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The Deccan Traps: an interpretation in terms of progressive lithospheric flexure in response to a migrating load

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Structural and geochemical data from the Western Ghats, India have been used to construct an accurate north–south section of the volcanic stratigraphy of the southwest part of the Deccan province. The characteristic style of the section is one of southerly dip, reversing in the extreme south, southward overstep of higher units onto pre-Deccan rocks, and down-dip thinning of individual formations. In contrast, an east–west section shows continuity of essentially horizontal stratigraphic units without overstepping relationships. Previous authors have interpreted these data in terms of the progressive southward migration of the volcanic source as India drifted northwards over a hot-spot now centered beneath Reunion. We have compared the observed stratigraphy to the predictions of a geophysical model based on the flexural response of the continental lithosphere to a migrating volcanic load. The best fit to the observed section is for the structurally lowest part of the modelled sections with an elastic thickness of the lithosphere of 100 km. This value explains the present day width of the Traps in peninsula India, but requires that up to 5.5 km of the upper part of the flank section has been removed by erosion. The origin of the erosion is not clear but, it may be related to flexural rebound following removal of the cone loads that formed along the trace of the plume. The model cannot explain the subsidence of the Traps beneath the shelf off Bombay or the "rim" uplift of the Traps in the Western Ghats. We attribute these modifications of the stratigraphy to vertical movements (uplift and subsidence) that followed rifting of India from the Mascarene Plateau during the Eocene.

1. Introduction

The Deccan Traps constitute a typical continental flood basalt province, currently covering about 800,000 km^2 of peninsular India. Along the west coast south of Bombay, the lavas are particularly well exposed in the seaward facing escarpment of the Western Ghats. This area has been the site of intensive geological mapping in the last decade, and its structure and stratigraphy are now comparatively well known.

Morgan [1] first suggested that the Deccan Traps were generated as the Indian continent passed over a mantle plume while drifting northwards during the Cretaceous and Tertiary. The Traps are contemporaneous with basalts on the Mascarene Plateau [2] which prior to continental rifting was conjugate to peninsular India [3]. Subsequently, the plume gave rise to the Chagos-Laccadive ridge and is now believed to be active beneath Reunion. Cox [4] pointed out that if the

plume model is correct, then the stratigraphic development of the Deccan should be characterized by older sequences in the north, with a progressive overstep and younging towards the south. At that time there was little hard evidence other than that occurrences of highly picritic lavas, thought to be the most primitive rock-type and therefore perhaps the oldest, were known to be confined to the northern edge of the province [5,6].

Other plume traces [7] suggest that during the Cretaceous and Tertiary, the Indian plate was moving northward at rates of about 14 cm/yr. At present the Traps extend for about 1000 km in the direction of plate motion and so, according to the plume model, they should be about 7.5 m.y. older in the north than the south. This estimate of age is complicated, however, by the fact that basalt flows have the capacity to flow large distances (up to several hundred kilometres) in the north–south direction. The migration of the actual focus of

eruptions may be substantially less than the length of the north–south section; so an age estimate based on a plume model is only a maximum estimate.

There has been considerable recent interest in the age of the Traps because of the suggestion [8] that the volcanic activity may have coincided with the Cretaceous/Tertiary boundary. Duncan and Pyle [9] analyzed age data from a 2000 m composite section east of Bombay and concluded that there was no significant difference in age from the top to the bottom of the sequence. The mean age for the section was 67.4 ± 0.7 m.y. Courtillot et al. [10] studied $^{40}Ar/^{39}Ar$ ages from the central region of the Traps and concluded that the volcanics were emplaced in the period 65–69 m.y. ago,
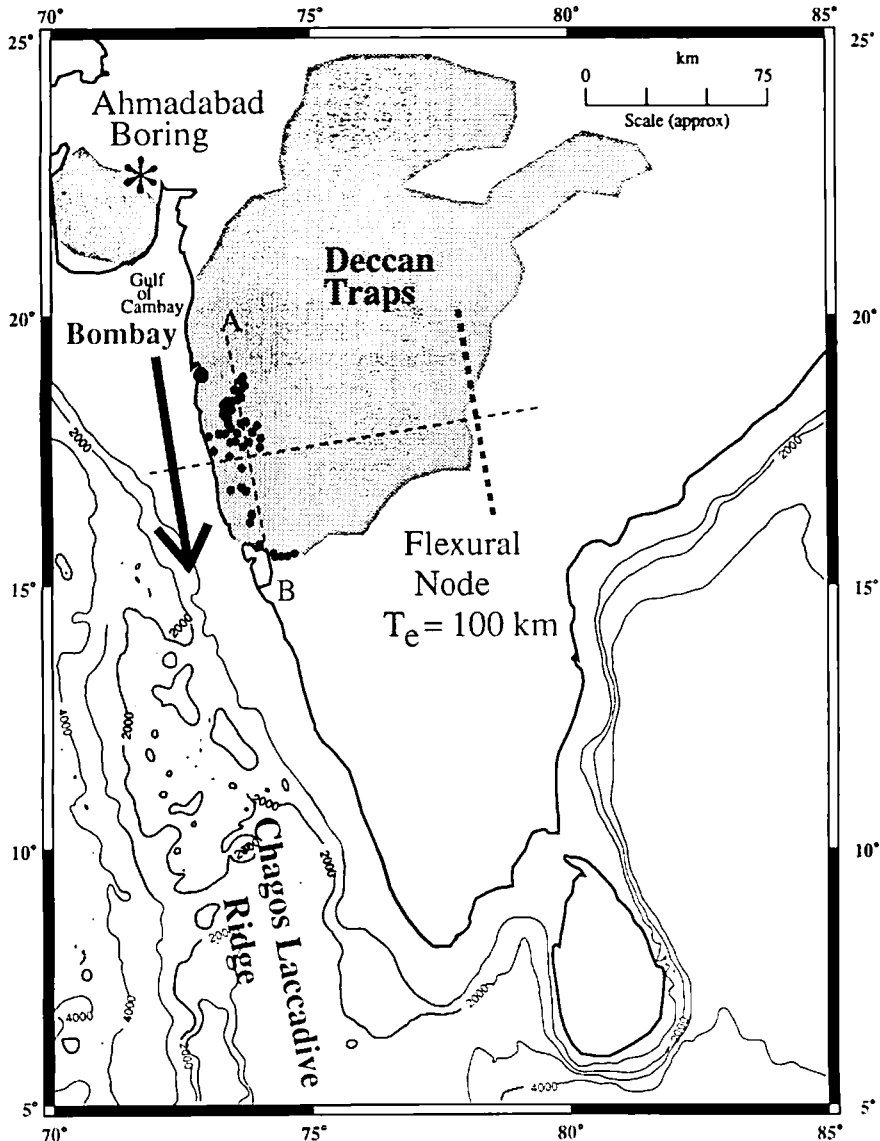

Fig. 1. Location map of the Deccan Traps. The bathymetry is shown at 1000 m intervals. The small solid dots show the locations of the sections used to define the stratigraphy along the Western Ghats escarpment. The heavy dot shows the location of Bombay. The heavy arrow shows the path of the migrating volcanic load which previous authors have proposed generated the Deccan Traps as India drifted north over a hot-spot now centered in Reunion. The light dashed lines show the location of the calculated profiles of the stratigraphy. The asterisk indicates the position of the picrite basalt, recovered from borings near Ahmadabad [5].

probably coincident with the Cretaceous/Tertiary boundary.

We believe that the age data are too sparse (there are no age determinations from the Traps south of Poona or north of Indore) and the measurement errors too large to determine at the present time whether the Traps are coincident with events at the Cretaceous/Tertiary boundary or whether they formed by a simple progression of ages from north to south as the plume model would predict.

Mapping based on the detailed tracing of marker horizons in the field [11,12] and on geochemically distinctive units [13,14] so far shows that the Deccan sequence does indeed behave as predicted by the plume model. Along the Western Ghats escarpment, successive formations traced from the north generally dip southward and overstep younger formations. The Mahabaleshwar Formation, for example, crops out on the top of the escarpment near Pune and overlies at least 1.5 km of earlier lavas [15], yet 300 km to the south it comes to rest on the pre-Deccan basement having completed the overstep of all the older rocks. By contrast, an east–west traverse towards the south end of the province [16] shows no signs of overstepping but simply an uninterrupted extension of the stratigraphic units observed on the west coast, with almost negligible apparent dips.

The geology as known at present is thus consistent with a migration of the vulcanism from north to south. Most of the erupted rocks in the Deccan are evolved basaltic types but picrite basalts, representing more primitive material, are known from borings 100 km southwest of Ahmadabad (Fig. 1). It seems probable therefore that the main source of the vulcanism migrated from the vicinity of Ahmadabad across the shelf off the coast of Bombay, to a point close to the present intersection of the Chagos-Laccadive Ridge with the Indian continental margin. Such a migration path is supported by geophysical studies in offshore regions. Seismic reflection profile studies [17] show that off Bombay, Tertiary sediments thin toward a north–south trending structural high—known as the Bombay high. Most of the wells that have been drilled on the high penetrated the Traps. The basement high has a relief of about 3–4 km, is about 70 km wide on an east–west section and is associated with a belt of large amplitude gravity anomalies. We believe that the topography and gravity anomaly high off Bombay may be a remanent of the cone loads that formed the Traps. Seismic reflection profile studies [18] have also delineated a sequence of seaward dipping reflectors beneath the slope 300 km ENE of Bombay. These sequences have been interpreted as a layered igneous assemblage of Deccan age that formed by sub-aerial vulcanism—prior to or during the earliest stages of the rifting of India from the Mascarene Plateau.

The base of the Deccan lava sequence dips northward along the Western Ghats escarpment, so that at the latitude of Bombay an unknown fraction lies below sea level. This observation led Devey and Lightfoot [14] to propose that a series of overlapping shield volcanoes had migrated from north to south, each one subsiding as the crust responded to loading. They showed, using an Airy-type model, that loading could explain the outlines of the stratigraphy and structure of the Deccan with some success.

Studies in oceanic regions [19] have shown that the lithosphere responds to volcanic loads not locally, as an Airy model would predict, but by flexure. The elastic thickness of oceanic lithosphere, T_e, is smaller than either its seismic or thermal thickness and depends strongly on the thermal structure of the lithosphere at the time of loading [20]. Some oceanic volcanoes are superimposed on broad swells in topography which Crough [21] suggested formed by reheating of the lithosphere as it passed over a plume. There is evidence at some volcanic loads [22] that T_e is lower than would be expected on the basis of the thermal age due to reheating of the lithosphere by a plume. The low values of T_e appear to be mostly located in a single region of the central Pacific [23], however, so it is not clear to what extent a plume is capable of modifying the strength of the upper part of the plate. At the Hawaiian islands, for example, T_e is normal [24] for the age of the lithosphere on which it was emplaced, despite the existence of a broad topographic swell on which the islands are superimposed.

The purpose of this paper is to examine the application of a flexure model to a continental flood basalt province. We focus our study on the Western Ghats area of the Deccan Traps since this is a well-exposed and well-mapped area. Although

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the source of the Traps in not known. the stratig-
raphy of the areas that may have flanked large
loads is exposed. and can be mapped to a much
greater accuracy than it can around oceanic
volcanoes such as Hawaii. The main objectives of
the paper are to evaluate the role of flexure in the
development of the Deccan Traps and, if possible,
use stratigraphic observations to constrain the
long-term mechanical properties of the continental
lithosphere.

2. Structure and stratigraphy

We summarize the known information about
the heights of formation boundaries in the West-
ern Ghats in Fig. 2. A total of 51 individual
measured sections, the localities of which are
shown in Fig. 1, has been used to construct Fig. 2
[12,14,25]. All heights were projected orthogonally
onto the line *AB* (azimuth 170°), and we have
made an approximate allowance for the seaward
dipping monoclinal flexure near the coast [12] by

adding 100 m to the heights of all the boundaries
west of 73.5° longitude.

We caution that the north–south section must
be interpreted with some care because of the ex-
treme vertical exaggeration. Thus, thickness esti-
mates of individual formations should be read
vertically, not at right angles to the formation
boundaries. The salient features of the profile are
as follows:

(1) Dips are southward from the northern end
of the section to Kohlapur, where there is a dip-re-
versal.

(2) At the northern end of the section, dips are
consistently higher at the top of the escarpment
than at sea-level at the same latitude. At the
southern end the converse is true.

(3) Following from this, where thickness
changes are detectable they characteristically con-
sist of down-dip thinning, though some forma-
tions such as the Poladpur and Ambenali appear
to maintain a constant thickness for large dis-
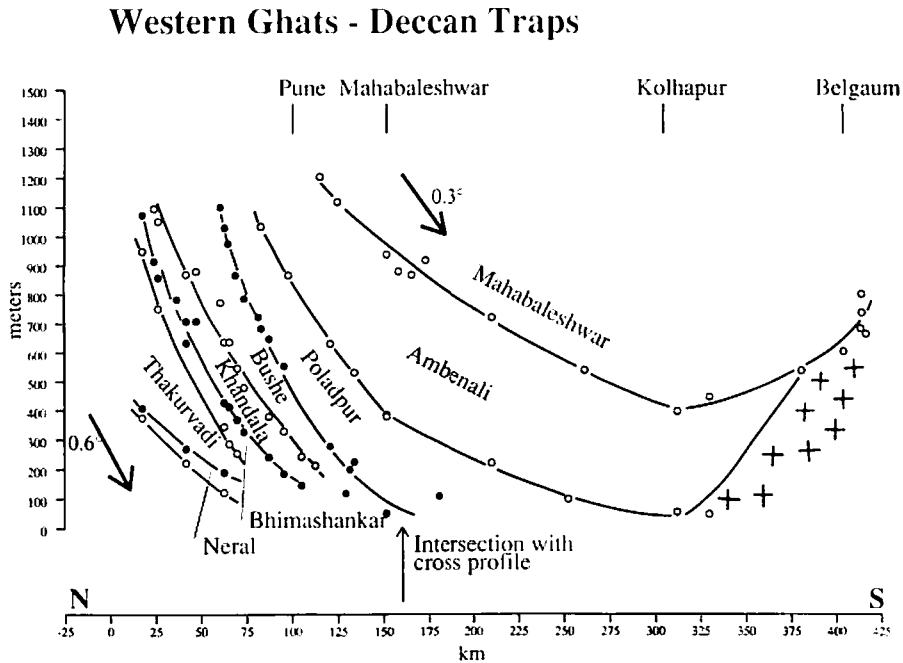tances.

Western Ghats - Deccan Traps

Fig. 2. Summary stratigraphic logs for all the sections used in this study. The circles show the depth to the base of each of the formations mapped previously [12,14,25]. Filled circles emphasise the top of the Neral. Bhimashankar and Bushe formations. The solid lines are smoothed formation boundaries between the open and filled circles. Each section has been projected onto north–south line with azimuth of 170°. The stratigraphy at each section is based on the chemical composition of the flows, particularly the major and trace elements. The vertical exaggeration is approximately 160:1. The formations dip at 0.3–0.6° to the south. At a distance of about 310 km there is a dip reversal and the base of Mahabaleshwar dips gently to the north.

3. Flexure

We have computed synthetic volcanic stratigraphy using a simple elastic plate model, similar to that used by previous workers [26] to study the flexure at islands and isolated seamounts in the ocean basins. The main differences are that the plate is subject to multiple loads as they move across the plate with time. The resulting stratigraphy is obtained by summing the contributions of individual loads and "updating" the depths to the pre-deformation surface, the load, and the flexure profile.

For purposes of calculation, we divided the load into parts: one a driving load which causes the flexure and one an infill load which modifies the flexure. The driving load is the volcanic material that has accumulated above a horizontal pre-deformation surface and, in the oceanic case, is the topography of the seamount above the normal depth of flanking sea floor. By contrast, the infill load is the material that fills in the flexure to the pre-deformation surface. Both loads act as an excess mass on the plate which responds by flexure.

The load that generated the Deccan Traps is assumed to have been made up of a series of cones which migrated at a constant rate across the plate as India drifted north. Each cone is made up of volcanic material of uniform density and is assumed to have a flat top and exponentially decreasing slopes. The central height of the cone was selected to be 500 m, which in our models typically gives rise (depending on the flexural rigidity) to an approximately 200 m thick lava sequence in the infill beneath the edge of the load. Thickness of individual flows in the Western Ghats are about 25–100 m, so each load and its infill represents several flows. An overall width of the cones of 250 km was chosen. In the model, different cumulative loads were simulated by varying the "offset" between cones: small offsets correspond to large cumulative loads and large offsets to small cumulative loads.

Fig. 3 shows the results of a simple calculation involving three loads, offset by a constant distance. We assumed an elastic thickness, T_e, of 100 km, a load density of 2.8 g/cm^3, and an offset of 120 km. The infill material was assumed to be of the same density as the load and to fill in the flexure up to a horizontal surface. The upper
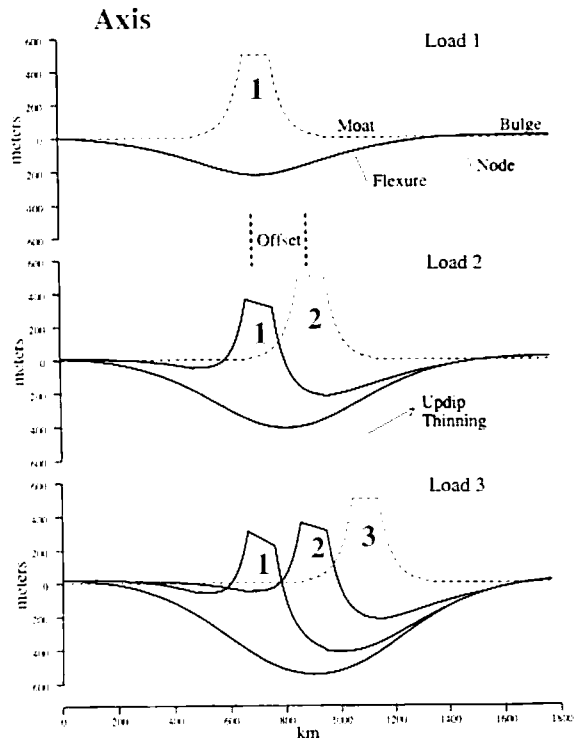

Fig. 3. Simple model for the progressive flexure of the lithosphere due to a migrating load. The upper profile shows the initial load and the resulting flexure. The load is assumed to be conical in outline and have a maximum amplitude of 500 m. The slope away from the top of the cone is defined by a simple exponential with standard deviation of 30 km. The load is assumed to be of uniform density of 2.8 g/cm^3 and to be emplaced on an elastic plate with a uniform flexural rigidity of 10^{32} dyne-cm, equivalent to an elastic plate thickness of 100 km. The middle profile shows the effect of adding a second load 150 km in front of the initial load on the flexure curves. The initial load and flexure are deflected down by the new load in the region flanking the new load and uplifted in peripheral regions. The net effect on the new load is to produce an apparent up-dip thinning of the material that infilled the flexural moat of the initial load. The lower profile shows an additional load emplaced at the same offset distance. For simplicity the actual stratigraphy on the crest of the loads is not shown.

profile shows the flexure curve that results from a single cone load. The maximum flexure of 200 m occurs directly beneath the cone. The flexure curve shows a broad area of subsidence, a nodal point of no subsidence or uplift, and a peripheral uplift. The middle profile shows the modifying effects on the flexure and predeformation surfaces of adding a second cone load at an offset distance of 120 km. At this offset, the pre-existing cone is located

in the flexural depression of the new cone causing subsidence. The subsidence, which reaches its maximum value beneath the new load, causes an apparent up-dip thinning to the material that originally infilled the flexural depression of the old cone and a tilting of its once flat top in the direction of load migration. The lower profile shows the effect of adding the third load. After this load, the stratigraphy begins to develop a characteristic pattern of offlap "upstream" (i.e. in the direction of plate motion) of the new load and onlap in the direction of load migration. The pattern consists of three sequences each of which corresponds to an individual load.

The synthetic stratigraphy in Fig. 3 was constructed assuming that the flexural bulges, which displace air, were reduced by erosion to sea level. Since the maximum height of the bulge is less than a few tens of meters, this assumption makes little difference to the shape of the resulting stratigraphic patterns. A more difficult problem concerns the stratigraphy in the vicinity of the cones themselves. As each new load is added, there would be some overlap of the old load (depending on the slope) which covers part of the top of the cone and its flank. While the loading effect of this overlap has been taken into account in Fig. 3, its effect on the stratigraphy has not. Again, this omission has little effect on the development of the offlap and onlap patterns.

4. Data analysis

For the purposes of model comparisons we have assumed that the Traps were erupted from a focal point migrating from north to south along the line of the heavy arrow in Fig. 1. This line was chosen to be co-linear with the known picrite basalt occurrence at the northern end of the province and with the Chagos-Laccadive Ridge to the south. Fig. 4 shows the model in plan view, and we visualize that the Western Ghats escarpment represents a flank section, offset by about 150 km from the load axial line.

We show in Fig. 5 the synthetic stratigraphy for a flank section assuming a value of T_e of 100 km, a load and infill density of 2.8 g/cm^3, and offset distances between cones of 15, 30 and 60 km. This value of T_e is similar to previous estimates for the Indian lithosphere based on gravity anomaly stud-
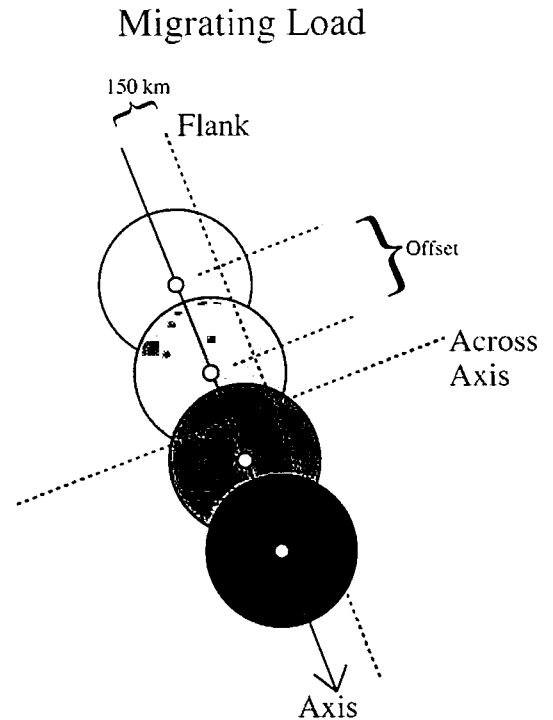
Migrating Load

Fig. 4. Schematic diagram illustrating the concept of a migrating load moving at a constant rate across a plate. The offset defines the distance between individual loads and determines the total amount of load at a point on the plate. Also shown are the locations of the flank, axis and across axis profiles referred to in the text.

ies [27,28] over the Ganges foreland basin to the north of the Traps. Laboratory measurements on holocrystalline, non-vesicular basaltic rocks show densities in the range 2.85-3.12 g/cm^2 [29] with a mean of 2.90 g/cm^3. Since the Deccan lavas are amygdoidal and contain laterite horizons, we chose a slightly lower density of 2.80 g/cm^3 for the load and infill density. This is in agreement with the bulk densities inferred from density measurements [30] and gravity anomaly studies [20] over seamounts and oceanic islands in the Pacific. The offset distances between cone loads were kept constant for each calculated profile and were chosen to represent both large and small total loads. In Fig. 5, the load size increases linearly between the upper and lower profiles (i.e. an offset of 15 km is 4 times the load as an offset of 60 km). The total number of loads was decreased from 80 for an offset of 15 km to 20 for an offset of 60 km so as to ensure that the distance of migration was the
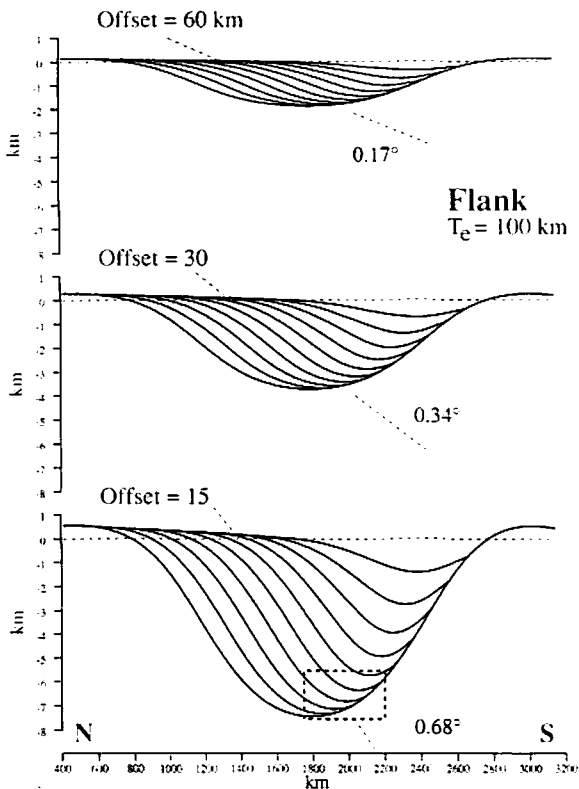
Fig. 5. Synthetic stratigraphy along the flank profile, 150 km from the crest of the load. The origin of the distance scale has been arbitrarily chosen to represent a point 1000 km to the north of the first load. The calculated profiles are based on a uniform elastic plate thickness of 100 km and offsets of the migrating loads of 15, 30 and 60 km. The total number of individual layers is the same for each offset (see text for explanation). The elastic thickness was chosen on the basis of the results of previous gravity anomaly studies of the Himalaya-Ganges system which suggest an elastic thickness of 80–100 km for the Indian continental lithosphere [27,28]. The thickness of the sequence ranges from 2 to 8 km, with the greatest thickness corresponding to the smallest offset distance (i.e. the largest load). The overall pattern of the stratigraphy shows a well developed onlap pattern in the direction of load migration. The formations within the sequence show down-dip increase in thickness and dip and an up-dip decrease in thickness. The heavy dashed lines show the portion of the calculated profiles compared to observations in Fig. 6.

same for each profile. For purposes of comparison, the number of layers was kept constant. This was achieved by displaying the cumulative stratigraphy after skipping a certain number of loads. In Fig. 5, for example, the load skip intervals for the offsets of 60, 30 and 15 km are 1, 2 and 4 respectively. The figure shows well developed stra-

tigraphic sequences, which bear a striking resemblance to the "clinoform" structures that develop in sedimentary sequences by progradation of sediment loads in river delta systems [31]. As would be the case for deltas, the dip of individual volcanic units in Fig. 5 is determined by the offset distance which is a measure of the size of the load —being largest for the smallest offset and smallest for the largest offset.

The computed dips in Fig. 5 are of the order of the measured dips along the north-south section of the Western Ghats, especially for offset distances of about 15 km. Offsets much smaller than this will produce dips that are too steep while larger offsets lead to too shallow dips. The only portions of the synthetic profiles that resemble the down-dip thinning and overstepping of relationships of the measured sections, however, are the structurally lowest parts of the sections.

Fig. 6 shows a detailed comparison of the lowest part of the modelled sequence for $T_e = 100$ km and offset = 15 km to the measured heights of the base of 4 of the formations plotted in Fig. 2. The solid lines show the synthetic stratigraphy that results from a load skip interval of 1 (which results in twice as many individual layers than are shown in Fig. 5). The symbols show the depth to the base of the Mahabaleshwar, Ambenali, Bushe and Neral Formations. We have made no attempt to find the load offset which will produce stratigraphy that passes through individual observed data points. Instead, the goodness of fit can be assessed by comparison of synthetic and measured dips. Fig. 6 shows a good overall agreement between the observed and synthetic dips. The fit is particularly close for the Mahabaleshwar, Ambenali and Neral Formations. Also, the base of the Mahabaleshwar shows a dip reversal at 300 km and this is clearly seen in the synthetic stratigraphy. The fit to the base of the Bushe is not quite as close, although a small offset occurs in the data at 62 km and the fits, are actually quite good either side of this point.

In our modelled sections, the dip reversal is the result of approaching the southern edge of the migrating load. The close fit between the observed and synthetic sections (Fig. 6) suggest that either the load terminated about 200 km to the south or that some other change took place in the tectonics of the region. Fig. 1 shows a point 200 km south
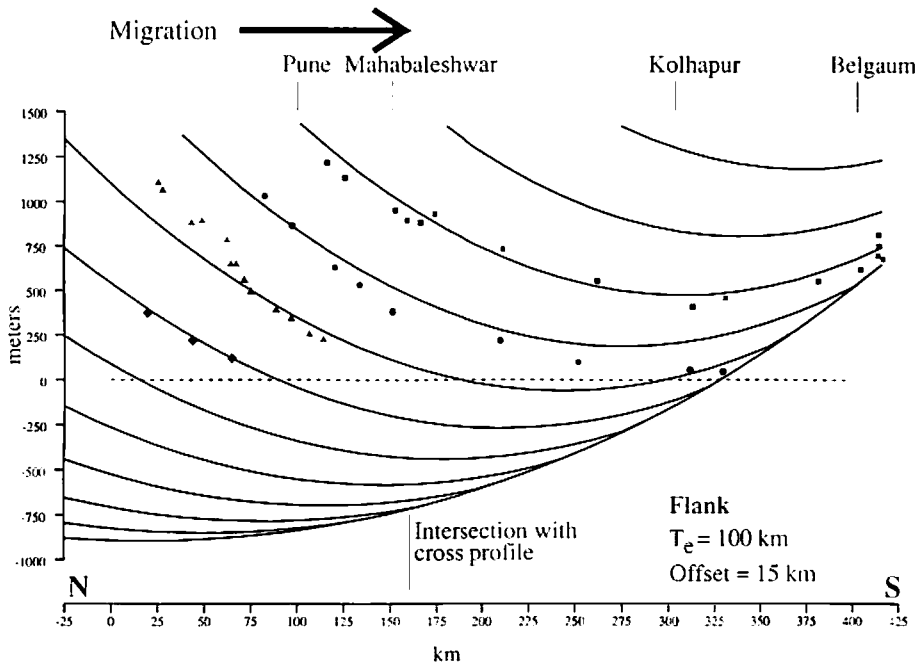
Fig. 6. Comparisons of observed depths in individual formations in the Deccan Traps (Fig. 1) to calculated profiles based on an elastic plate thickness of 100 km. The best fits to the dips of the observed data are for an offset of 15 km. The solid symbols show the observed heights of the top of selected formations: diamond = Neral, triangles = Khandala, circles = Poladpur, and boxes = Ambenali. There are twice as many layers in the section than in the lower profile in Fig. 5 (see text for explanation).

of the end of line A-B that corresponds almost exactly to where the northernmost bank of the Chagos-Laccadive Ridge intersects the Indian continental margin. We suggest therefore that the dip-reversal was caused by a change in the loading regime as India separated from the Mascarene Plateau [3]. Prior to rifting, peninsular India and the Mascarene Plateau (including the Seychelles Bank and Saya de Malha Bank) were flexed, causing flanking subsidence and infill of volcanic material over a relatively broad area while following rifting, the load and infill were confined to the newly formed narrow oceanic rift of the Arabian sea.

5. Discussion

It was shown in the previous section that a model in which the lithosphere is progressively flexed by a migrating volcanic load can explain the present day dips of the Deccan Traps. Surfaces that were once horizontal or close to horizontal at the time of loading (or soon after) are now tilted because of flexural effects of the new loads. While the magnitude of the tilts is a function of load

size, we would also expect that the dips would be sensitive to T_e—since this parameter determines the overall shape of the flexure profile, particularly the wavelength of flexure.

We assumed in the models that $T_e = 100$ km, in agreement with previous estimates for the Indian lithosphere [27,28] beneath the Ganges basin. Similar values have been obtained from flexure studies of the Appalachian foreland basin [32]. Both sets of studies involve flexure of relatively old ($> 10^9$ years) continental lithosphere. By contrast, the relatively young ($\sim 2 \times 10^8$ years) Variscan basement underlying the Molasse basins of the central and western Alps is associated with values of T_e in the range of 25–45 km [27]. On this basis, Karner et al. [33] suggested that T_e for the continents, like that of the oceans, may increase with thermal age.

By contrast, it has been argued [34] that continental lithosphere should be much weaker than oceanic lithosphere of the same thermal age because of compositional differences. Barton and Wood [35] suggested that T_e of stretched continental lithosphere beneath the North Sea basin may
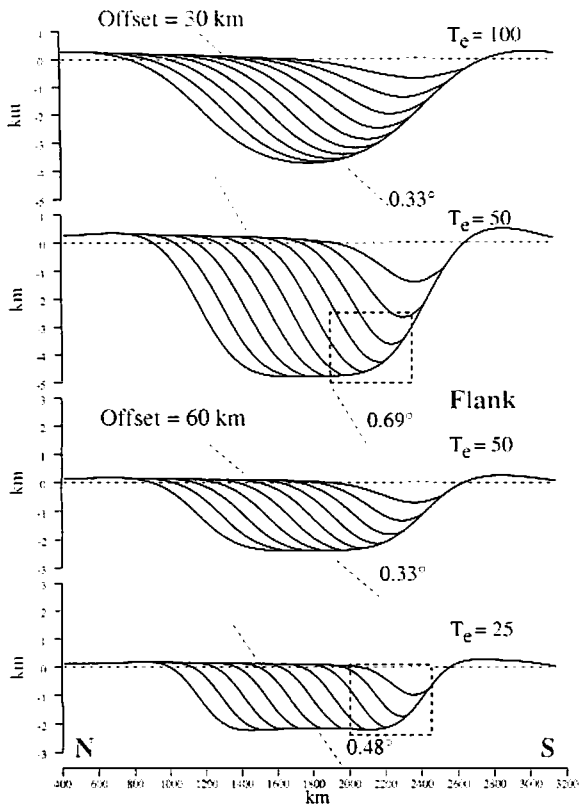
Fig. 7. Synthetic stratigraphy along the flank profile based on different values of the offset distance and elastic thickness of the plate. The origin of the distance scale is as defined in Fig. 5. The lower values of the elastic thickness have been chosen to test the possibility of whether, as some workers have recently suggested, the continental lithosphere is relatively weak in its response to loads of long-term duration. The two upper profiles show that it is possible to obtain dips of 0.69° for the case of T_e = 50 km if the offset distance is increased to 30 km. The two lower profiles show that if the offset distance is increased to 60 km, then elastic thicknesses of 25 km or lower could produce dips of 0.48° or greater. The total number of layers shown in each of the profiles [10] was kept constant by using a load skip interval of 2 for the upper profiles and 1 for the lower profiles. The heavy dashed lines show the structurally lowest parts of the synthetic stratigraphy which are compared to observations in Fig. 8.

be only 5 km. Watts [36] and Fowler and Mckenzie [37] have argued that stretched crust at passive continental margins is similarly weak.

An important question, then, is whether the measured dips in the Deccan Traps could be explained by values of T_e smaller than 100 km. Fig. 7 shows that the dips of the synthetic profiles can be produced by flexure of relatively weak plates—providing that the offset distance between

individual cone loads is increased. A greater offset reduces the cumulative load size thereby compensating for the increase in flexure due to a lower rigidity. This is well seen in Fig. 8 which shows a detailed comparison of the measured depths to the structurally lower parts of Fig. 7. It is not difficult to fit the average measured dips for a T_e as low as 25 km, providing the spacing between loads is increased to 60 km.

It is apparent from Fig. 8, though, that the synthetic section based on the lower bound of T_e of 25 km begins to depart from the known stratigraphic and structural relationships. Models such as this show if anything down-dip thickening, and an increase of dip at the foot of the escarpment relative to the top at the same latitude.

Although the maximum thickness of the volcanic sequence is determined by the offset that is assumed between loads, the shape of the flexure profile is a strong function of the T_e value assumed. Figs. 5 and 7 show, for example, that while the distance to the flexure node (the point of no subsidence of uplift) is approximately the same for the case of a constant T_e and load offsets of 30 and 60 km, it increases by up to 200 km as T_e changes in value from 25 to 100 km—independent of any difference in load size.

Fig. 9 shows the across axis profiles for the combination of T_e and offset parameters that fit the measured dips on the flank section. The figure shows that the distance from the load center to the node increases from about 275 km for T_e = 25 km to about 600 km for T_e = 100 km. The distance to the node for T_e = 100 km is in good agreement with the present-day outcrop of the Deccan in central India (Fig. 1). Furthermore, this value of T_e also helps to explain the widespread occurrence of basaltic flows of Deccan age on the Mascarene Plateau [2]. Prior to rifting, the plateau was conjugate to peninsula India and would therefore have formed the other "limb" of the flexed system. According to the reconstruction of White and Mckenzie [38], the calculated node would be located just to the west of the Seychelles which geological evidence [39] suggests was uplifted during the Early Tertiary. These considerations provide additional support for an African/Indian plate of relatively high flexural strength.

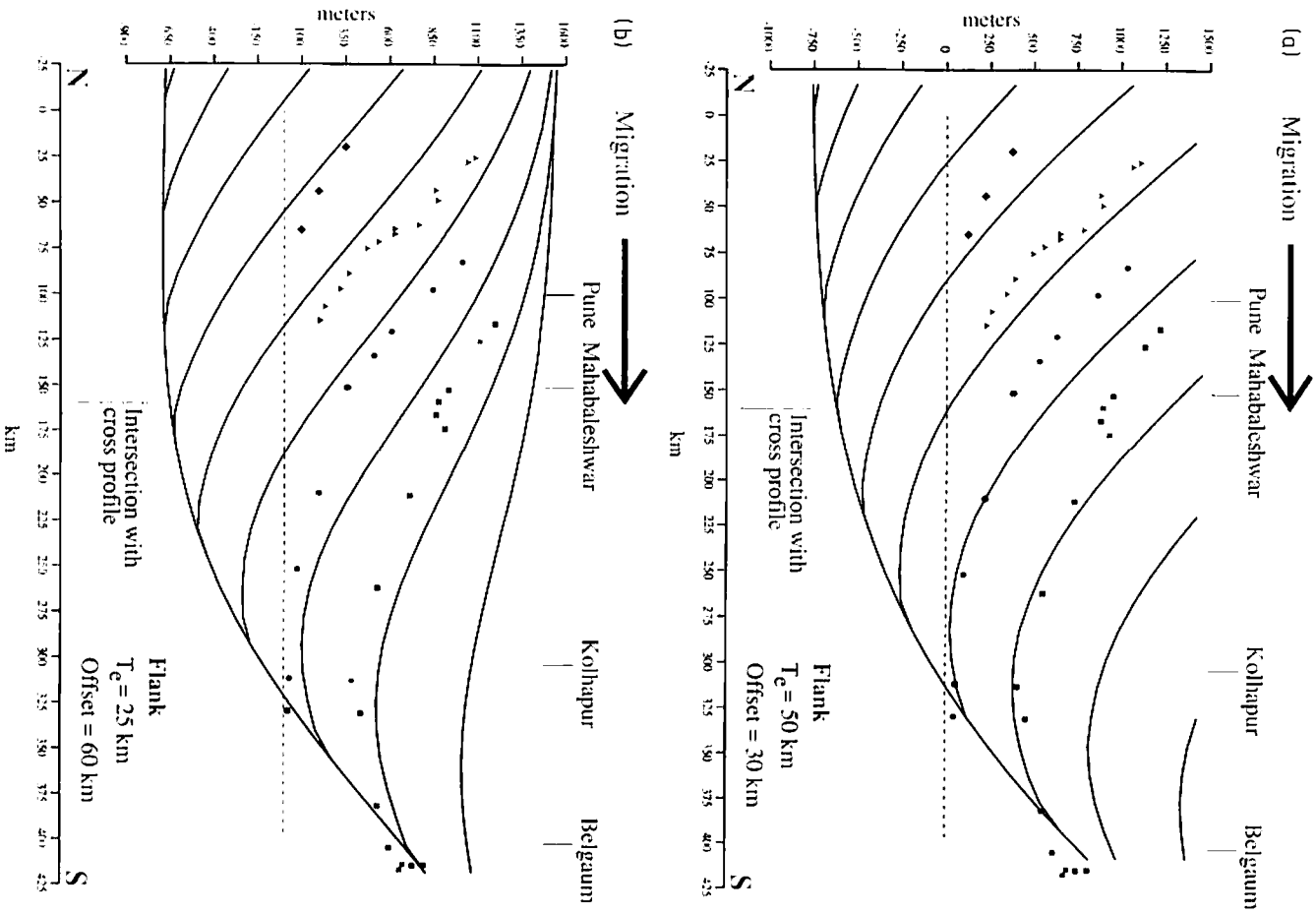A characteristic of a high T_e model is that it requires large loads and a substantial thickness of

Fig. 8. Comparison of observed depths to individual formations in the Deccan to calculated profiles based on (a) $T_e = 50$ km, offset = 30 km and load skip interval = 1, and (b) $T_e = 25$ km, offset = 60 km and load skip interval = 0. The solid symbols are as defined in Fig. 6.

infill material. On the flank section in Fig. 5, for example, a maximum thickness of up to 7 km is predicted. In order to explain the present-day thickness of the Deccan Traps in western India of 1.5 km [15] therefore about 5.5 km of material would have had to be removed from the structur-
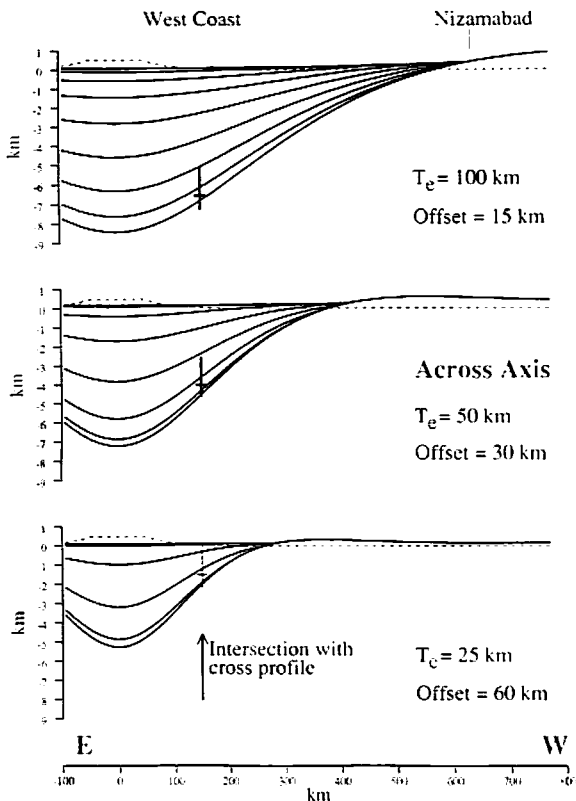
Fig. 9. Synthetic stratigraphy along the across axis profile based on different values of the elastic thickness of the plate. A load skip interval of 4, 2 and 1 were used for the upper, middle and lower profiles respectively. The tick lines show the location of the calculated flank profiles in Figs. 6 and 8. The open circles show the measured thickness of the Deccan lavas according to seismic refraction measurements [15]. There is good agreement between the position of the flexural node of $T_e = 100$ km and the eastern boundary of the edge of the Deccan Traps (Fig. 1). A large discrepancy exists, however, between the calculated thickness for this elastic thickness and the thickness of the lavas measured seismically. This discrepancy could be explained by subsequent erosion of upper part of the lava pile. The figure shows that the required amount of erosion in the Western Ghats is about 5.5 km for $T_e = 100$ km or about 2.5 km for $T_e = 50$ km. A plate thickness of $T_e = 25$ km (or less) would require little or no erosion of the lava pile.

ally upper part of the flank section. This amount of erosion would have been accompanied by substantial crustal uplift which would reduce the westward dip-component of the remaining infill material to near horizontality, as is presently observed. One possibility is that the removal of the axial cone loads by erosion was sufficient to initiate an uplift (by rebound) that eventually led to

the removal of the load and a large part of the flanking infill material. The cone loads are no longer seen along the migration path, although their remnants may be present in the deep structure of the continental margin off the Western Ghats.

By contrast, the main feature of a *low* T_e model is that it reduces the amount of uplift and erosion that is required. However, there are a number of difficulties with such a model. First, the weakening of the plate causes a significant increase in the dip on the cross profiles which are still quite steep even allowing for the removal of the infill material. Second, the node no longer coincides with the eastern limit of lava outcrop so that additional sources of volcanism may be required in order to explain the areal extent of the lavas.

We caution though that the present position of the flexural node may not be a reliable constraint on the rigidity of the plate. This is because the modelling in Fig. 9 assumes that loading took place over a sufficiently long time for any stress relaxation of the plate from its short-term (?seismic) thickness to its long-term thickness to be essentially complete following loading. It is possible instead that during loading the plate has not quite relaxed and therefore appears to have a high flexural rigidity—even in cases where the rigidity of the lithosphere may actually be quite low.

The flexural rebound model can account for the present thickness of the Traps but, it cannot explain the monoclinal flexure of the Traps observed at the west coast. This is because rebound only restores the flexed surfaces to the horizontal predeformation surface. We believe the monoclinal flexure is the result of post-Deccan Traps differential movements involving subsidence of the Indian continental margin and flanking uplift of the Western Ghats. If this is correct, then post-Deccan movements may have modulated the uplift and erosion of the load and infill material: prolonged shelf subsidence would eventually submerge the cone loads and reduce their capacity to be eroded whereas uplift would further encourage erosion of the infill material.

Seismic reflection and refraction studies [17, 40,41] suggest the continental shelf and slope off Bombay is underlain by as much as 6 km of Tertiary sediments. The velocity structure of the

crust appears to be similar to the Indian shield and the crustal thicknesses are intermediate in value between oceanic and continental-type thicknesses. We suggest that the thinned continental (?) crust was produced by extension at the time of the initial rifting of India from the Mascarene Plateau. Evidence of extension has been documented in the Gulf of Cambay [42], which is a graben infilled by Tertiary sediments, and off Bombay [17], where normal faults have been observed in the Deccan age basement. The distribution of extension across the Indian shelf is not known, but it is likely that post-rift thermal contraction following heating and thinning of the lithosphere at the time of rifting led to substantial subsidence of both the slope and shelf regions. The lithosphere includes the crust and we speculate that the Deccan load (and its flanking infill) was stretched and thinned by a sufficiently large amount causing a portion of it to subside below sea level. The Bombay high [17], which has been drilled in several localities and has large amplitude gravity anomalies, may be a remnant of the Deccan load—left by the plume as it passed from loading continental to oceanic lithosphere.

By contrast, the origin of the uplift, which seems to be required if large amounts of the lavas have been removed by erosion, is more problematic. The rebound following removal of the cone loads may be one component of the uplift, and may account for the initiation of the essentially eastward-flowing drainage system of the main part of peninsular India. However, other mechanisms are required to explain the uplift of the Western Ghats since it appears to be a permanent feature. We can rule out thermal effects such as uplift due to the lateral flow of heat at the rifted margin [43] and small-scale convection [44] since these are transient. Of the various mechanisms that have been proposed to explain permanent uplift only those associated with uplift on the flanks of fault-bounded rifts [45] and thickening of the crust by underplating [14] seem of sufficient magnitude to explain all the observations.

The effect of the uplift on the dips in the Deccan cannot be precisely determined at the present. Flexural rebound could affect the dips on a north–south section, although it would be difficult to explain the dip reversal by this mechanism. Topographic maps show that the Western Ghats escarpment extends beyond the Traps almost the entire length of peninsula India. This uplift is therefore unlikely to cause the *relative* difference in dip along the north–south section in the Traps, especially if it was caused by a broad region of crustal underplating.

In summary, our preferred model favors a plate with a T_c of 100 km. This model requires that as much as 5.5 km of the structurally upper part of the traps has been removed by uplift and erosion. The origin of the uplift is not clear, but it may have involved flexural rebound of peninsular India and the Mascarene Bank (including the Seychelles and Saya de Malha Banks) following removal of the cone loads. We believe that the pattern of rebound was greatly modified by subsidence and uplift associated with the development of the Seychelles Bank and Indian passive continental margins and of oceanic crust in the Arabian sea. Our main constraint on the value of T_e is on the across axis profiles, particularly on the dips and lateral extent of the lavas. A model with $T_c = 100$ km—modified by uplift and erosion—is in accord with gentle dips observed on east–west sections in western India, but more detailed mapping, particularly in the east, will be needed in the future in order to verify whether the formations in the western Ghats actually pinch-out towards the east in the manner predicted by the models.

Acknowledgements

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