A reappraisal of the coastal Panvel flexure, Deccan Traps, as a listric-fault-controlled reverse drag structure

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Abstract

The Panvel monoclinal flexure of the Deccan Traps flood basalt province, along the rifted west coast of India, is neither a monocline formed due to simple downbending of the lava pile (e.g., due to sag), nor due to compressional folding, nor merely an extensional fault structure as previously proposed, but is interpreted here as a reverse drag structure on an east-dipping listric master fault that should lie offshore Bombay, with numerous, subsidiary, antithetic (west-dipping) and sympathetic (east-dipping) faults. The proposed model satisfactorily explains a wide range of observations such as the systematic westerly increase in dip of the basalts, their occurrence at shallow levels on the continental shelf, syn-volcanic subsidence and sedimentation, and oil reserves of the shelf. Innumerable graben systems of the continental interiors in the world are indeed characterized by listric faults and reverse drag structures, and the reverse drag model appears highly applicable to most flood basalt provinces with coastal flexures and seaward-dipping reflector sequences at rifted continental margins, namely Karoo, Parana, East Greenland, West Greenland, and Afar.

Keywords: Deccan Traps; Panvel flexure; listric faulting; reverse drag; flood basalt; rifted margins

1. Introduction

Rifted continental flood basalt (CFB) provinces of the world exhibit coastal monoclinal flexures (along the edge of the newly created ocean basin). Prominent examples are the Lebombo monocline associated with the ~180 Ma Karoo province of South Africa, the Torres flexure of the ~130 Ma Parana province of South America, the ~65 Ma East Greenland province coastal flexure (and the less famous West Greenland province coastal flexure), and the ~65 Ma Panvel flexure of the Deccan province of India (Nielsen and Brooks, 1981; Cox, 1988a,b). It is in the flexure zone that the essentially flat-lying lava pile of the interior of a province acquires significant seaward dips (up to 45° or more in the Karoo), and this is where significant volumes of rhyolitic and trachytic lavas, scarce over the rest of the province, are concentrated (Cox, 1988a,b).

The Deccan is one of the best studied CFB provinces in the world, and its Panvel flexure has been noted for more than a century now (Blanford, 1867; Wynne, 1886). These workers, and subsequently Auden (1949), ascribed the flexure to simple
monoclinal bending of the lava pile. Likewise, the East Greenland flexure was explained by Wager and Deer (1938) and later Faller and Soper (1979) and Myers (1980) as due to simple coast-parallel monoclinal folding or bending of the sediments and volcanics. However, Nielsen (1975, 1978) and Nielsen and Brooks (1981) pointed out and emphasized the associated brittle deformation, and preferred a half-graben structure with few large, inland normal faults, dominated by antithetic faulting and block rotation.

In several more recent papers on the Deccan (Devey and Lightfoot, 1986; Cox, 1988b; Watts and Cox, 1989), the ultimate origin of the Panvel flexure has been correctly linked to west coast rifting, subsidence and the uplift of the Western Ghats, but even these explanations have been rather superficial, in that the exact mechanism and cause of flexing were not defined. To my knowledge, the paper by Dessai and Bertrand (1995, abbreviated to D and B henceforth) has been the latest contribution to this debate. They, however, doubted the very nature of this Panvel structure as a ‘flexure’, and following Nielsen and Brooks (1981), suggested that this feature was actually an extensional fault structure, comprising en echelon east-dipping faults and westerly tilted fault blocks. I think that this picture of the Panvel flexure is closer to reality than all that have been propagated until now, but for several reasons discussed herein, it is still inadequate. The present paper goes a step further, and I argue below that the Panvel flexure is actually a reverse drag flexure developed along a controlling master fault of listric geometry, lying to the west of the west coast of India.

2. Regional geology

The west coast region of India is a highly tectonized, rifted continental margin. The west coast and its northern continuation, the Cambay rift, as well as the cross-cutting Narmada–Satpura–Tapi rift zone (Fig. 1a), are characterized by varied magma-
tism, regional dike swarms, earthquake epicentres, high positive gravity anomalies, and high heat flow (e.g., Sheth and Chandrasekharam, 1997a,b). The Deccan province proper is composed of vast accumulations of flood basalts. In the spectacular Western Ghats just east of the Panvel flexure axis (Fig. 1b), the lavas are nearly 2 km in thickness and are all tholeiites. Other rock types are found only to the west of the flexure axis, such as the trachytes and rhyolites of Bombay (Lightfoot et al., 1987). Spilites, pillow basalts, and basalts interlayered with sediments (the ‘intertrappeans’) at Bombay indicate that the area was undergoing active subsidence throughout the volcanic episode (see also Sethna, 1981). The prominent N–S-trending dike swarm along the west coast comprises dolerites, basalts, and alkaline rocks like lamprophyres, with nepheline–basanite plugs (Dessai, 1987; Dessai et al., 1990; D and B).

Seismic studies and drilling for oil along the western Indian continental shelf (Fig. 1a) clearly show a block-faulted and rifted crust (see Chandrasekharam, 1985; Biswas, 1988) with some N–S-trending basement ridges traversing an otherwise almost continuous cover of Deccan volcanics. Recovery of Precambrian biotite gneiss directly below Tertiary (post-Deccan Trap) sediments in several boreholes between 18°N and 20°N on the shelf indicates that these areas were palaeohighs during Deccan volcanism, and later they subsided to receive the Tertiary sediments (Ramanathan, 1981).

3. Listric faults

Listric normal faults form during rifting and the formation of passive continental margins with concomitant basinal development (e.g., Bosworth, 1985; Brune and Ellis, 1997). Their unequivocal recognition requires unusually extensive outcrop data, close subsurface control, or high-quality seismic data, though their presence is suggested indirectly by such features as increasing dip with depth toward the controlling fault (‘reverse drag’), thick progradational sandstone overlying ductile strata, arcuate fault patterns, basins, or uplifts (Shelton, 1984) and differential tilt between imbricate fault blocks with progressively steeper dips in the dip direction of the (antithetic) faults (Wernicke and Burchfiel, 1982; Jackson and McKenzie, 1983).

Fig. 2a shows the phenomenon of normal drag. According to Hamblin (1965), movement along a curved fault plane tends to move the blocks apart, creating a gap. Attempts to fill this gap either result in antithetic faults (faults with minor displacement which dip into the major listric fault plane, Fig. 2b), or, if conditions are favourable, in reverse drag (Fig. 2c). In nature the scenario obtained is usually a combination of these two.

4. Dip variation in lavas of the Bombay–Panvel area

To the west of the Panvel flexure axis, the lavas dip west by variable, often substantial amounts. On Bombay Island the dips are 15°–25°W at different places, and the basalts, sediments and the trachytes–rhyolites all dip west. Fig. 3a, which integrates the field observations of D and B with my own, shows
the dips and strikes of the basalts in an E–W zone between Panvel and Bombay. Although dips locally become higher in some places adjacent to mapped faults (up to 50°, Auden, 1949) in this general region, a progressive westward increase in dips in the area of Fig. 3a is obvious. Thus the dips are 2°W at Panvel, 4°W to the west of Panvel, ~10° at Elephanta, 2–3°W at Sheva and 15–25°W at Bombay. A similar variation in dips was noted by D and B at the latitude of Bassein as well. They have explained this systematic dip variation as due to several en-echelon east-dipping faults which have produced block rotation and progressively steeper westward dips (Fig. 3b). However, they have failed to recognize that even this phenomenon requires overall control by a master fault situated far to the west, one with a listric (concave upward) geometry and eastward dip (Fig. 3c). The entire structure observed, namely that of progressive westward increase in dip of the fault blocks and the lavas, is that of ‘reverse
drag’. Thus, the Panvel flexure is a real flexure, not one resulting from simple downward bending due to sag, or compressional folding, of the lava pile, but it is a reverse drag flexure (‘roll-over anticline’) on a listric master fault, cut by numerous, en echelon, synthetic and antithetic faults. This listric fault lies offshore, and should be detectable with reflection seismic surveys (Bally et al., 1981).

For East Greenland, Nielsen and Brooks (1981) did note very briefly that the continental margin faults would become listric at depth due to necessary ductile deformation at 10–15 km, but they did not visualize the listric faults as the controlling, and in fact necessary, factor (which I do), and strongly emphasized the brittle deformation (antithetic faulting) instead. Actually, for the Afar volcanic margin of Ethiopia too, Kazmin (1991) found it difficult to explain the fault geometries unless an idea of a low-angle detachment was utilized.

5. Explanatory power of the proposed model

In the case of the Panvel flexure, the value of my proposed listric fault model lies in its ability to explain a wide range of observations as follows (see Fig. 3c).

1. The reverse drag observed, which is not dubious.

2. The interstratification of basalts and freshwater sedimentary beds at places like Bombay, indicating that the area was undergoing active subsidence and receiving sediments (and, by implication, was on the hanging wall side of the fault).

3. The rich oil reserves of the Bombay offshore—west coast continental shelf. It is well known that listric (and planar) faults are important producers of traps for oil and gas in faulted strata (e.g., Shelton, 1984).

4. Parallel sets of faults and fault-controlled blocks themselves.

5. Thinning of the lava pile offshore.

6. The existence of the basalts at shallower levels on the continental shelf than expected by straightforwardly extrapolating the westerly dips. ((4) to (6) are the observations that led D and B to correctly question a simple monoclinal fold model, and note that since the trend of dip variation in the basalts is that of westerly increase, the problem of accounting for the shallow elevations of the basalts becomes even more severe.) However, the shallow depths of basalts offshore can be easily reconciled with the idea that we may have crossed the proposed fault already. The basalts on the footwall side of the listric fault should obviously (and by necessity) be at shallower levels than they are on the hanging wall side (Fig. 3c). Dr. K.G. Cox kindly points out (official review) that at the southern end of the Lebombo monocline, on land, and also along the offshore Davis Strait to the west of the West Greenland flexure, around Ubekendt Ejland and Svartenhuk Halvø, the basement rocks are known to be faulted up immediately on the seaward side of the flexure.

Thus the proposed model for the Panvel flexure is consistent with all of the field observations.

6. Physical viability, age and duration of flexing

The reverse drag of hanging wall strata into the Colorado plateau border faults was explained by Hamblin (1965) as a geometric consequence of the downward decrease in dip of these listric faults. This downward decrease in dip takes place (i.e., listric faults form rather than planar ones) when there is a difference in rheological properties between upper and lower strata in a sequence. The depth of normal faulting or their ‘soling out’ occurs in the depth range of 5–17 km. A preferred interpretation is that extension in the brittle upper crust is taken up by ductile stretching and detachment faulting in the lower crust (see Bally et al., 1981). The formation of listric normal faults is enhanced by, or perhaps requires, a ductile ‘substrate’ (Shelton, 1984).

The freshly erupted basalts and acid lavas, and interstratified sedimentary beds and spilites (watersaturated) would have been rather ductile at the time of listric faulting and flexing. An anonymous referee of this paper found my proposed detachment “unjustified and physically unsound”, writing that the cooling of basalt is a geologically instantaneous process and once solidified, the basalt would behave as a competent unit. This is not true. As demonstrated by Self et al. (1996, 1997), tube-fed pahoehoe compound flows, such as those characterizing much of the Columbia River province or the Deccan province
including the area of the present study, cannot have been emplaced and cooled over days or weeks as thought earlier (Shaw and Swanson, 1970), but over many years. Such flows remain hot and actively inflating for many years to decades, and the Bombay–Panvel flows would have been amenable to ductile deformation during downfaulting and subsidence, which was anyhow concurrent with eruptive activity (recall the interlayered basalts and sediments).

The final phase of flexing was obviously younger than the final eruptive activity (as it imparted a tectonic dip to the lavas). However, the fact that flexing did not continue much later than the deposition of the flows and sedimentary beds comes from an excellent piece of evidence—the timing of intrusion of dike swarms. There were at least two generations of these, as suggested by the fact that one set of dikes has been affected by flexing. These dikes are perpendicular to the bedding of the (westerly dipping) lavas and dip 60°–80° east. On the other hand, the younger dikes are alkaline, vertical or very steeply east-dipping (80°–85°) and follow the Panvel flexure axis (D and B). Thus these dikes are syn- or post-flexure, but this itself indicates that magmatic (dike) activity continued still after the formation of the flexure, and thus that flexing did not occur much later than the eruption of the lavas (say, during Recent times). From these critical observations, the Panvel flexure is neither much younger than its constituent lavas, nor much older than the final alkaline dike intrusive activity. Indeed, the Lebombo monocline of the Karoo province was actively flexing down during the period of lava extrusion (White and McKenzie, 1989, p. 7719) and in East Greenland also the flexing occurred shortly after the plateau basalt eruptions (Nielsen and Brooks, 1981).

7. Conclusions

The listric fault-reverse drag model proposed here explains satisfactorily not only the nature of the Panvel flexure, but also its mechanism. I lack a personal experience and field study of the coastal flexures of the other rift-margin CFBs, but this model is highly testable (if not eminently applicable) to them, and I suggest that the specialists of these provinces subject it to rigorous testing. If the model is correct for the coastal flexures of other rift-margin CFBs as well, namely Karoo, Parana, East Greenland, West Greenland, and Afar, a considerable advance is made in our understanding of a major tectonic issue, which has hitherto remained enigmatic and controversial. My explanation suggests that there is no fundamental difference in the mechanics of continental margin rifts and the rifts of the continental interiors, all of which evolve by listric faulting. The proposed model may also be applicable to the seaward-dipping reflector sequences off many rift-margin CFBs, and listric faults may prove to be the rule rather than the exception.

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References


