Plume-related regional pre-volcanic uplift in the Deccan Traps: Absence of evidence, evidence of absence

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Abstract

The mantle plume model predicts regional, domal, kilometer-scale lithospheric uplift 5-20 million years before the onset of flood basalt volcanism. Field evidence for such uplift would comprise progressively shallowing sedimentary sequences, or (with differential uplift along faults) widespread conglomerates derived from the basement rocks and underlying the lavas. Local uplifts and subsidences cannot be used to invoke or rule out plume-caused uplift. Over large areas, the base of the late Cretaceous Deccan flood basalts is in the subsurface. Basalt-basement contacts are observed along the periphery of the province, and in central India (the Satpura and Vindhya Ranges), where substantial post-Deccan uplift is evident. Here, horizontal Deccan basalt flows directly overlie extensive low-relief planation surfaces cut on various older rocks (Archean through Mesozoic). Locally, thin, patchy late Cretaceous clays and limestones (the Lameta Formation) separate the basalts and basement, but some Lameta sediments were derived from already erupted Deccan basalt flows in nearby areas. Thus, the eruption of the earliest Deccan basalt lava flows onto extensive, flat planation surfaces developed on varied bedrock, and the near-total absence of basement-derived conglomerates at the base of the lava pile throughout the province are evidence against pre-volcanic lithospheric uplift (both regional and local), and thereby the plume head model. There has been major (>1 km) post-Deccan, Neogene uplift of the Indian peninsula and the Sahyadri (Western Ghats) Range which runs along the entire western Indian rifted margin, well beyond the Deccan basalt cover. This uplift has raised the regional, late Cretaceous planation surface developed on the Deccan lava pile to a high elevation. This uplift cannot reflect Deccan-related magmatic underplating, but is partly denudational, is aided by a compressive stress regime throughout India since the India-Asia collision, and possibly also related to active eastward flow of the sub-lithospheric mantle. The easterly drainage of the Indian peninsula, famously speculated to be dome-flank drainage caused by a plume head, predates the uplift. Field evidence from the Deccan and India is in conflict with a model of plume-caused regional uplift a few million years prior to the onset of volcanism.

…one true inference invariably suggests others. (Sherlock Holmes, in "Silver Blaze")

Introduction: Flood basalts, plume heads, and lithospheric uplift

The deep mantle plume model (*Richards et al.*, 1989; *Campbell & Griffiths*, 1990) postulates that thermal plumes rise buoyantly from the core-mantle boundary and develop large bulbous "heads" by entrainment surrounding mantle. The heads remain connected to the source region by narrow "tails". A new ("starting") plume head, 1000 km in diameter, flattens to a disc twice as wide after impinging on the base of the lithosphere, and lifts the lithosphere up over a broad area ~1000 km across before flood basalt volcanism begins. Significant domal uplift (1-4 km depending on parameters such as plume temperature) is predicted 10-20 million years (m.y.) before flood volcanism, when the plume head is still well below the lithosphere (*Campbell & Griffiths*, 1990; *Farnetani & Richards*, 1994). The uplift is followed by subsidence as the plume head begins to melt extensively and the magmas are drained.

Geological evidence for pre-volcanic uplift can take the form of pre-eruption sedimentary sequences that reflect progressive basin shallowing before volcanism (*e.g., Rainbird & Ernst,* 2001). Alternatively, with differential tectonic uplift along faults, rapid erosion of the basement rocks would produce beds of conglomerate or coarse clastics below the first lavas. If the uplift were regional, such sediments should have a regional distribution. It has been claimed that geological and geomorphological evidence from flood basalt provinces of the world fullfills the predictions and patterns of the above model (*Cox*, 1989; *Campbell*, 2005). Here I examine the evidence from the Deccan flood basalt province and India, showing that this is not true there.

Deccan and Indian geology

The late Cretaceous (~65 Ma) Deccan province was associated with India-Seychelles break-up (Figure 1) [Ed: see also other Deccan pages]. Earlier, at ~88 Ma, Greater India (India plus the Seychelles) broke off from Madagascar, an event which was associated with flood basalt volcanism on Madagascar and relatively minor volcanic-intrusive activity in India (*Storey et al.*, 1995; *Pande et al.*, 2001). A description of the main features of Indian and Deccan geology can be found in Sheth (2005a).

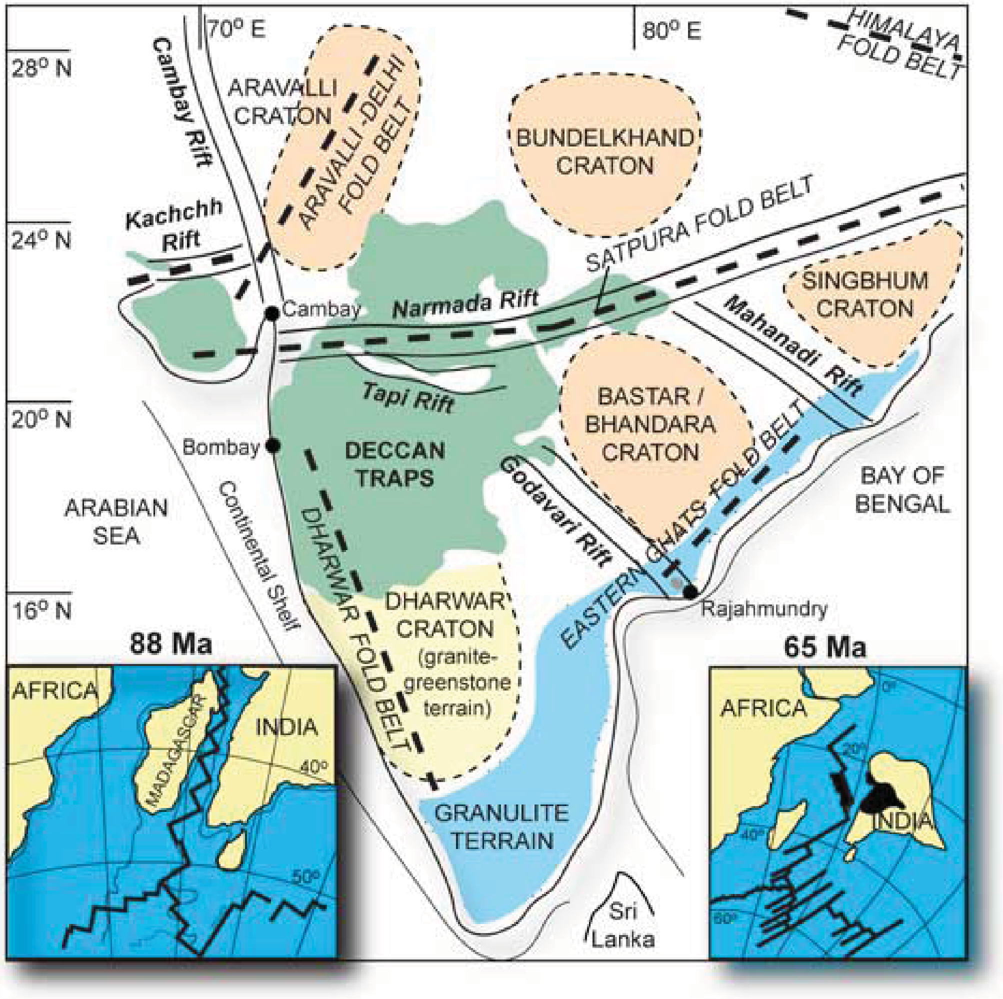

Figure 1. Map showing the structural framework of the Indian subcontinent, including Precambrian cratons (boundaries approximate), structural trends defined by Precambrian fold belts (primarily Proterozoic), the rift zones (primarily Phanerozoic), and the present outcrop area of the Deccan flood basalt province (green). Modified after Sheth (2005a,b). The inset figures show the breakup of Greater India from Madagascar at ca. 88 Ma (Storey et al., 1995; Pande et al., 2001), and the breakup of the Seychelles microcontinent (located at the northern tip of the Mascarene Plateau, black) from India at ca. 65 Ma (Norton & Sclater, 1979).

Figure 2 shows the main rock formations that make up the Indian shield. Over a large part of the province, the contact of the Deccan lavas with the pre-volcanic basement is not exposed. The Deccan lavas overlie a complex Archaean and Proterozoic basement along the the southern and southeastern periphery of the province. In the northern and northeastern parts of the province, i.e., central India, they overlie diverse geological formations: the Vindhyan sedimentary basin (mid-late Proterozoic), the Gondwana sedimentary basin (Carboniferous to Jurassic-early Cretaceous), late Cretaceous Bagh and Lameta sediments, and Archaean and early Proterozoic crystalline rocks (granites, gneisses and metasediments).

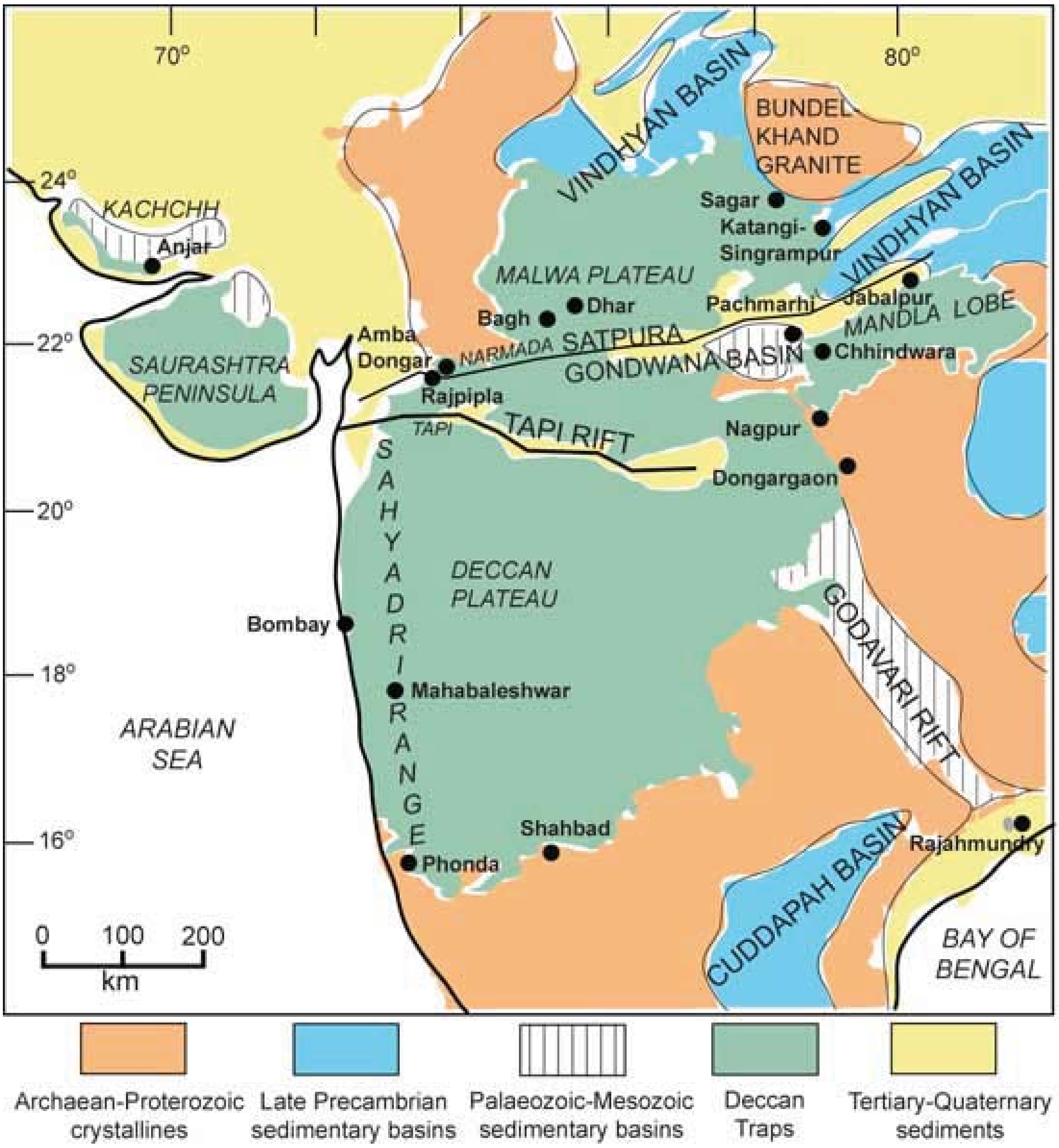

Figure 2. Sketch-map of western and central India showing its main geological features, main geographic-physiographic features (italicized), and the outcrop of the Deccan flood basalts (green). The Bagh and Lameta sediments and the Bijawar metamorphics are too small to show at the scale of the map, but the locations of the Vindhyan and Satpura Gondwana Basins are indicated. Also shown are localities mentioned in the text. Modified after Sheth (2005a)

Many major Indian rivers originate in the Sahyadri Range (Western Ghats), and instead of draining into the Arabian Sea a few tens of kilometers to the west, they flow for hundreds of kilometers eastward to the Bay of Bengal (Figure 3). *Cox* (1989) speculated that this was a consequence of regional domal uplift caused by a Deccan plume head. He presented drainage maps from the Karoo (South Africa) and the Parana flood basalt provinces, and considered each example as the preserved half of an originally complete dome-flank pattern produced by a plume head. *Summerfield* (1990) pointed out that the *Cox* (1989) model ignored aspects such as the Cenozoic drainage development in Africa. The model also ignores and is incompatible with well-known geological facts from India, and no quantitative data (such as apatite fission-track ages) have ever been offered in support of the postulated plume-caused doming.

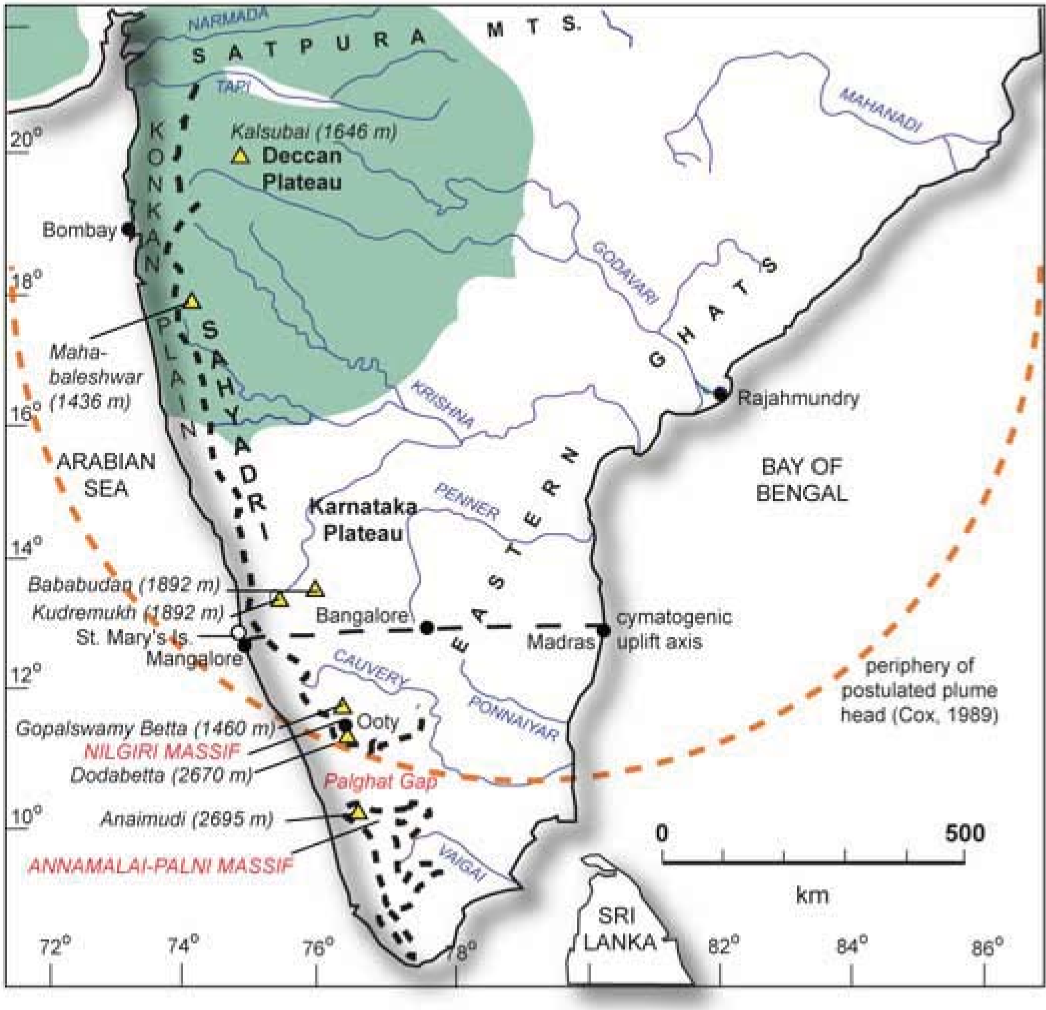

Figure 3. The main elements of the physiography of the Indian peninsula, based on Ollier & Powar (1985) and Sheth (2005a). Note the pronounced easterly drainage. The outcrop area of the Deccan flood basalts is shown in green. The Sahyadri (Western Ghats) escarpment is shown by the heavy broken line, and some major summits of the Ghats are indicated, as are some localities cited in the text. The circumference of the plume head proposed by Cox (1989) and the axis of cymatogenic uplift at 13°S latitude proposed by Subrahmanya (1994) are also shown. The St. Mary's Islands rhyodacite lavas (~85 Ma) along the west coast are older than the Deccan Traps, and related to the India-Madagascar break-up event (Pande et al., 2001).

The Sahyadri Range constitutes a NNW-SSE-trending and 1500-km-long “Great Escarpment” along the western Indian rifted margin (*Gunnell & Radhakrishna*, 2001) and has been retreating eastward due to erosion (*Widdowson*, 1997a). There is only one break in the escarpment, the controversial “Palghat Gap” (Figure 3) which has a maximum elevation of 300 m above sea level, an average width of only 13 km, and which is entirely rock-floored without alluvium cover (*Gunnell & Radhakrishna*, 2001). On its sides, the Ghats reach great heights of >2.5 km above MSL. The Nilgiri massif to the north of the Gap, and the Palni-Kodaikanal massif to the south, are made up of Precambrian hypersthene-bearing granites and granulites (“charnockites”). These mountains are the highest in peninsular India, and among the highest in shield areas anywhere (*Gunnell &*

Louchet, 2000). Summits of the Western Ghats and the Karnataka plateau, between the Deccan basalts and the southern charnockite massifs, also approach 2 km in height (*e.g.,* Bababudan, Figure 4) and are built of Precambrian quartzites and gneisses. The summit of the Deccan basalts, Kalsubai, stands at 1646 m (Figure 3).

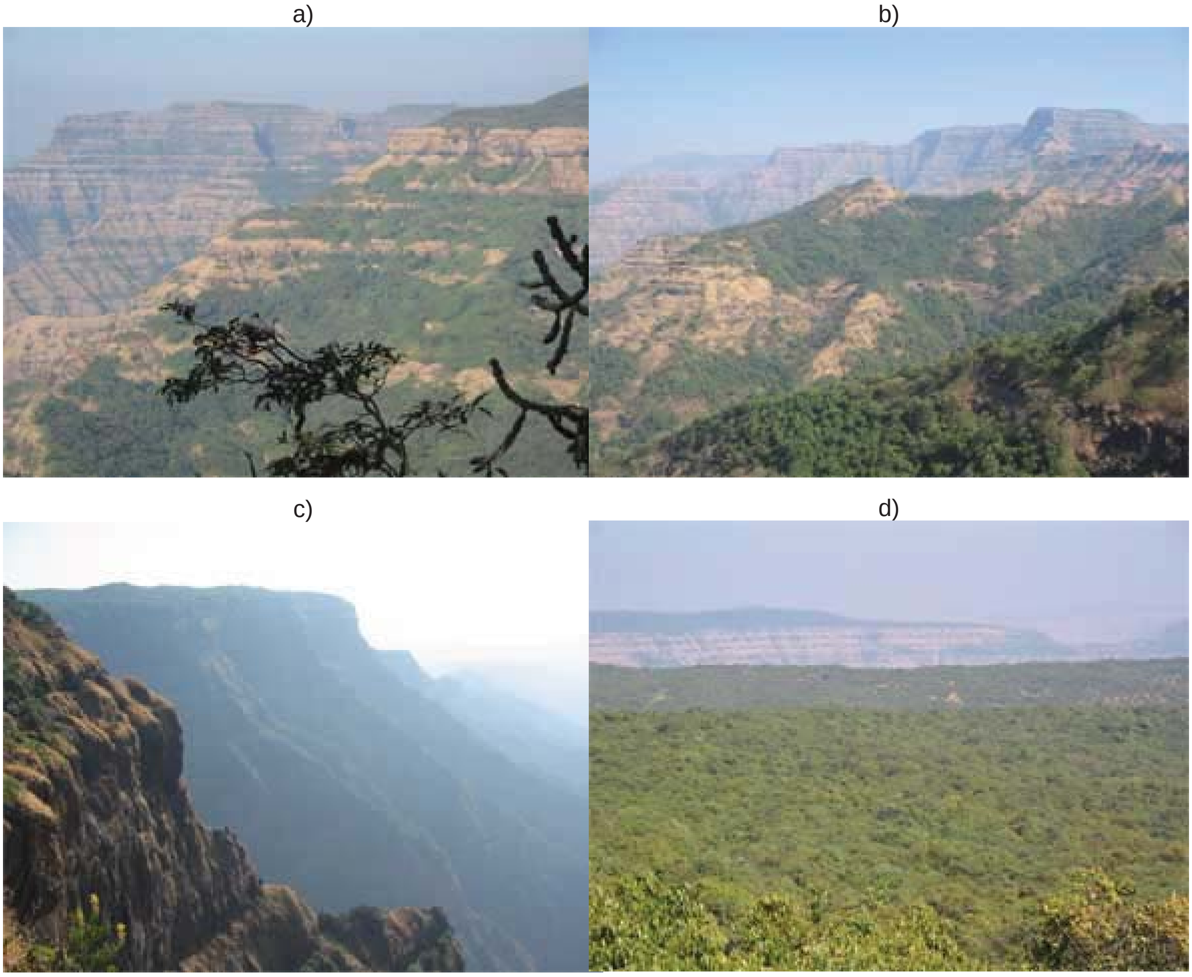

Figure 4a,b,c,d. Views of the Sahyadri (Western Ghats) escarpment at Mahabaleshwar, showing the 1200-m-thick, horizontally disposed Deccan flood basalt lava pile. The top of the lava pile is a heavily lateritized late Cretaceous planation surface. (d) The extensive, lateritized, heavily forested Mahabaleshwar plateau surface. Photos by Hetu Sheth, December 2005.

The great heights of the charnockite massifs may reflect both the original topography and the greater weathering resistance of charnockite than basalt (*Gunnell & Louchet*, 2000). *Most importantly, the entire youthful Sahyadri is the precipitous western edge of an uplifted plateau that has been tilted eastward, and the plateau surface has an aged character – it is an ancient flat land surface rejuvenated relatively recently (Neogene) by major tectonic uplift (Radhakrishna, 1952, 1993; Vaidyanadhan, 1977), the uplift continuing during the Quaternary (e.g., Powar, 1993; Valdiya, 2001).* Mahabaleshwar sits atop a spectacular, ~1200-m-thick exposed Deccan basalt sequence (Figure 4a,b,c), and the top of the Mahabaleshwar plateau represents a regional, low-relief, late Cretaceous palaeosurface or peneplain developed on the uppermost basalts after the cessation of the eruptions, represented by 25-50 m thick laterite (*Widdowson*, 1997a). In southern India, laterites or bauxites cap the high-elevation summits built of Precambrian rocks. Sahyadri uplift, extending well beyond the Deccan lava cover, is evidently not related to Deccan volcanism, but is more appropriately considered “rift-shoulder uplift”. Along with the Sahyadri, the Konkan Plain to the west of it has also been rising during the Tertiary (*e.g., Powar*, 1993).

Ollier & Powar (1985) observed that the drainage pattern of peninsular India is dendritic over both Deccan lavas and the older basement, and suggested that the drainage developed subsequent to the eruption of the Deccan lavas. The newly formed lava field could have had a regional eastward slope. However, they also noted that the drainage is antecedent (prior to) the uplift of the Sahyadri Range. *Widdowson & Cox* (1996) showed that around Mahabaleshwar, the easterly drainage cuts through a N-S-aligned, south-plunging anticlinal structure identified from regional dips of the basalt lavas and the laterite cap. The anticlinal structure developed subsequent to the drainage and had no effect on the drainage lines. The eastward-draining Godavari-Krishna River system also was already in existence by the time the Deccan lavas were in eruption, if the thin basalt flow sequence at Rajahmundry on the southeastern coast of India (Figures 2,3) represents intra-canyon flows (akin to many in the Columbia River basalt province) (*Baksi et al.*, 1994).

The easterly drainage of the peninsula is also antecedent to the uplift of the Eastern Ghats, according to *Ollier & Powar* (1985). The Eastern Ghats, made up primarily of Precambrian metamorphic rocks, form disconnected hill ranges in eastern India and are thus unlike the Western Ghats, except in southeastern India, and major rivers such as the Cauvery are antecedent to them and have cut gorges (*Ollier & Powar*, 1985). Even the easterly drainage in southern India is an oversimplification, as there is a distinct E-W axis of cymatogenic uplift (crustal arching) at 13°N latitude, to the north of which the rivers flow NE, and to the south of which they flow SE (*Subrahmanya*, 1994; Figure 3). Mangalore on the west coast and Madras on the east coast are both located on this axis, and both are actively rising relative to the sea (*Bendick & Bilham*, 1999). The uplift of the Sahyadri (Western Ghats), and the attendant uplift of the Konkan Plain to the west of it, are definitely post-Deccan, and offshore sedimentary evidence and apatite fission-track data are consistent with this (*Gunnell & Gallagher*, 2001; *Gunnell et al.*, 2003). *In summary, the easterly drainage of the Indian peninsula is older than the uplift of the Ghats (both the Western and the Eastern), and the uplift of the Ghats is much younger than Deccan volcanism (Sheth, 2007).* The proposition of *Cox* (1989), that the easterly drainage is a result of a plume-generated lithospheric dome, is therefore baseless, but has never been examined, far less questioned, by plume enthusiasts and regional experts influenced by them.

Deccan basalt and basement contacts

Over most of the Deccan province the lava-basement contact is in the subsurface. There is a huge thickness (~1700 m exposed) of Deccan basalts in the Sahyadri region, and ~500 m in the subsurface, as identified from seismics, which also suggest two linear, kilometer-thick, Mesozoic sedimentary basins in the subsurface below the Deccan basalts in the Narmada-Tapi region (*Kaila*, 1988; *Sridhar & Tewari*, 2001). North of the Narmada River, Deccan basalts overlie the mid-late Proterozoic Vindhyan sediments, or older crystalline basement directly. To the south of the river, in the Satpura Range, Deccan lavas overlie the Gondwana sedimentary basin (Carboniferous to Jurassic-early Cretaceous), or the Precambrian basement. The Gondwana Basin is particularly well-exposed in the Pachmarhi area (Figure 2) due to substantial post-Deccan uplift along basin boundary faults.

Two other late Cretaceous sedimentary formations – the Bagh and Lameta – underlie the Deccan basalts locally in central India (*e.g., Mohabey*, 1996; *Tandon*, 2002). Both separate the Deccan basalts from the Vindhyans, the Gondwanas, or the Archaean-Proterozoic crystalline basement. The Bagh Formation consists of sandstones and limestones formed during a marine transgression in the western Narmada valley (*Sheth* 2005a), where one would expect maximum uplift from a putative Deccan plume head at this exact time. The fluvial and lacustrine Lameta Formation consists of thin (~20 m) limestones and clays. The Lametas overlie the Gondwana sediments or Precambrian rocks, and are themselves overlain by the Deccan basalt flows in some sections, based on which they were considered older than the basalts. More recent work indicates that Lameta clays around Jabalpur (Figure 2) were derived from the Deccan basalts themselves, already erupting in nearby areas (*Shrivastava & Ahmad*, 2005). Pre-eruption uplift is recorded in the Lameta sediments of the Dongargaon Basin of the Nagpur region (Figure 2), where *Tandon* (2002) recorded a clear "shallowing up" trend from shallow lake deposits to a palaeosol before the terrain was buried by the first Deccan basalt flow. He invoked, however, pre-volcanic surface uplift of the area of meters only and possibly also mock aridity (*Harris & van Couvering*, 1995).

Thus there were both local uplifts and subsidences just before volcanism in parts of central India, but such cannot be used to support or refute the plume model and are easily related to the filling and emptying of magma chambers, emplacement of intrusions, and faulting. At Rajpipla (Figure 2), a basalt- and basement-derived conglomerate bed that unconformably overlies tilted late Cretaceous sediments and is overlain by the Deccan basalts (*Widdowson*, 2005) suggests that uplift and/or tilting and erosion of the late Cretaceous sediments occurred in quick succession just before volcanism. One or more basalt flows were then erupted nearby, and continuing uplift and erosion produced the conglomerate, which was in turn covered by subsequent lavas. This is local uplift as can be produced by moderately large intrusions, or faulting, both well recognized in this area (*Ray et al.*, 2003). This conglomerate appears similar to conglomerates interlayered with Palaeogene basalt flows on the Isle of Skye, Scotland. Here, a basaltic lava flow of the Talisker Bay Group is underlain by a conglomerate of the Preshal Beg Conglomerate Formation (Figure 5). The conglomerate is a very poorly sorted and chaotic deposit, and was derived from the nearby lavas by local uplift and probably slope instabilities (*Williamson & Bell*, 1994).

(a)

(b)

Figure 5. (a) Chaotic, completely unsorted Preshal Beg Formation conglomerate under a spectacularly columnar-jointed olivine tholeiite lava flow of the Talisker Bay Group, Isle of Skye, Scotland. Person near lower right corner of photo provides a scale. (b) Closer view of the chaotic conglomerate and the columnar lava flow above, with more recognizable folk for scale. Photos by Hetu Sheth, September 2005.

What, then, is the evidence in central India for or against regional pre-eruption uplift? Planation surfaces are a key evidence bearing on this issue.

Planation surfaces: key evidence

Planation surfaces are regional, flat or nearly flat surfaces produced by advanced erosion (usually fluvial) of any earlier topography to the existing base level of erosion, in most cases the sea level. (Large, high inland plateaus like Tibet have their own base level, and a large river may act as a sub-regional base level.) Planation surfaces are also called erosion surfaces or peneplains. Palaeosurfaces (*Widdowson*, 1997b) constitute a broader category of ancient land surfaces that can be exogenic (erosion/weathering) or endogenic (*e.g.,* lava plains). A planation surface is therefore a kind of exogenic palaeosurface.

On a peneplain, relief is minor to absent, and erosion is therefore negligible, but deep in situ weathering and lateritization and ferricretization are typical (*Summerfield*, 1991). A planation surface indicates long-term tectonic stability and the absence of uplift and erosion. If a low-lying peneplain is uplifted to form a plateau, the dissection of the plateau by further erosion works towards forming a younger planation surface at a lower level, broken only by some surviving remnants (“monadnocks”) of the higher surface (Figure 6a). Also, because no process can produce a flat erosional surface out of jagged terrain at high elevation, a geologically young planation surface at high elevation today suggests rapid and recent uplift (*Ollier & Pain*, 2000).

It is important to recognize planation surfaces correctly. They are products of bedrock erosion, not sediment deposition. Horizontally-bedded rocks tend to produce flat surfaces which are purely structural. A planation surface is most easily recognized when it cuts across, or bevels, diverse rocks with varied internal structures (Figure 6b). Bevelled cuestas over a wide area of folded or tilted rocks are a good indicator of a former planation surface, because in the absence of a former planation surface, cuestas – structurally controlled landforms on dipping strata – would show a sharp ridge crest, never a level top (Figure 6c,d). “Accordant summit levels” –complexly deformed rocks of widely varying types with their summits at roughly the same general level – also suggest a former land surface somewhat higher and getting dissected now (Figure 6e). Planation surfaces are of great significance in tectonics, as *Ollier & Pain* (2000) show with many examples worldwide. Planation surfaces at rifted continental margins such as of East Greenland have been used (*Bonow et al.*, 2006a,b; *Japsen et al*., 2006) to track post-volcanic uplift (post-mid-Eocene and mostly Neogene) – there are obvious parallels with the Sahyadri, which has experienced major uplift in the Neogene.

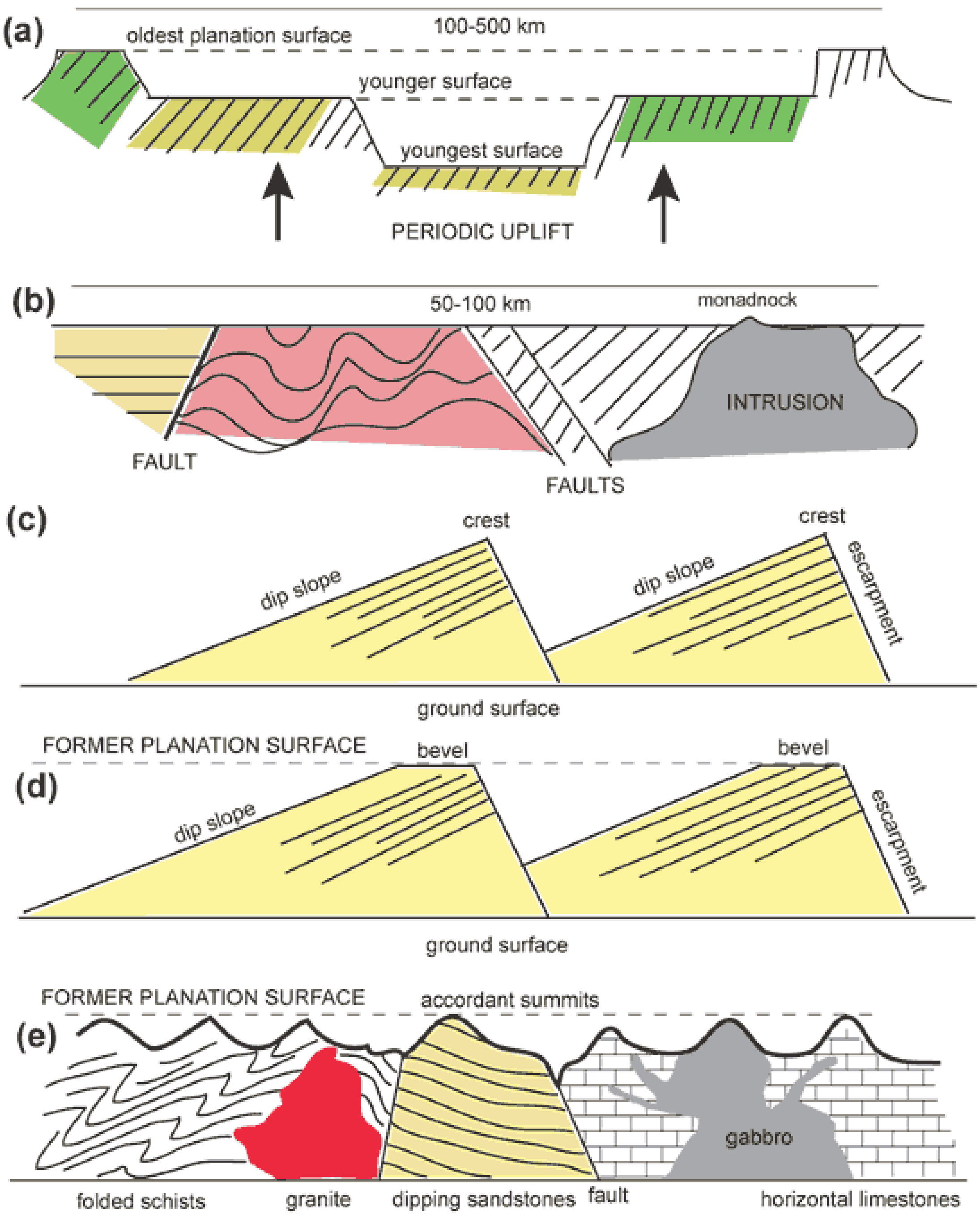

Figure 6. Schematic sketches showing (a) Multiple, successive planation surfaces in an area undergoing periodic uplift, i.e., a "polycyclic" landscape. (b) A planation surface cut on complex rocks with a resistant monadnock left behind. (c) Cuestas on dipping resistant rocks normally have sharp crests. View is along strike direction. (d) Bevelled cuestas representing a former planation surface. (e) Accordance of summit levels in a lithologically diverse and complexly deformed terrain suggesting a former planation surface. Based on Ollier & Pain (2000). The vertical scale is greatly exaggerated in (a), (b), and (c).

Figure 7 shows a schematic NNW-SSE profile (after *Gunnell*, 1998) through southern India showing the multiple planation surfaces that bevel varied bedrock types and structures. S_0 (~2500 m elevation) is the original, Gondwanic planation surface (late Jurassic or early Cretaceous), S_1 (~2200 m) is a late Cretaceous surface well seen in the Nilgiri massif (around Ooty, Figure 3) and surrounding highlands, S_2 probably an early- or mid-Tertiary surface (identified partly based on bauxite occurrences and suggested to be the top of the Deccan basalt pile), and S_3 a late Tertiary surface. S_4 is the lowest and youngest surface, Mio-Pliocene in age. Post-denudational upwarping has produced a fanning of the surfaces S_1 to S_3, which according to *Gunnell* (1998) is probably unrelated to the rift-flank uplift of the Western Ghats, but to crustal loading by the Deccan basalt pile and late Neogene intraplate crustal deformation in the Indian Ocean Basin that has been affecting peninsular India as well (*Subrahmanya*, 1996).

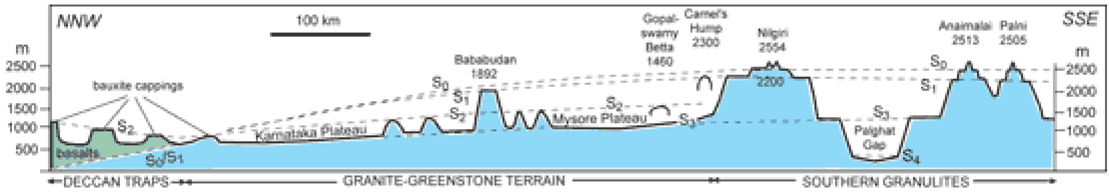

Figure 7. Schematic NNW-SSE profile through the polycyclic landscape of southern India, showing the multiple planation surfaces. After Gunnell (1998).

Sub-Deccan planation surfaces in central India

As noted, the top of the Deccan basalt pile in the Western Ghats, such as at Mahabaleshwar (1436 m), is a heavily lateritized planation surface of late Cretaceous to early Tertiary age (Figure 4a,b,c), developed after the eruptions during stable tectonic conditions (*Widdowson & Cox*, 1996; *Widdowson*, 1997a; *Widdowson & Gunnell*, 1999). Its present high elevation today reflects post-Deccan uplift, very probably of >1 km. A planation surface *below* the Deccan basalt pile in a region would indicate long-term tectonic stability *before* flood volcanism.

Evidence for pre-Deccan planation surfaces is best sought in central India, where the basalt-basement contacts are exposed over large areas, and the basement is very diverse (Figure 2). *Dixey* (1970, reprinted in *Subbarao*, 1999) and *Choubey* (1971) identified erosion surfaces under the Deccan lavas in central India, and noted their usefulness in deciphering subsequent tectonics. *Choubey* (1971) noted that in central India most Vindhyan and Bijawar hills stand approximately at a level of 590 m, a remarkable summit accordance and considered these the remnants of a vast Cretaceous peneplain. The Deccan basalts cap this surface. At lower elevations, the basalts cap another planation surface, developed on the softer Gondwana sediments. Both surfaces existed before the Deccan eruptions, and represented a long inverval of weathering with a deep lateritic saprolith. Their main observations from specific areas have been compiled by [*Sheth* (2007)].

The sub-Deccan Gondwana Basin is spectacularly exposed in the Satpura mountain range due to post-Deccan cymatogenic uplift (Figure 8a,b) (*Venkatakrishnan*, 1984, 1987). Pachmarhi town sits on a thick (~1000 m) lens of mid-Triassic sandstone containing subordinate shales and conglomerates, and capped by extensive ferricrete. A very spectacular feature is the ENE-WSW-trending, 160-km-long, up to 280 m high, south-facing, free-face scarp that has been carved into the Pachmarhi Sandstone (Figure 8a,b). Many outliers of this sandstone lie scattered south of the present position of the scarp, which has been retreating northwards. The Pachmarhi sandstones are underlain by the Bijori Formation (Permian) dominated by shales (Figure 8b). Many Deccan dolerite dykes and intrusions can be found in the Pachmarhi and Bijori rocks at lower elevations. The dipping strata are beveled by planation surfaces recognized by *Venkatakrishnan* (1984, 1987). The lowest and youngest is the Bijori Surface (640 m) that is currently forming, and slopes northwards towards Pachmarhi from the basalt cliffs to the south. Older and higher is the Pachmarhi Surface (920 m), and still older and higher is the Dhupgarh Surface (~1300 m) preserved in the three accordant sandstone summits of Dhupgarh (1352 m), Mahadeo (1330 m) and Chauragarh (1308 m) that rise over Pachmarhi. *Venkatakrishnan* (1984) suggested that the Narmada river valley to the north of Pachmarhi has been recurrently acting as a local base level, periodically rising and falling, for streams eroding the plateau.

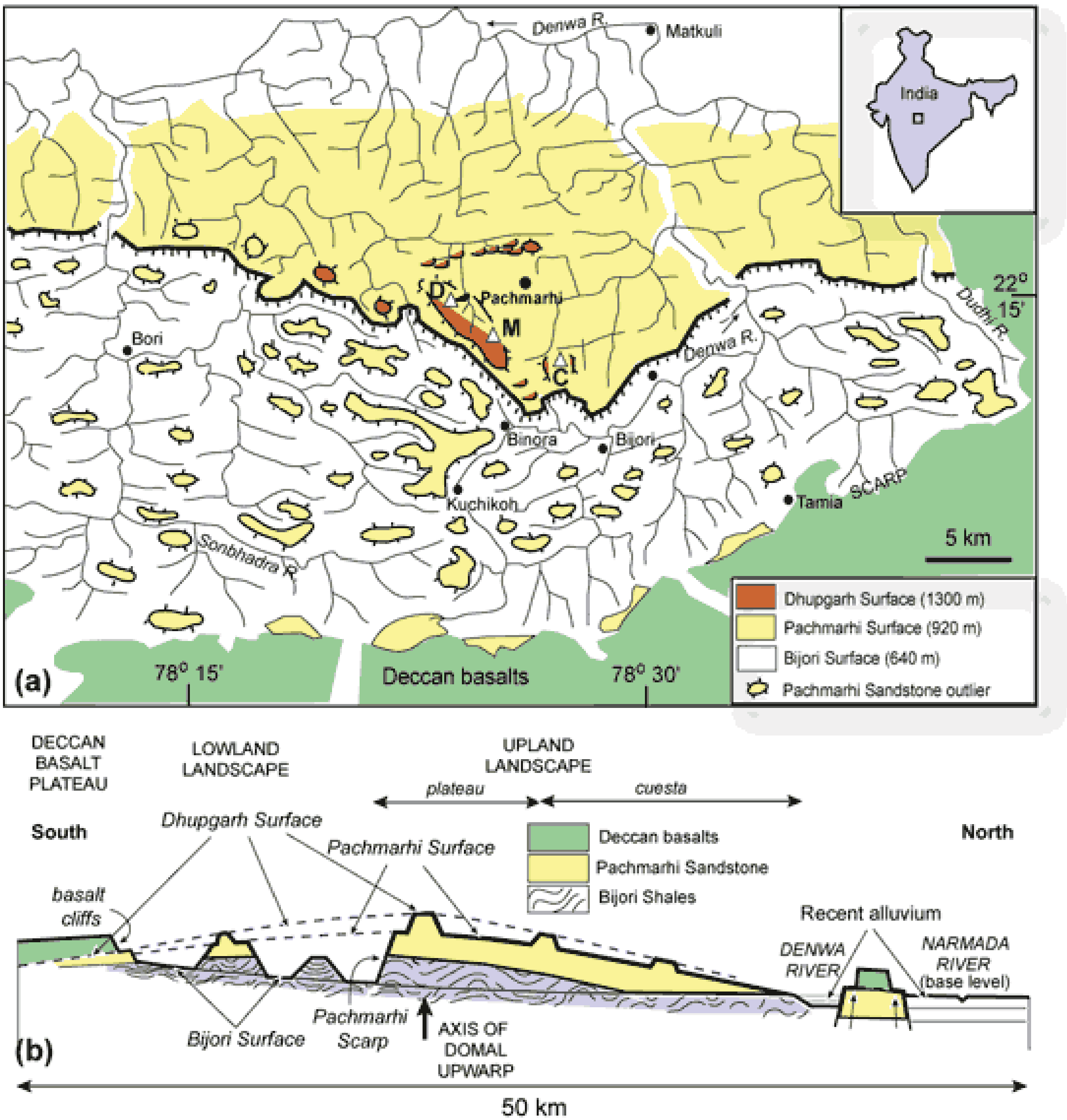

Figure 8. (a) Geomorphological map of the Pachmarhi region on the Satpura dome, showing the Pachmarhi scarp, planation surfaces, structural elements, Pachmarhi Sandstone outliers, drainage lines, and some localities. The many Deccan Trap dykes and intrusions in the sandstones are not shown for clarity. D is Dhupgarh (1352 m), M is Mahadeo (1330 m) and C is Chauragarh (1308 m). Based on Venkatakrishnan (1984). (b) Generalized geological cross-section of the Pachmarhi area showing the main landscape elements, slightly modified from Venkatakrishnan (1987). Note the upwarped planation surfaces, and that the surfaces bevel the internal structure of the Pachmarhi Sandstones and the underlying Bijori Shales. The surfaces are also characterized by laterite/ ferricrete development. The highest and oldest planation surface is the Dhupgarh Surface (only approximate in (a), and it is the pre-Deccan-Trap erosion surface of Choubey (1971), and the late Cretaceous peneplain of Dixey (1970).

On Dhupgarh, the highest peak in the Satpura Range, a Deccan basalt flow unconformably overlies the north-dipping Pachmarhi Sandstone (*Venkatakrishnan*, 1984), and he considered the base of the basalt flow – the Dhupgarh Surface – to be the same as the late Cretaceous peneplain of *Dixey* (1970), the sub-Deccan Trap erosion surface of *Choubey* (1971), and probably also the inter-continental Gondwana or African Surface of *King* (1953). Though the sandstone-basalt contact at Dhupgarh is an unconformity, this does not mean uplift and erosion right before the Deccan eruptions, because the entire rock record from mid-Triassic to late Cretaceous is missing. Also, because the unconformity is a regional planation surface, indicating long-term tectonic stability, the missing rock record cannot be ascribed to rapid erosion just before volcanism.

Venkatakrishnan (1984, 1987) observed that the multiple planation surfaces around Pachmarhi were warped as a result of post-Deccan uplift. He identified the doming and warping in the Satpura region on the basis of the warped contact between the Pachmarhi sandstones and the Bijori shales, reversals of structural dips, warped planation surfaces, cave levels, and the drainage pattern. A key observation by him is that *the rivers such as Denwa and Dudhi originate well to the south of the present-day scarp, several hundred meters below the Pachmarhi Surface, and have cut their way northward through the evolving Satpura dome in spectacular gorges* (Figure 8a). He suggested that the most reasonable explanation of this is drainage antecedence.

To summarize, the uplift and warping of the Pachmarhi block, with its planation surfaces, is post-Deccan (just as the uplift of the Sahyadri and the Indian peninsula is post-Deccan). What is the cause of this post-Deccan uplift? The Sahyadri uplift (all along the rifted margin) cannot be related to any magmatic underplating that may have occurred during Deccan volcanism, because such essentially thermal uplift decays rapidly after magmatism (*Clift*, 2005). The uplift and deformation of large regions of peninsular India may be related at least in part to the compressional stress regime throughout peninsular India since the India-Asia collision at ~55 Ma (*Valdiya*, 1998), which is causing reactivation of ancient and older weak zones and much recent intraplate seismicity (*Subrahmanya*, 1994; *Valdiya*, 2001; *Vita-Finzi*, 2002). Sahyadri uplift is denudational in part (*Widdowson & Cox*, 1996; *Widdowson & Gunnell*, 1999), and may also be potentially related also to active eastward flow of the sub-lithospheric mantle relative to the lithosphere as hypothesized by *Doglioni et al.* (2003).

Discussion and conclusions

Campbell & Griffiths (1990) cited Pachmarhi as the center of a broad, uplifted dome produced by their conjectured plume head, quoting *Choubey* (1971) that the lava-basement contact at Pachmarhi is over 1 km above sea level. But the doming of the Pachmarhi region and the entire Satpura Range, is not pre-Deccan but post-Deccan. *Casshyap & Khan* (2000) argued for "pre-Deccan Trap doming" of the Indian landmass, based on sedimentological studies around Pachmarhi, but this doming cannot be related to a putative Deccan plume by any means. They identified three separate uplift events, the youngest of which resulted in late Jurassic to earliest Cretaceous sediments derived from northwestern India. An uplift event centered on northwestern India, and preceding Deccan volcanism by ~70 m.y., cannot be considered pre-volcanic uplift from the Deccan plume.

The flatness of the pre-Deccan landscape constructed on various older rocks in central India, the horizontality of the Deccan basalt flows over long distances, and laterites found on the pre-Deccan landscape, together form compelling evidence for pre-Deccan planation surfaces and long-term tectonic stability prior to the eruptions. This, along with a near-universal absence of indicators of pre-eruption uplift throughout the province, runs counter to the idea that a large plume head produced regional domal uplift, the current drainage pattern, and Deccan flood basalt volcanism. There has been major, kilometer-scale post-Deccan uplift, which has brought the pre-Deccan planation surfaces from their originally low elevations (relative to the then-existing base level) to their present high elevations. A very similar scenario has been noted in the flood basalts of Yemen by *Menzies et al.* (1997).

How are we to explain the lack of pre-eruption uplift in flood basalts? *Campbell & Griffiths* (1990) argued that pre-volcanic regional domal uplift due to a plume head may not be significant due to lateral migration of magma in the crust, or difficult to recognize as early uplift may be overprinted by later subsidence. These are not satisfactory explanations. Subsidence that overprints and erases evidence of early pre-eruption uplift is simply not seen in flood basalts like the Deccan, which show major post-volcanic uplift instead (*Sheth*, 2007). This uplift should expose evidence of early, pre-eruption uplift, if there ever was any. *Burov & Guillou-Frottier* (2005) argue that uplift patterns can be complex depending on factors such as lithospheric strength and plume excess temperature, buoyancy and shape; all plumes do not cause uplift and flood basalt provinces without pre-volcanic uplift may well be plume-generated [Ed: See also Lithosphere Uplift page]. If so the model makes no specific and testable predictions for field geologists and cannot be evaluated against their observations. The plume head model would become untenable, however, when a flood basalt province shows not merely an absence of evidence for pre-volcanic uplift, but also evidence for absence of such uplift. This is exactly the case in the Deccan. Nevertheless, *Campbell* (2005) claims that all the predictions of the model, including that of pre-volcanic regional uplift, are supported by data from flood basalt provinces of the world, the Deccan included.

In summary, the uplift of the Sahyadri (Western Ghats), India, is not related to a Deccan mantle plume: it is not domal, it occurred all along the western Indian rifted margin, well beyond the Deccan lava cover, and is most appropriately considered a rift-shoulder uplift affecting the Deccan basalt pile and the basement rocks equally, and maintained at least in part by denudational unloading (*Widdowson*, 1997a). Planation surfaces below the basalts reflect long-term tectonic stability prior to volcanism, and their significant elevations today reflect post-Deccan uplift, major uplift having occurred in the Neogene (i.e., <23 m.y.). The uplift may have been aided by a compressional regime throughout the Indian shield since about 55 Ma. The easterly drainage of the Indian peninsula is not dome-flank drainage produced by a plume head but is antecedent to the uplift. The uplift of both the Western and the Eastern Ghats postdates Deccan volcanism and the easterly drainage. There is thus not only an absence of evidence for pre-volcanic regional uplift in the Deccan flood basalt province, but actual evidence for absence thereof. The abundant plume conjecture in the voluminous Deccan literature has no factual basis (Sheth, *2005a*,*b*, 2007).

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