988). The NNW–SSE-trending fracture system that controls the west coast and the "Panvel Flexure" could be a manifestation of the stretching, fracturing and breaking of continental lithosphere (White et al., 1987) in response to rifting. Burke and Dewey (1973), however, regarded this fracture system as running parallel to one arm of the triple junction located around Cambay (Fig. 1c).

5. Structural lineaments along the West Coast of India

Landsat imagery revealed the presence of three major lineament trends (Fig. 2): N–S, NE–SW

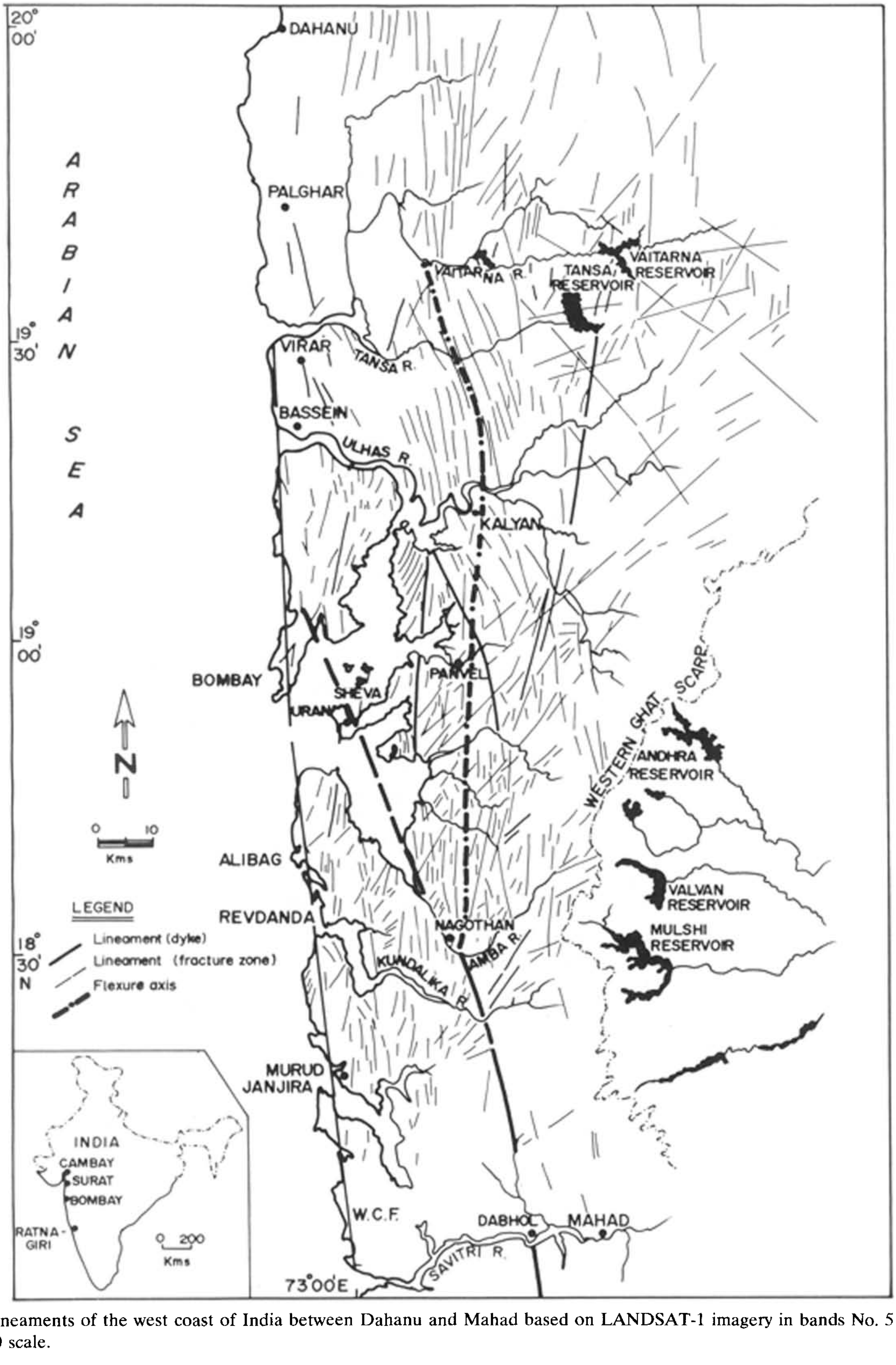

Fig. 2. Lineaments of the west coast of India between Dahanu and Mahad based on LANDSAT-1 imagery in bands No. 5 and 7, 1:250 000 scale.

and NW–SE. Field observations showed that the lineaments represent fracture zones, faults and dykes. The N–S lineaments are very prominent and some of these are seen to extend for tens of km. A very clear lineament extends from Uran to Dabhol (Fig. 2) in a SSE direction for a distance of over 100 km. A major NW–SE (Fig. 2) lineament passes through the Vaitarna reservoir. It is a fault zone along which relative displacement of lavas is seen (V.V. Peshwa, pers. commun, 1992). When traced southwards, it coincides with the Kurduwadi lineament (Fig. 1c) of Krishna Brahmam and Negi (1973). The Landsat lineaments represent deep-seated structures as seen from seismic records (Chandrasekharam, 1985). The majority of them are shear zones and fracture zones. In certain cases, e.g. Murud-Janjira, the fractures have tapped alkaline magmas which intruded as lamprophyres with mantle xenoliths (Dessai, 1987) and nephelinites/basanites (Dessai et al., 1990).

The N–S dyke swarm was intruded along the

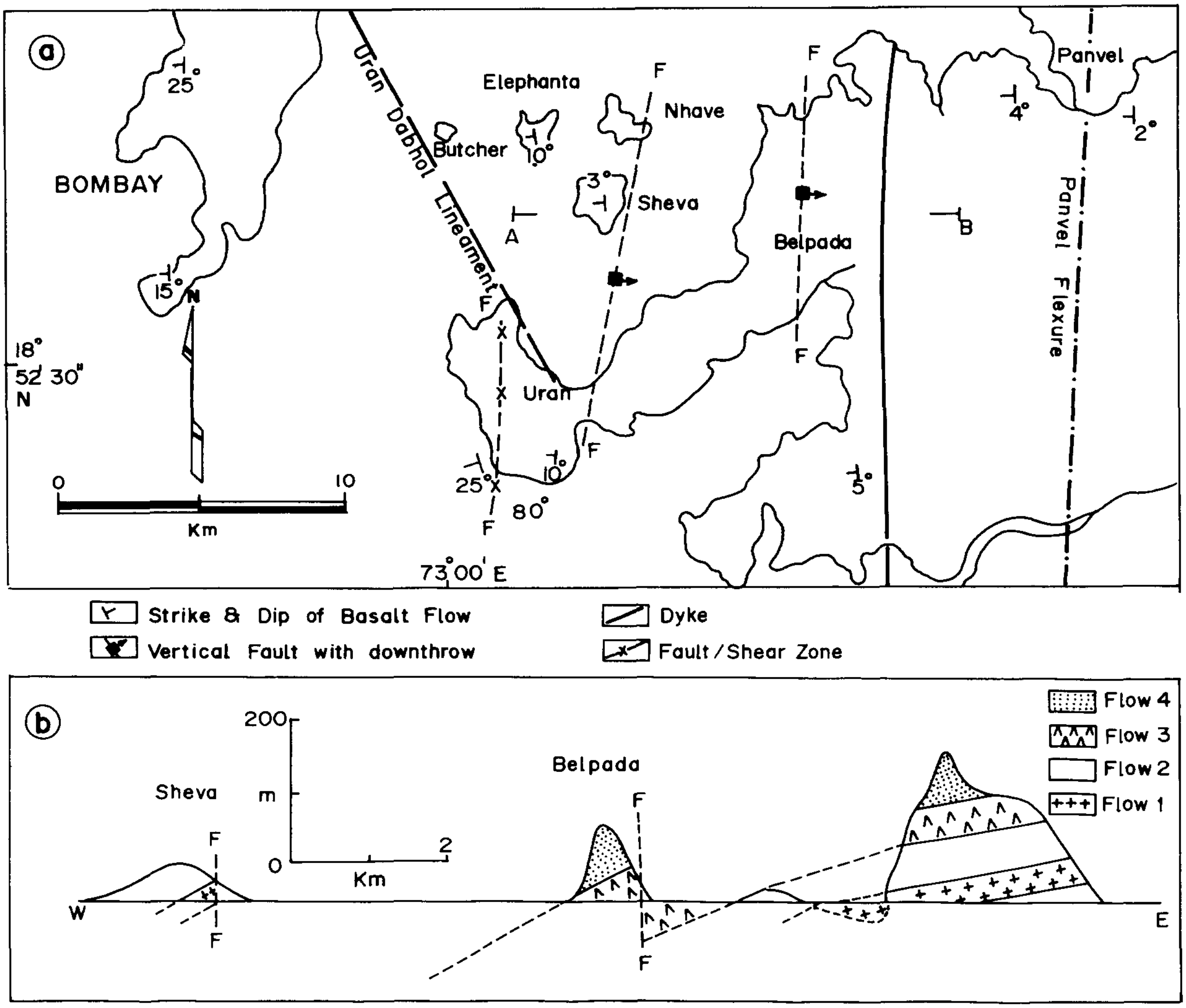

Fig. 3. (a) Map showing attitude of lava flows and faults/shear zone between Panvel and Bombay. (b) Cross section between Sheva and Belpada (see *A–B* in Fig. 3a; modified after Ghodke, 1978).

N–S fracture system as a result of an E–W lithospheric extension associated with the rifting of India from the Seychelles during the incipient opening stage of the Indian Ocean (White and Mckenzie, 1989). The swarm, therefore, parallels the West Coast Lineament of Devey and Stephens (1992) corresponding to the southern arm of the Cambay triple junction (Burke and Dewey, 1973). A present-day analogue for this type of junction is the Tertiary triple junction centered around the Afar depression (Mckenzie and Morgan, 1969). Two of the rifts (namely the Red Sea and the Gulf of Aden), have just begun to separate, whereas the third rift (the Ethiopian rift) is the failed arm corresponding to the Indian Narmada–Son lineament (Fig. 1a).

The N–S fracture system was cut by NNW- to NNE-oriented fractures, as a result of a N–S-directed compressive stress field possibly imposed by the collision of India with Eurasia during early Tertiary. Pronounced shearing along the western margin is observed all along the west coast, as also reported by Naini and Talwani (1982). The alkaline dykes along the west coast, some of which are localised along shear zones and fracture zones, are emplaced along this fracture system. These alkaline rocks (especially those from Bombay), have yielded ages of 60 ± 2 Ma (quoted in Mahoney, 1988) and 61.5 ± 1.9 Ma (Lightfoot et al., 1987) and have normal magnetic polarity (Narain et al., 1973; Beane et al., 1986).

6. Aerial photo interpretation

Aerial photo interpretation on 1:45,000 scale of the area between Bombay and Panvel, shows that the lava flows have varying dips: 2°W at Panvel, 4°W west of Panvel, 6–10°W at Elephanta, 2–3°W at Sheva and 15°W or WSW at Bombay (Fig. 3a). A similar variation in dip is also observed from west to east at the latitude of Bassein (Fig. 1b). Thus, it is seen that within the last 20 km to the coast the dips change from about 4° to as much as 15°, and in some places to over 50° (Auden, 1949). To illustrate the variation of dips observed in the lava flows, one section with 3 faults (namely the Belpada, the Sheva and the Alibag–Uran faults) along an E–W profile between Panvel and Bombay is described (Fig. 3a) The N–S-trending Belpada fault (1, Fig. 1; A–B, Fig. 3a) exhibits intense fracturing and slickensliding, the eastern side being downthrown by about 60 m (Ghodke, 1978; Fig. 3b).


Fig. 4. The fault zone exposed to the north of Alibag. Note close-spaced fracturing and an iron-oxide vein-network.

Along the N–S-trending Sheva fault (2, Fig. 1c; A–B, Fig. 3a), the lava flows to the east of the fault are repeated to the west (at Sheva) at higher elevation, showing downthrow to the east (Ghodke, 1978; Fig. 3b). The third fault to the north of Alibag (3, Fig. 1c) trends N 35° and becomes N–S at Uran. The fault zone is about 25 m wide at Alibag and over 200 m at Uran. The basalts exhibit slickensliding, close-spaced fracturing, and a cris-cross pattern of veins filled with iron oxide (Fig. 4). At Alibag the fault plane dips 40° east; however, no relative displacement of lavas can be measured due to lack of marker horizons. To the east of the fault at Uran, the lava flows show dips of 10° towards the west. However, along the fault zone (exposed in the intertidal zone) the basalts show block rotation and high dips of 25° west or southwest (Fig. 5). Further west of the fault, the lavas again show lower values of dip (10°). Shear zones and fracture zones are very common in the Deccan Traps, but in many cases (e.g. at Uran) no displacement can be deciphered due to lack of marker horizons. The lava flows in the vicinity of fracture zones locally dip at higher angles than the regional dips. Thus, the change in dip occurs principally along fault zones which are exposed on the surface as zones showing closely spaced fracturing. Note that these observations conform with those reported by White and Mckenzie (1989) from the Etendeka flood basalts in South Africa. Our observations indicate that the western limb of the Panvel structure consists of fault-controlled blocks. These faults display an en echelon pattern.

7. Bombay coastal dyke-swarm

The coast-parallel N–S-trending dyke-swarm extends over 90 km from Bombay to south of Murud. It is best exposed in the intermittent rocky beaches between Alibag and Murud (Fig. 2) where the frequency of dykes increases considerably as compared to their frequency inland due to fracturing of the lavas in the fault zone along which post-flexure dykes are emplaced (White, 1992). The average inferred crustal extension (e.g. at Revdanda) exceeds 30% (Dessai, 1987; Dessai et al., 1990).

The dykes belong to at least two generations. The older dykes (pre-“flexure”) are dolerites dipping 60 to 80° east and vary in thickness from 1 to 3 m. To bring out the relationship between the dykes and the basalts, E–W sections between Alibag and Murud are described. The basalts about 2 km east of Alibag show dips of about 5° west. However, towards the coast at Alibag the basalts locally display dips of 20° to 30° west in the vicinity of Alibag fault. Thus, older dykes

Fig. 5. The fault zone at Uran (looking North). Note block rotation (shown by arrow), tilting and steepening of dips. Gentle dips to the west of the fault zone. The fault is occupied by a dyke (foreground).

which dip 60° to 80° east, are perpendicular to the bedding of the lavas. In a 3-km profile at right angles to the coast at Revdanda, (Fig. 2) the regional dips of the basalts inland are about 5°–10° west, whereas locally on the coast the basalts dip 15° to 30° west. The older dykes here dip 45° to 85° east.

In contrast, the younger dykes both at Alibag and Revdanda are alkaline, less than 1 m thick and are almost vertical or show irregular dips of 80° to 85° east or west. They exhibit a zig-zag, en echelon pattern, pinching and swelling along the trend. At many places, e.g. south of Murud and at Uran, they occupy fracture zones (Fig. 5). They are generally unaltered, dark grey in colour and stand out forming ridges as compared to pre-"flexure" dykes which are relatively more altered, paler greyish brown in colour, fractured, traversed by veins and lenses (20 cm × 8 cm) of secondary silica and invariably form depressions. The younger dykes therefore, belong to the post-flexure category and show close resemblance to what has been described by Dutoit (1929) as 'dyke faulting' for the Lebombo flexure. The en echelon disposition of dykes could be a result of en echelon shift of the axis (the region where the lava flows bend towards west) of the "flexure". Thus to the west of the "Panvel Flexure" axis, although the regional dips of basalts are low (10 to 15°), locally the dips within individual faulted blocks are much higher (20–30°) and westerly due to rotation of faulted blocks.

The analogue of the Bombay coastal dyke swarm has been identified in the Seychelles (Devey and Stephens, 1991, 1992): the tholeiitic dykes from Praslin and Felicite Island are compositionally similar to Bushe Formation tholeiites of Deccan whereas the alkaline dykes from Mahe and North Island resemble those from Murud–Janjira (Devey and Stephen, 1992).

7. Offshore data

Offshore in the vicinity of Deccan, Hinz (1981) has shown seaward-dipping reflectors on seismic reflection profiles. Gravity and seismic refraction data suggest that the Deccan Traps continue offshore into the seaward-dipping reflectors (Hinz and Closs, 1969. This is corroborated from the drill hole data of ONGC of India.

On the continental shelf 80 km west of Bombay (inner shelf) basalts are encountered at depths of 2 to 3 km (2.5 km in well B-28-1, 2 km in B-37-1 and 2.4 km in BS-1) in oil wells drilled by ONGC, and vary in thickness from 0.2 to 1.8 km (Fig. 1c). Seismic studies (Gopala Rao, 1990) reveal that basalts occur at shallower depths near shore than westward. Further west, on the middle outer shelf (offshore basin), basalts occur at depths varying between 3.8 and 5 km with a thickness of 2 to 2.5 km (Gopala Rao, 1990). Even further west, about 140 km from Bombay (Bombay High region), 3 wells (BH-13, NM-5 and BH-12) all ended in Precambrian basement without encountering Deccan Traps. However, in wells BH-16 and BH-7 (Fig. 1c), basalts are encountered at depths of 2 to 3 km. In general, in the Bombay High region the basalts vary in thickness from zero to 0.8 km at depths of 2 to 3 km (Gopala Rao, 1990). Thus, the "Bombay High" structure represents a topographic high (palaeohigh). In relatively low-lying areas outliers of basalt are encountered.

A number of basement controlled NW–SE- and N–S-trending faults have been located on the continental shelf (Biswas, 1982; Mitra et al., 1983). These faults cut across the overlying basalts and lower portions of the Tertiary sedimentary sequence giving rise to horst and graben features (Chandrasekharam, 1985).

8. Discussion

Auden (1949) proposed a model for the "Panvel Flexure" based on a simple coast-parallel monoclinal bending of the lava pile. His model was probably inspired by the description of the East Greenland coast-parallel flexure (Wager and Deer, 1938) and the Lebombo flexure (Dutoit, 1929). Das and Ray (1973, 1977) have extended the "Panvel Flexure" axis up to Rajapur in Ratnagiri district. Auden (1975) modified his original proposal in a geological profile across the part of the continental shelf NW of Bombay, and showed that the lavas near the coast represent a zone of many folds rather than one "monoclinal flexure". Qureshy (1981) suggests "cymatogenic warping" along the coast between 19 and 20°N, attributing this process to uplift due to addition of mantle material to the sialic crust. This is analogous to "real" uplift (McKenzie, 1984), which involves underplating of igneous material to the continental crust (Devey and Lightfoot, 1986; Cox, 1989). Cox (1988) draws an analogy between the "real" uplift of the Deccan and the Parana Basin of Brazil, and suggests that the Deccan sequence, like the Parana, is only in the initial stages of "monoclinal flexuring" in the Panvel region. The "monoclinal flexure" is believed to be the result of post-Deccan differential movements involving subsidence of the continental margin and flanking uplift of the Western Ghats (Watts and Cox, 1989), a mechanism akin to that suggested by White et al., (1987) on the Hatton Bank of the North Atlantic. Devey and Lightfoot (1986) as-

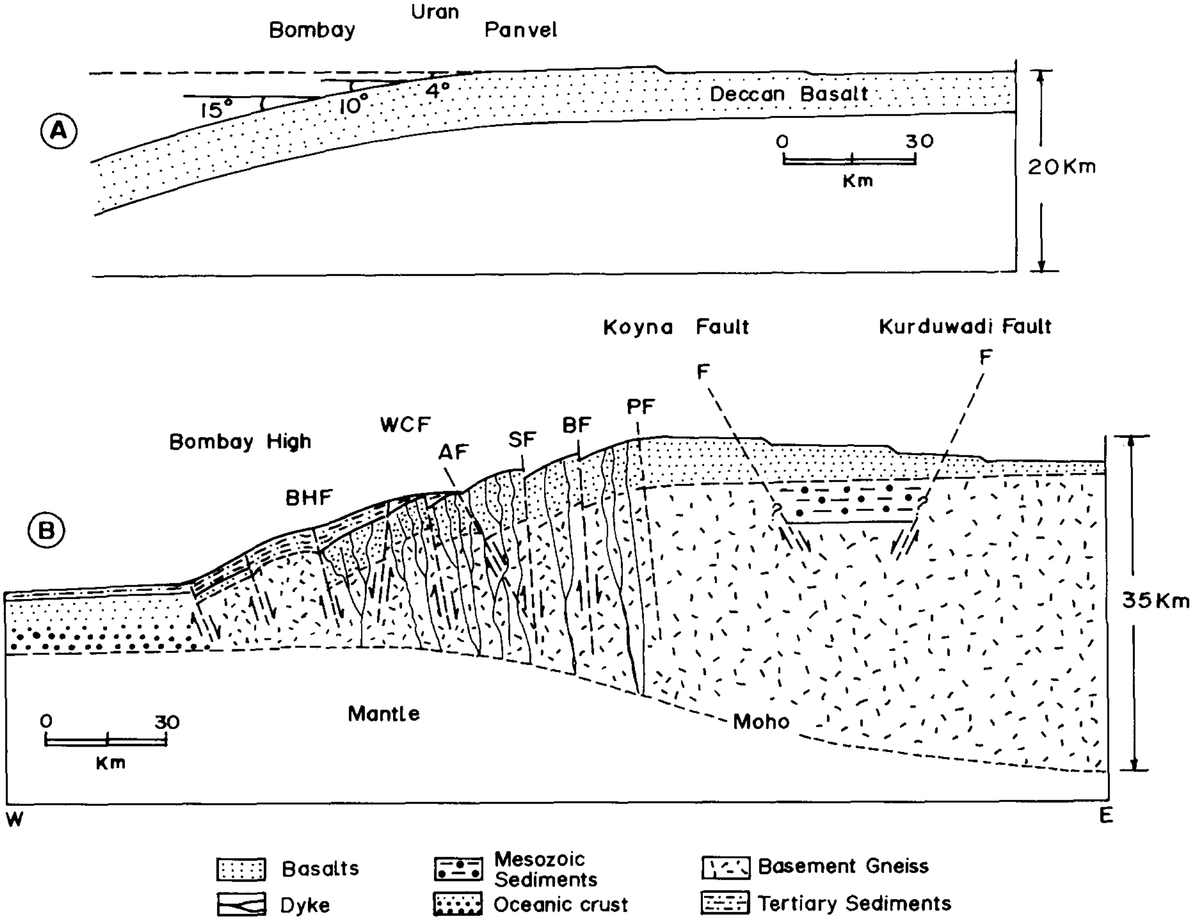

Fig. 6. (a) Schematic section through the "flexure" drawn on the basis of regional dips of the lava flows. (b) Schematic section between Bombay High and Ghod depicting the gross structure of the western continental margin [modified after fig. 1 from Nielsen (1975) and fig. 6 from Nielsen and Brooks (1981)] to apply to the "Panvel Flexure"]. Faults: *PF* = "Panvel Flexure"; *BF* = Belpada; *SF* = Sheva; *AF* = Alibag-Uran; *WCF* = West Coast; *BHF* = Bombay High.

cribed the "Panvel Flexure" either to warping of the crust or to draping of the lavas over transcrustal faults.

The various models outlined above (Auden, 1949, 1975; Qureshy, 1981; Biswas, 1982; Devey and Lightfoot, 1986; Watts and Cox, 1989) however, cannot satisfactorily account for:

(1) the existence of faults in parallel sets giving rise to fracture-controlled blocks;

(2) the variation in the dip of the lava flows and their spatial distribution (e.g. steepening of dips in the vicinity of faults/fracture-zones);

(3) existence of Traps on the continental shelf at depths shallower than would be expected by extrapolation of regional dip values in a "monocline"; or

(4) thinning of the lava pile offshore.

These observations are similar to those of Nielsen and Brooks (1981) along the east coast of Greenland which led to the proposal of an extensional fault structure for the continental margin.

In the region between Panvel and Bombay, the volcanic pile shows a very gentle regional warp about 35 km wide (Fig. 6A). If the observed steep local dips are extrapolated, the Deccan basalts should be encountered at a depth of more than 10 km below MSL at a distance of about 60 km west of Bombay (inner shelf) considering minimum values for the amount of dip. However, it is observed that basalts occur at shallow depths on the inner shelf, at deeper levels on the middle outer shelf and at shallower depths on the "Bombay High" structure. This suggests that regional dips between Bombay and the middle outer shelf are actually low, whereas locally dips within faulted blocks are high on the continental shelf. Similarly, between Panvel and Bombay, regional dips are low, whereas local dips within faulted blocks are high. Therefore, we agree with Nielsen and Brooks (1981) that the western margin of India represents an extensional fault structure. The warp can be interpreted to be composed of a number of rotated blocks bounded by fault/fracture zones. This has given rise to variation in the dips of the lava. The major fault pattern is NNW–SSE-trending, parallel to the west coast. A number of subsidiary easterly dipping faults produce rotation of the lava. The faulting implies lithospheric extension and attenuation (White, 1992) over the width of the flexure. Attenuation due to lithospheric thinning (White and Mc Kenzie, 1989) combined with loading by intense dyke intrusion (Larsen, 1978) could account for foundering of the crust by block rotation and tilting along easterly dipping faults.

This structure is very similar to the East Greenland coastal flexure (Nielsen, 1975; Nielsen and Brooks, 1981; Larsen, 1988; Larsen and Jakobsdottir, 1988), and, in some respects, to the escarpment of the Afar depression (Black et al., 1972; Morton and Black, 1975; Zanetin and Justin-Visentin, 1975) and the Lebombo flexure (Dutoit, 1929; Eales et al., 1984). Thus, the westward dips on the west side of the Deccan Trap structure are not a truly primary regional feature, but are the result of post-eruptive faulting possibly associated with the thermal relaxation of the stretched lithosphere (White and McKenzie, 1989; White, 1992) as it subsides to maintain isostatic equilibrium (White et al., 1987) with attendant uplift of the Western Ghats (Watts and Cox, 1989; Cox, 1989).

The process of block fracturing and tilting which is operating at Afar may have occurred along the western Indian margin during early Tertiary about 65 Ma ago. The tectonomagmatic evolution of the western Indian continental margin is akin to the eastern margin of Seychelles (Clifford and Gass, 1970; Bridden and Gass, 1974; White and McKenzie, 1989; Devey and Stephens, 1991). The structural features are complementary to each other.

9. Model for the continental margin

From the above discussion, we suggest a model for the gross structure of the continental margin on the principles of the one suggested for the East Greenland coast. Fig. 6B is modified after Nielsen (1975) and Nielsen and Brooks (1981) and shows the visualised structure. The pre- and post-Trappean geological data are based on geophysical studies (Kaila et al., 1981; Schlumberger, 1983). On the basis of deep seismic soundings along an E–W profile at 18°N latitude (Kelsi–

Loni), Kaila et al. (1981) have located a deep, easterly dipping fault about 13 km east of Mahad, due to which the eastern block has been thrown up by 1.5 km. The Moho which is here at a depth of 39 km rises to 31.5 km near the coast. Towards the north however, especially between Surat and south of Bombay along the west coast, a linear N–S Bouguer anomaly (300 km × 60 km) is delineated. It has been variously interpreted as mafic material (Glennie, 1951), a secondary magma chamber (Takin, 1966), a plutonic body (Qureshy, 1981) and a Moho upwarp as shallow as 18 km (Kaila, 1988). East of Mahad, on the Western Ghat plateau, Krishna Brahmam and Negi (1973) on the basis of gravity data have delineated two lineaments (Fig. 1c) namely Koyna (kn.L.) and Kurduvadi (kd.L.), in the Precambrian basement, which correspond to the axes of gravity low. These lineaments (rifts of Krishna Brahmam and Negi, 1973), possibly represent active faults in the basement, if the seismicity associated with them is anything to go by. The Koyna region has been experiencing seismicity since the last 25 years (note the major earthquake of magnitude 6.5 on Richter scale on 11th December, 1967). Kurduwadi, on the other hand, has been seismically active since in the last year (experienced a devastating earthquake of magnitude 6.4 at Umarga - 130 km E of Kurduwadi on 30th September, 1993). The seismicity has produced fracturing in the Deccan Traps, although with no major displacement in the lava pile. However, recent field observations in the earthquake-affected areas have shown minor NW–SE lateral movement in the lavas along the Kurduwadi lineament.

10. Implications in the Indian context

On the basis of regional dip analysis Raja Rao et al. (1978) proposed a SSW-plunging domal structure for the Deccan Traps. This was later corroborated by Devey and Lightfoot (1986) with the help of a stratum contour map. They showed that around Nasik and areas to the east, lava flows dip gently towards the southeast, whereas along the coast the flows dip 3 to 4° west and around Bombay they dip 10 to 20° west (Sethna, 1981). Thus, the western limb of the structure is steeper than the eastern. It was suggested that the domal structure represented a primary constructional shield volcano (Beane et al., 1986). In the light of the interpretation presented above, the westerly dips of the western limb of the Deccan Trap domal structure appear to be secondary formed due to post-eruptive faulting, shearing and block rotation as a result of foundering of the stretched lithosphere (White and McKenzie, 1989; Hooper, 1990). The possibility of such secondary deformation is also pointed out by Beane et al. (1986) and Mahoney (1988). Therefore, caution will have to be exercised in interpreting the gross structure of the Deccan Traps. Further work is therefore required in critical areas before a final conclusion could be drawn.

Again the widely held view that a huge thickness of Deccan Traps is downfaulted in the Arabian Sea will have to be reviewed as the Deccan Traps thin out both to the west of Bombay and to the east on the Deccan plateau, attaining maximum thickness in the "Panvel Flexure" region (K.G. Cox, pers. commun., 1992.).

The interpreted structure is akin to a half-graben structure in the plate tectonic model suggested for the Deccan Traps, in conformity with the model suggested by Nielsen (1975) for the East Greenland Coast (Nielsen, 1975; Larsen, 1988).

The present location of the Deccan plateau at an elevation of over 1500 m is primarily the result of post-volcanism uplift along the plume-flanks (Campbell and Griffiths, 1990). The isostatic balance is maintained by subsidence in the axial region of the plume aided by a system of deep crustal faults. Subsidence is expressed in the form of grabens, e.g., the Cambay Basin, the Narmada Graben and the Bombay offshore Basin.

The little known west coast dyke-swarm comprises dykes that belong to more than two generations. The older dykes which show dips opposite to those of the lavas may belong to the pre-spreading stage described by Nielsen (1975) and Larsen (1988) amongst others from East Greenland. The alkaline dykes, which are later than the above, are post-flexure. The high intensity of dykes seen along the west coast is therefore a consequence of "flexuring" and foundering of the lithosphere along a N–S oriented fracture system.

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References

Agarwal, A.K., Singh, B.P., Rastogi, R.G. and Srinivasan, S., 1986. On utility of space-borne vector magnetic measurements in crustal studies. Phys. Earth Planet. Inter., 41: 260–268.

Auden, J.B., 1949. Dykes in western India. Trans. Nat. Inst. Sci. Ind., 3: 123–157.

Auden, J.B., 1975. Report on the problem of seismicity associated with the Koyna reservoir, Maharashtra, India. Government of Maharashtra, Irrigation Dept., Koyna dam and design circle, Poona, 1–25.

Beane, J.E., Turner, C.A., Hooper, P.R., Subbarao, K.V. and Walsh, J.N., 1986. Stratigraphy, composition and formation of Deccan basalts, Western Ghats, India. Bull. Volcanol., 48: 61–83.

Biswas, S.K., 1982. Rift basins in western margin of India and their hydrocarbon prospects with special reference to Kutch basin. Bull. Am. Assoc. Pet. Geol., 66: 1497–1513.

Black, R., Morton, W.H. and Varet, J., 1972. New data on Afar tectonics. Nature (Phys. Sci.), 240: 170–173.

Blanford, W.T., 1867. Traps and intertrappean beds of western and central India. Mem. Geol. Surv. Ind., 6: 155–156.

Bose, M.K., 1972. Deccan basalts. Lithos, 5: 131–145.

Briden, J.C. and Gass, I.G., 1974. Plate movement and continental magmatism. Nature, 248: 650–653.

Burke, K. and Dewey, J.F., 1973. Plume generated triple junctions; Key indicators in applying plate tectonics to old rocks. J. Geol., 81: 406–433.

Campbell, I.H. and Griffiths, R.W., 1990. Implication of mantle plume structure for the evolution of flood basalts. Earth Planet. Sci. Lett., 99: 79–93.

Chandrasekharam, D., 1985. Structure and evolution of the western continental margin of India deduced from gravity, seismic, geomagnetic and geochronological studies. Phys. Earth Planet. Inter., 41: 186–198.

Clifford, T.N. and Gass, I.G., 1970. African Magmatism and Tectonics. Oliver and Boyd, Edinburgh, 343 pp.

Courtillot, V.E. and Cisowski, C., 1987. The Cretaceous–Tertiary boundary events; external or internal causes? EOS, 68: 193–200.

Courtillot, V.E, Feraud, G., Maluski, H., Vandamme, D., Moreau, M.G. and Besse, J., 1988. Deccan flood basalts and the Cretaceous/Tertiary boundary. Nature, 333: 843–846.

Cox, K.G., 1983. The Deccan Traps and the Karoo: stratigraphic implications of possible hot-spot origins. IAVCEI Abstr., Hamburg, p. 96.

Cox, K.G., 1988. Inaugural address In: K.V. Subbarao (Editor), Deccan Flood Basalts. Geol. Soc. Ind. Mem., 10: 15–22.

Cox, K.G., 1989. The role of mantle plumes in the development of continental drainage patterns. Nature, 342: 873–877.

Crawford, A.R., 1971. Gondwandland and the growth of India. J. Geol. Soc. Ind., 12: 205–221.

Das, S.R. and Roy, A.K., 1973. Photogeological interpretation of structure and tectonics of Koyna region and part of west coast, Maharashtra. Rec. Geol. Surv. Ind., 105: 83–94.

Das, S.R. and Roy, A.K., 1977. Fracture pattern within Deccan Traps of west coast of India. Geol. Soc. Ind. Misc. Publ., 31: 75–79.

Dessai, A.G., 1987. Geochemistry and petrology of xenolith-bearing lamprophyres from Murud-Janjira, Raigarh district, Maharashtra, India. J. Geol. Soc. Ind., 30: 61–71.

Dessai, A.G., Rock, N.M.S., Griffin, B.J. and Gupta, D., 1990. Mineralogy and Petrology of xenolith-bearing alkaline dykes associated with Deccan magmatism, south of Bombay, India. Eur. J. Mineral., 2: 667–685.

Devey, C.W. and Lightfoot, P.C., 1986. Volcanological and tectonic control of stratigraphy and structure in the western Deccan Traps. Bull. Volcanol., 48: 195–207.

Devey, C.W. and Stephens, W.E., 1991. Tholeiitic dykes in the Seychelles and the original spatial extent of the Deccan Traps. J. Geol. Soc. London, 148: 979–983.

Devey, C.W. and Stephens, W.E., 1992. Deccan related magmatism west of the Seychelles–India rift. In: B.C. Alabaster and R.J. Pankhurst (Editors), Magmatism and the Causes of Continental Break-up. Geol. Soc. London, Spec. Publ., 68: 271–291.

Dietz, R.S. and Holden, J.C., 1970. Reconstruction of Pangea, breakup and dispersion of continents, Permian to Present. J. Geophys. Res., 75: 4939–4956.

Duncan, R.A., 1981. Hot-spots in the southern oceans—an absolute frame of reference for motions of the Gondwana continents. Tectonophysics, 74: 29–42.

Duncan, R.A. and Pyle, D.G., 1988. Rapid eruption of the Deccan flood basalt at the Cretaceous–Tertiary boundary. Nature, 333: 841–843.

Dutoit, A.L., 1929. The volcanic belt of the Lebombo—a region of tension. Trans R. Soc. S. Afr. 18: 189–217.

Eales, H.V., Marsh, J.S. and Cox, K.G., 1984. The Karoo igneous province: an introduction, petrogenesis of the volcanic rocks of the Karoo province. Spec. Publ. Geol. Soc. S. Afr., 13: 1–26.

Gallet, Y., Weeks, R., Vandamme, D. and Courtillot, V., 1989. Duration of Deccan Trap volcanism: a statistical approach. Earth Planet. Sci. Lett., 93: 273–282.

Ghodke, S.S., 1978. Geology of the area around Panvel, Kolaba district, Maharashtra. Ph. D. thesis, University of Poona (unpubl.).

Glennie, E.A., 1951. Density of geological correction to gravity anomalies for the Deccan Traps, India. Mont. Nat. R. Austr. Soc. Geophys. Suppl., 6: 179.

Gopala Rao, D., 1990. Magnetic studies of basement off the coast of Bombay, West of India. Tectonophysics, 175: 317–334.

Hinz, K., 1981. A hypothesis on terrestrial catastrophes; Wedges of very thick oceanward dipping layers beneath passive continental margins. Geol. J., E 22: 3–28.

Hinz, K. and Closs, H., 1969. Ergebenisse seismischer Untersuchungen im nordlichen Arabischen Meer, ein Beitrag zur Internationalen Indischen Ozean Expedition, III, Auswertung und Ergebnisse der seismischen Messungen und ihre geologische Deutung. "Meteor" Forschungsergebn., Reihe C, 2: 9–28.

Holmes, A., 1965. Principles of Physical Geology. Thomas Nelson and Sons, London, 1288 pp.

Hooper, P.R., 1990. The timing of crustal extension and the eruption of continental flood basalts. Nature, 345: 246–249.

Jaegger, J.J., Courtillot, V. and Tapponnier, P., 1989. Paleontological view of the ages of the Deccan Traps, the Cretaceous–Tertiary boundary and the India–Asia collision. Geology, 17: 316–319.

Kaila, K.L., 1988. Mapping the thickness of Deccan Trap flows in India from DSS studies and inferences about a hidden Mesozoic Basin in the Narmada–Tapti region. In: K.V. Subbarao (Editor), Deccan Flood Basalts. Geol. Soc. Ind. Mem., 10: 91–116.

Kaila, K.L., Murty, P.R.K., Rao, V.K. and Kharetchko, G.E., 1981. Crustal structure from deep seismic soundings along the Koyna II (Kelsi–Loni) profile in the Deccan Traps area, India. Tectonophysics, 73: 365–384.

Kailasam, L.N., Murthy, B.G.K. and Chayanala, A.Y.S.R., 1972. Regional gravity studies of Deccan Traps areas of Peninsular India. Curr. Sci., 41: 403–407.

Krishan Brahmam, N. and Negi, J.G., 1973. Rift valleys beneath Deccan Traps (India). Geophys. Res. Bull. 14: 207–237.

Larsen, H.C., 1978. Offshore continuation of the East Greenland dyke-swarm and its bearing on North Atlantic ocean formation. Nature, 274: 220–223.

Larsen, H.C., 1988. A multiple and propagating rift model for the NE Atlantic. In: A.C. Morton and L.M. Parson (Editors), Early Tertiary Volcanism and the Opening of the NE Atlantic. Geol. Soc. London, Spec. Publ., 39: 157–158.

Larsen, H.C. and Jakobsdottir, S., 1988. Distribution, crustal properties and significance of seaward-dipping sub-basement reflectors off E. Greenland. In: A.C. Morton and L.M. Parson (Editors), Early Tertiary volcanism and the opening of the NE Atlantic. Geol. Soc. Lond. Sp. Publ., 39: 95–114.

Le Pichon, X. and Heitzler J.R., 1968. Magnetic anomalies in the Indian Ocean and sea-floor spreading. J. Geophys. Res., 73: 2101–2117.

Lightfoot, P.C., Hawkesworth, C.J. and Sethna, S.F., 1987. Petrogenesis of rhyolites and trachytes from Deccan Trap; Sr, Nd and Pb isotope and trace element evidence. Contrib. Mineral. Petrol., 95: 44–54.

Mahoney, J.J., 1988. Deccan Traps. In: J.D. MacDougall (Editor), Continental Flood Basalts. Kluwer, Dordrecht, pp. 151–194.

Mckenzie, D.P., 1984. The generation and compaction of partially molten rock. J. Petrol., 25: 713–765.

Mckenzie, D.P. and Morgan, W.J., 1969. Evolution of triple junctions. Nature, 224: 125–133.

Mitchell, C. and Cox, K.G., 1988. A geological sketch map of the southern part of Deccan province. In: K.V. Subbarao (Editor), Deccan Flood Basalts. Geol. Soc. Ind. Mem., 10: 27–33.

Mitchell, C. and Widdowson M., 1991. A geological map of the southern Deccan Trap, India and its structural implications. J. Geol. Soc. London, 148: 495–505.

Mitra, P., Zutshi, P.L., Chourasia, R.A., Chugh, M.L., Ananthanarayana, S. and Shukla, B., 1983. Exploration in western offshore basins. Petroleum Asia J., 1: 15–24.

Morgan, W.J., 1981. Hot-spot tracks and the opening of Atlantic and Indian oceans. In: C. Emiliani (Editor), The Sea. Wiley-Interscience, New York, NY, 7: 443–487.

Morton, W.H. and Black R., 1975. Crustal attenuation in Afar. In: A. Pilger and A. Rosler (Editors), Afar Depression of Ethiopa. E. Schweizerbartsche Verlagsbuchhandlung (Nagel and Obermiller), Stuttgart, pp. 55–65.

Naini, B.R. and Talwani, M., 1982. Structural framework and the evolutionary history of the continental margin of western India. In: J.S. Watkins and C.L. Drake (Editors), Am. Assoc. Pet. Geol. Mem., 34: 167–191.

Narain, H., Kaila, K.L. and Verma, R.K., 1968. Continental margins of India. Can. J. Earth. Sci., 5: 1051–1065.

Narain, H., Sankarnarayan, P.V., Mishar, D.C. and Achuta Rao, D., 1973. Results of airborne magnetometer profile from offshore Mangalore to offshore Madras (India) along the 13th degree parallel. Pure Appl. Geophys., 75: 133–139.

Nielsen, T.F.D., 1975. Possible mechanism of continental break-up in the North Atlantic. Nature, 253: 182–184.

Nielsen, T.F.D. and Brooks, C.K., 1981. The E. Greenland rifted continental margin: an examination of the coastal flexure. J. Geol. Soc. London, 138: 559–568.

Norton, I.O. and Sclater, J.G., 1979. A model for the evolution of the Indian Ocean and the break up of Gondwanaland. J. Geophys. Res., 84: 6803–6830.

Pascoe, E.H., 1964. A manual of geology of India and Burma. Govt. of India Publ., New Delhi, 3: 1345–2130.

Qureshy, M.N., 1981. Gravity anomalies, isostasy and crust mantle relations in the Deccan Trap and contiguous areas. In: K.V. Subbarao and R.N. Sukheshwala (Editors), Deccan Volcanism. Geol. Soc. Ind. Mem., 3: 184–197.

Raja Rao, C.S., Sahasrabudhe, Y.S., Deshmukh, S.S. and Raman, R., 1978. Distribution, structure and petrography of the Deccan Traps. Geol. Surv. Ind. Rep., 1–43.

Schlumberger, 1983. Well evaluation conference, India Schlumberger Technical Services Inc., 1: 1–64.

Sclater, J.G. and Fisher, R.L., 1974. Evolution of the east Central ocean with emphasis on the tectonic setting of 90 E ridge. Geol. Surv. Am. Bull., 85: 683–709.

Sethna, S.F., 1981. Geology around Bombay some intriguing problems. Geol. Soc. Ind. Mem., 3: 279–286.

Subbarao, K.V. and Hooper, P.R., 1988. Reconnaissance map of the Deccan Basalt Group in the Western Ghats, India. In: K.V. Subbarao (Editor), Deccan Flood Basalts. Geol. Soc. Ind. Mem., 10 (enclosure).

Surendar, K., 1975a. A model of the subsidence history of the west coast of India. Tectonophysics, 27: 165–175.

Surendar, K., 1975b. Structure of the western Indian continental shelf between Bombay and Goa. J. Geol. Soc. Ind., 16: 90–93.

Takin, M., 1966. An interpretation of positive gravity anomaly over Bombay and west coast of India. Geophys. J. R. Astron. Soc., 11: 527–537.

Verma, R.K., 1970. Review on heat flow studies in India. Proc. Second. Symp. Upper Mantle Project, Hyderabad, pp. 147–174.

Verma, R.K. and Mittal, G.S., 1974. Palaeomagnetic study of vertical sequence of Traps, from Mt. Pavagarh, Gujrat, India. Phys. Earth Planet. Inter., 8: 63–74.

Wager, L.R. and Deer, W.A., 1938. A dyke-swarm and crustal flexure in East Greenland. Geol. Mag., 75: 49–56.

Watts, A.B. and Cox, K.G., 1989. The Deccan Traps: An interpretation in terms of progressive lithospheric flexure in response to a migrating load. Earth Planet. Sci. Lett., 93: 85–97.

Wensink, H., 1973. The India–Pakistan subcontinent and the Gondwana reconstruction based on palaeomagnetic results. In: D.H. Tarling and S.K. Runcorn (Editors), Implications of Continental Drift to the Earth Sciences. Academic Press, London, pp. 103–116.

Wensink, H. and Klootwijk, C.T., 1971. Palaeomagnetism of the Deccan Traps in the Western Ghats near Poona (India). Tectonophysics, 12: 175–190.

White, R.S., 1992. Magmatism during and after continental break-up. In: B.C. Storey, T. Alabaster and R.J. Pankhurst (Editors), Magmatism and the Causes of Continental Break-up. Geol. Soc. London, Spec. Publ., 68: 1–16.

White, R.S. and Mckenzie, D.P., 1989. Magmatism at rift zones: The generation of volcanic continental margins and flood basalts. J. Geophys. Res., 94: 7685–7729.

White, R.S., Spence, G.D., Fowler, S.R., Mckenzie, D.P., Westbrook, G.K. and Bowen, A.N., 1987. Magmatism at rifted continental margins. Nature, 330: 439–444.

Wynne, A.B., 1886. On the geology of island of Bombay. Mem. Geol. Surv. Ind., Pt. 2: 174–227.

Zanetin, B. and Justin-Visentin, E., 1975. Tectonical and volcanological evolution of the western Afar margin (Ethiopia). In: A. Pilger and A. Rosler (Editors), Afar Depression of Ethiopia. E. Schweizerbartsche Verlagsbuchhandlung (Nagel and Obermiller), Stuttgart, pp. 300–309.