# Chapter 8
# Cretaceous Volcanism in Peninsular India: Rajmahal–Sylhet and Deccan Traps

**Vivek S. Kale**

**Abstract** The Indian Peninsula hosts Cretaceous continental flood basalts (CFB) that manifest its passage over the Kerguelen and Reunion hotspots in succession. The former yielded the Early Cretaceous Rajmahal–Bengal–Sylhet Province (113–118 Ma) in the eastern parts of the Indian plate. The ensuing passage over the Reunion yielded one of the largest CFB provinces, namely, the Deccan Volcanic Province (~68–61 Ma), linked to end-Cretaceous mass extinction event. This compilation of the available knowledge on these two provinces enumerates some of the more evident gaps that require focus in future studies.

**Keywords** Rajmahal · Sylhet traps · Deccan traps · Continental flood basalt provinces · Indian peninsula · Cretaceous

## 8.1 Introduction

The Cretaceous represents ~80 million years (~145–66 Ma) in Earth history characterised by the gigantism of terrestrial reptilian and aquatic molluscan faunas and lush thick rain forests with signature floral assemblages that flourished in a conducive warm and humid climate. The end of this period (named as the Cretaceous–Tertiary (K-T) Boundary (or Cretaceous–Paleogene (K-Pg) Boundary) witnessed one of the largest known mass extinctions in Earth history. Added to this was the breakup of the vast Gondwanaland supercontinent leading to a large volume of volcanic eruptions, both oceanic and continental. The Rajmahal and Deccan Traps (Fig. 8.1) represent continental flood basalts that erupted in Peninsular India, the former of Early Cretaceous age (Ray et al. 2005), and the latter dated close to the K-T Boundary (Renne et al. 2015; Schoene et al. 2019; Sprain et al. 2019).

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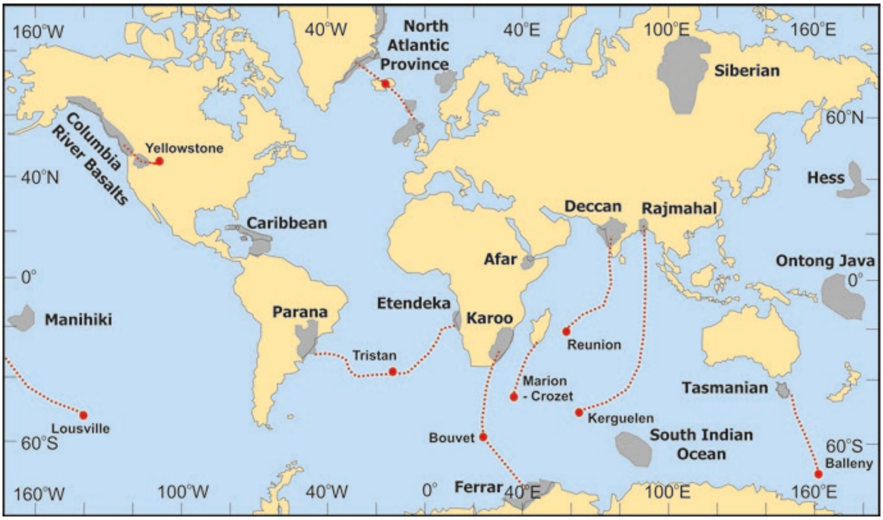


**Fig. 8.1** Phanerozoic LIPs on the Earth's surface and their source hotspots (modified after Morgan (1981); Courtillot (1990) with inputs from Large Igneous Provinces Commission: www.largeigneousprovinces.org). The Rajmahal Province of eastern India is linked with the Kerguelen hotspot, while the Deccan volcanism is associated with the passage of the Indian plate over the Reunion hotspot. Although appearing the largest (due to the map projection), the Siberian Province (~250 Ma) is almost equal to the projected area occupied by the Deccan Province (~2 million km$^2$), making them the largest continental flood basalt provinces on the Earth. The Central Atlantic Magmatic Province (CAMP)/North Atlantic Province (204–191 Ma) is arguably the largest LIP with an area of >12 million km$^2$ but has a very small (less than 5%) continental segment, while the rest is all oceanic

## 8.2 Rajmahal–Bengal–Sylhet (RBS) Province

The Rajmahal–Bengal–Sylhet (RBS) Province has also been termed as Rajmahal–Sylhet or simply the Rajmahal Province. It is represented by two disconnected exposures, one on south of the Shillong Plateau in Meghalaya and the other east of the Chottanagpur Plateau in Jharkhand, termed as the Sylhet Traps and Rajmahal Traps, respectively (Fig. 8.2). Based on similarity of ages and continuity of basalt flows below younger cover (Sengupta 1966), they are considered to be part of a single volcanic province, spread over an estimated area of >100,000 km$^2$.

### 8.2.1 *Basement Contact and Succession*

The Rajmahal Traps rest with a sharp igneous contact on the Precambrian basement of the Chottanagpur terrain in the western parts. At places, commercial bentonite deposits have been documented along this contact (Das Gupta 1996). Patchy occurrences of the Gondwana Supergroup sediments (represented by the Talchir, Barakar

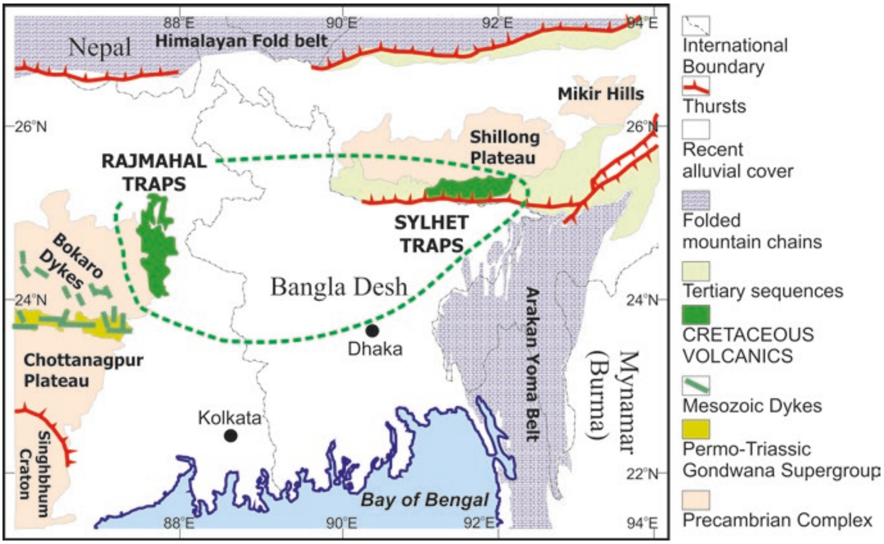


**Fig. 8.2** Sketch map of the Early Cretaceous RBS Province (shown with green dashed outline) from eastern India (modified after Ghatak and Basu 2011) depicting exposures of the Rajmahal and Sylhet Traps in relation to the Precambrian basement complexes, Gondwana Supergroup and other Tertiary sequences. Drilling in the Recent Gangetic (Bengal) alluvium has established that the basaltic flows extend continuously beneath them between the Rajmahal and Sylhet exposures with a thickness of up to 250 m (Sengupta 1966; Baksi et al. 1987). Cretaceous age has been recorded for some dykes intruding the Gondwana Supergroup and Chottanagpur terrain east of the Rajmahal exposures that are clubbed together as the Bokaro dykes. The Arakan Yoma Belt is also known as the Indo-Burmese (Indo-Myanmar) fold belt

and Dubrajpur Formations) have been recorded between the Precambrian crystalline rocks and the volcanics along the western margin of the Rajmahal Traps (Fig. 8.3a). On the eastern side, they are covered by Quaternary and Recent alluvium of the Ganga–Brahmaputra delta system. A concealed fault (Chottanagpur Frontal Fault: Sengupta 1966) runs in a NNE-SSW direction along the south-eastern margin of the Rajmahal Traps.

More than 15 lava flows of the Rajmahal Traps are exposed with gentle eastward to ENE-ward dips, with a thickness of about 250 m. Borehole data from the Bengal basin has revealed around 28 basaltic flows with maximum thickness of around 275–300 m (Das Gupta and Mukherjee 2006). The Rajmahal Formation has been informally divided into the Lower (constituted of 6 flows with several intertrappean sedimentary beds) and Upper (containing a singular intertrappean bed at its base) units (Mahadevan 2002: p. 459–486). The individual flows vary from around a metre to more than 30 metres in thickness. Intertrappean sedimentary beds from this sequence have yielded a large variety of fossils but are best known for the paleofloral assemblage in them (Sahni 1932; Tripathi et al. 2013). Figure 8.3b gives an example of some of the measured sections from the Rajmahal Formation.

The Sylhet Traps (Das Gupta and Mukherjee 2006) are exposed in narrow 4 km wide and 60 km long E-W striking strips (Fig. 8.4a), with gentle (<7° south)

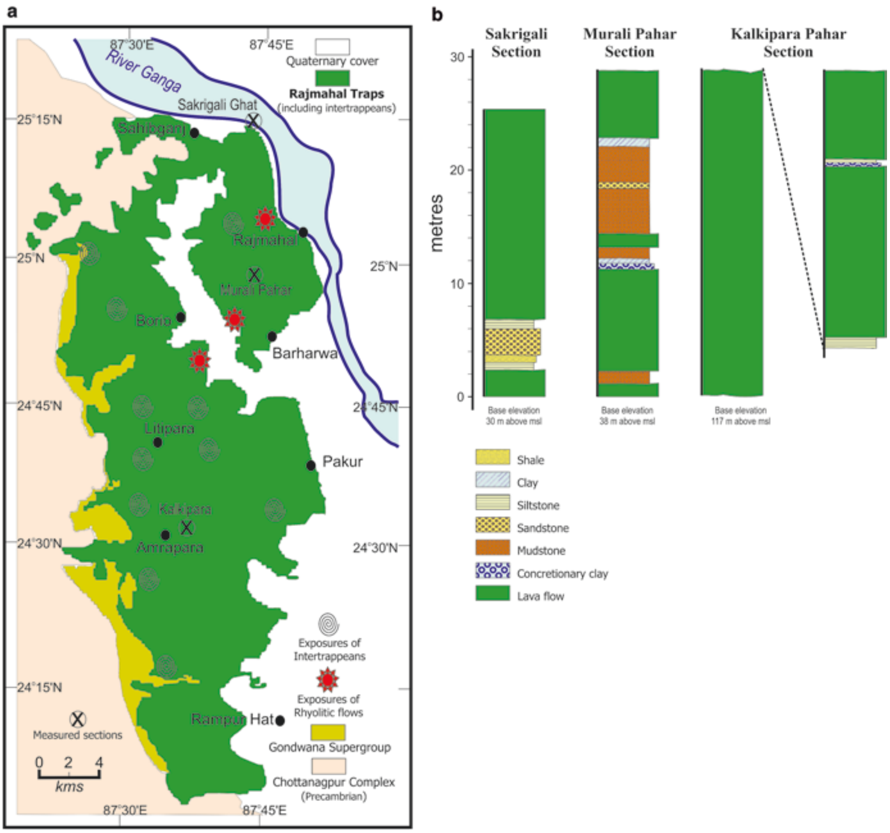


**Fig. 8.3** (**a**): Sketch map of the Rajmahal Traps depicting locations of exposures of rhyolitic lavas (after Kent et al. 2002) and intertrappean beds (after Tripathi et al. 2013). (**b**): Three representative measured sections (see locations marked with a cross-in-circle in the map) from Rajmahal Traps (after Tripathi et al. 2013)

monoclinal dips between the Raibah fault in the north and the Dhauki (/Dauki) fault in the south. They have been studied in two road sections (Cherrapunji–Shella bazar and Mawsynram–Balot (located further south of Therrai) in earlier works (Talukdar 1967; Baksi et al. 1987)). Figure 8.4b gives the 245 m thick sequence of flows recorded from Cherrapunji with 20 flows (having individual thickness ranging from 4 to 12 m) and 3 interbedded tuffaceous horizons.

## 8.2.2 Constituents

The Rajmahal Province is dominantly constituted of tholeiitic basalts that occupy almost 75% of the thickness of the lava piles (Talukdar 1967; Mahoney et al. 1983; Baksi et al. 1987; Kent et al. 1997). The subsurface basalts (sampled by drilling)

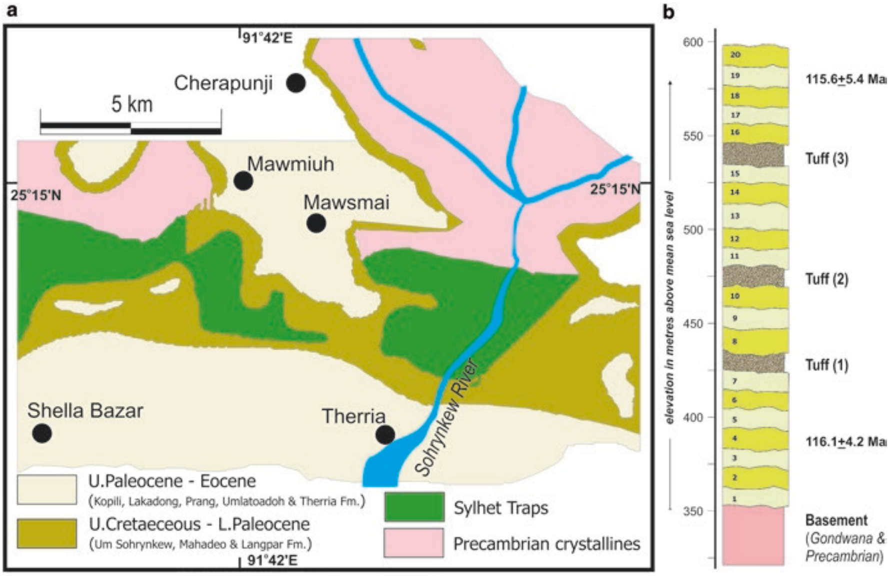


**Fig. 8.4** (**a**): Schematic map of the main exposures of the Sylhet Traps (modified after Tewari et al. 2010). (**b**): Representative litholog of the Cherrapunji-Shella bazar road section of the Sylhet Traps. Precision Ar/Ar dates were determined for flow numbers 4 and 19 by Ray et al. (2005) are given on the side

from the Bengal basin also conform to this overall pattern, besides recording the occurrence of alkali basalts. Three exposures of rhyolitic flows have been recorded in the Rajmahal exposures (Fig. 8.3a), while the Sylhet Traps include flows of alkali basalts, nephelinites and rhyolites in the western parts of Khasi Hills (Krishnamurthy 2008). A flow of pitchstone has been reported from the Rajmahal hills (Raja Rao 1953), while tuffaceous volcanics interbedded within the lava flows are present in all the sequences. Ghosh and Kent (2003) have recorded the presence of ignimbrites, pyroclastic flows and volcanic vents from parts of the Rajmahal hills.

Although several basic, lamprophyric and related dykes are known to intrude the Chottanagpur gneisses and the Gondwana sediments in the vicinity of the Rajmahal hills, only three known incidences of dykes (Sakrigali Ghat, Brindaban and Tinpahar) intruding the basaltic flows have been recorded from this province (Sarbadhikari 1968). Ultrabasic carbonatite complexes related to the Sylhet volcanics have been reported in the adjoining areas in Meghalaya and Assam (Srivastava and Sinha 2007).

Sheet flows with large lateral extent and limited thickness are typically found in these lavas. Vesicular bases and spongy tops are common in them, indicating that each lava flow was emplaced as a separate unit. Some of them display flow-top breccias that grade into the overlying tuff clayey layers. Columnar joints (sometimes displaying entablature, colonnade or multi-tiered column structures) are common in the compact core of these basalt flows. They may therefore be compared to the typical sheet pāhoehoe type subaerial basalt flows recorded from other continental flood basalt provinces (Self et al. 1998; Duraiswami et al. 2003, 2008).

Kent et al. (1996) recognised the Rajmahal basalts to be of high-Ca, low-Ca and ferro-tholeiite type and demonstrated their similarities with the basalts from the Kerguelen Plateau. Kent et al. (1997) demonstrated the upper crustal contamination of Indian Ocean MORB sources for these magmas based on Sr, Pb and Nd isotopes. They assigned them to a rifted volcanic margin origin. Geochemical and isotopic analyses of the Sylhet Traps indicate the presence of MORB-like tholeiitic basalts and potassic basalts with OIB affinities in them (Islam Md et al. 2014). There are differences of opinion whether mantle melts from the Kerguelen hotspot directly contributed to the magmas in the RBS Province or whether the mantle plume only provided the heat for upper mantle melts that fed the province. Continental crustal contamination and a possible sequence of ultra-alkaline (including carbonatitic) melts preceding the main tholeiitic flood basalts and terminating with heterogeneous differentiates such as andesites and rhyolites are indicated in the RBS Province (Krishnamurthy 2008).

### *8.2.3 Intertrappeans*

The intertrappean sediments in the Rajmahal hills (Fig. 8.3) are represented by sandstone, siltstone, arenaceous clay bed, carbonaceous and siliceous shale and tuffesites, besides a chert bed. Their thicknesses vary from a few centimetres to about 11 m (Tripathi et al. 2013). Subsurface exploratory drilling in the Bengal basin has indicated that some intertrappean detrital sedimentary beds may be up to 100 m in thickness. These intertrappean beds have yielded a rich collection of fossils belonging to the *Ptilophyllum* assemblage typical of the Upper Gondwana age. A detailed listing of the fossil remains from these intertrappeans is given by Vaidyanadhan and Ramakrishan (2008: p. 632–643 & p. 728–730). Although earlier considered to be of Jurassic age (Sahni 1932; Sah and Jain 1965; Bose and Sah 1968), this assemblage is now unquestionably recognised to be of Early Cretaceous age (Tiwari and Tripathi 1995; Tripathi 2008). In terms of depositional environments, these sediments have been shown to be continental fluvio-lacustrine deposits. This further reinforces the interpretation of the host lavas being erupted in subaerial environments.

### *8.2.4 Age and Linkage*

A very Late Jurassic to Early Cretaceous age of these basaltic flows was previously interpreted from the fossils in the underlying and interbedded sedimentary rocks (Baksi 1995). However, accurate Ar-Ar dating (Kent et al. 2002; Ray et al. 2008) showed that they were erupted within a short duration of a few million years between 113 and 118 Ma. The reverse magnetisation of the Rajmahal Traps and the paleolatitude of ~43°S (Klootwijk 1971; Poornachandra Rao et al. 1996) are consistent with the position of the Indian plate at the Kerguelen hotspot around 118 Ma. These studies and the available knowledge of the petrogenetic characters of the RBS province show that it is a consequence of the thinning and rifting of the crust atop the Kerguelen mantle plume leading to the generation of a large amount of basaltic (MORB-like) melt that eventually erupted on the eastern rifted margin of the Indian plate.

## 8.3 Deccan Province

The Deccan Volcanic Province (DVP) is arguably the most important of LIPs of the subcontinent because of the volume (>2.5 million km$^3$), the dominance of the tholeiitic basalt flows in it (Subbarao 1988, 1999; Hooper et al. 2010; and citations therein), as well as its temporal proximity to the K-Pg Boundary (Schoene et al. 2019; Sprain et al. 2019). Exposed over a vast contiguous area of more than half a million km$^2$ in the Indian Peninsula; it straddles the Dharwar craton in the south and the Aravalli–Bundelkhand craton in the north. Its eastern limits are defined by the Pranhita–Godavari rift belt beyond which the basement of the Bhandara craton is exposed (Fig. 8.5). The Deccan Traps occupy most of the Saurashtra peninsula and continue

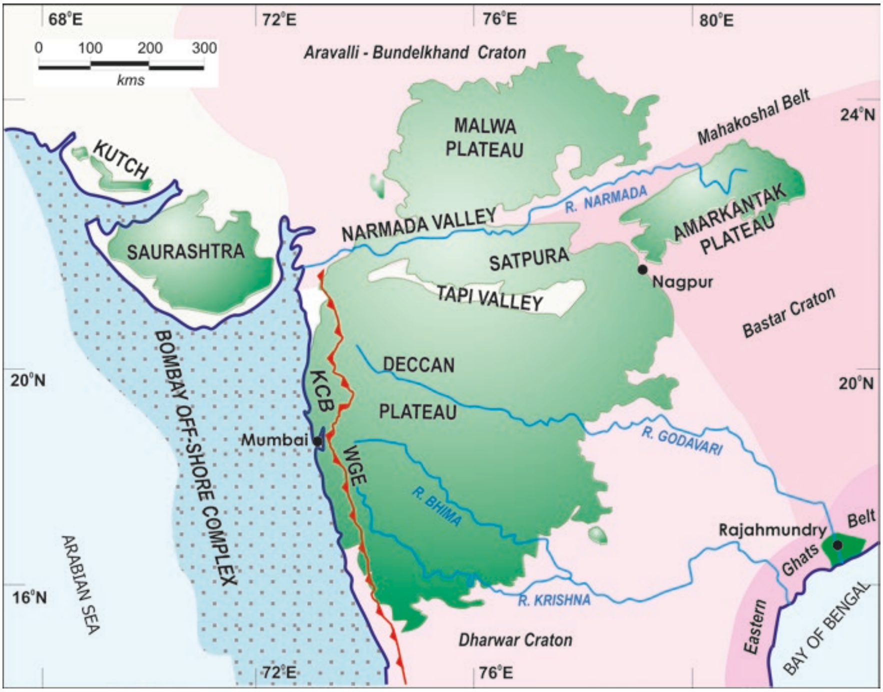


**Fig. 8.5** Outline map of the Deccan Volcanic Province, India (in green shades), showing the geographical sectors of the province and major rivers that drain it. Precambrian blocks of the basement of the Deccan Traps are shown in shades of pink for easy reference

westwards into Kutch where they are exposed as a narrow strip between the Late Cretaceous and Eocene sedimentary sequences. Several outliers of the Traps resting upon older rocks in Rajasthan (around Kota–Jhalawar), Madhya Pradesh (in Gwalior, Sagar, Bhopal, Ratlam, Indore, Hoshangabad, Chhindwara, Jabalpur and Khargone districts), Maharashtra (in Dhule, Nagpur, Chandrapur, Yawatmal, Beed, Solapur and Kolhapur districts) and Karnataka (in Belgaum, Bijapur and Bagalkot districts) testify to the paleotopography on which the Deccan Trap flows were erupted.

The exposure of basaltic flows interbedded within the terminal Cretaceous–Paleogene sequences around Rajahmundry (Sen and Sable 2011) and the offshore sections in the Bay of Bengal (named Razole Formation: Bastia et al. 2010) have been ambiguously considered to be a part of the Deccan Volcanic Province by some workers (e.g. Baksi et al. 1994; Self et al. 2008b). They bear a very close temporal relationship with the K-Pg Boundary (Keller et al. 2011; Keller et al. 2016b). Others have doubts about the genetic linkage between them notwithstanding the similarities in their ages (e.g. Knight et al. 2003; Manikyamba et al. 2015; Kale et al. 2019). They are excluded from the ensuing documentation, given that (a) they are normally polarised (Baksi 1994), whereas the normally polarised lavas in the western DVP are all significantly younger than the K-Pg Boundary (see Renne et al. 2015), and (b) the possibility of their affinities with the Kerguelen hotspot trail along the Bengal basin and the 85°E ridge and consequently a different source of magma.

Large areas of the Bombay offshore complex have yielded several hundred metre thick sequences of basaltic flows at the base of the petroliferous Tertiary sediments during drilling (Biswas 2008). They represent the western continuation of the basaltic flows that were faulted down below the Arabian Sea (Dessai and Bertrand 1995; Hooper et al. 2010; Pande et al. 2017b). There is also a possibility of expanding this area further, if one accepts the possible representatives of the Late Cretaceous Deccan volcanism from Rajasthan (e.g. Pande et al. 2017a) and the Bastar region (Chalapathi Rao et al. 2014). Taken together, the projected area that was once occupied by the Late Cretaceous flood basalts in Peninsular India and adjoining offshore shelf basins is more than 2 million km$^2$.

### *8.3.1 Trap: Basement Relations*

The Deccan Traps display a sharp (igneous) nonconformable contact with the basement on which they rest. Calcareous material is generally modified or recrystallises at temperatures as low as 150 °C, while the emplacement temperatures of the basaltic lavas are not less than 800°–1000 °C. Paucity of the thermal imprints on the calcareous sediments or paleosol layers (including Bagh Group, Lameta Formation, Bhima Group, Vindhyan and Kaladgi Supergroups) occurring immediately below the Deccan lavas is a remarkable feature. The only exceptions are wollastonites recorded at the contact between the Deccan Traps and the Neoproterozoic Bhima Group limestones in the Adki area (Kale and Peshwa 1995) and the baking of the tuffaceous interflow horizons (boles) in the western parts of the Deccan Plateau (Widdowson et al. 1997; Srivastava et al. 2018).

#### 8.3.1.1 Paleotopography

The other facet is the nature of the paleotopographic surface on which these flood basalts were erupted (Fig. 8.6). The models of eruptive history of the Deccan Traps (Mitchell and Cox 1988- Fig. 2; Watts and Cox 1989; Mitchell and Widdowson 1991) tend to disregard the paleotopographic aspect of their basement and depict it as smooth to a gently undulating one. Blanford (1867b) and Auden (1954) were amongst the earliest authors to record the undulating nature of this contact in different parts of the DVP. They have documented the elevational differences of the magnitude of 'roughly 1000 ft' (200–300 m) for this contact. Amplitudes of 200 m and more in the pre-trappean paleotopography is particularly accentuated in the exposures where the Deccan Traps rest on the Proterozoic sediments of Vindhyan (in the north) and Kaladgi Supergroups (in the south) at Jhalrapatan (near Kota) in

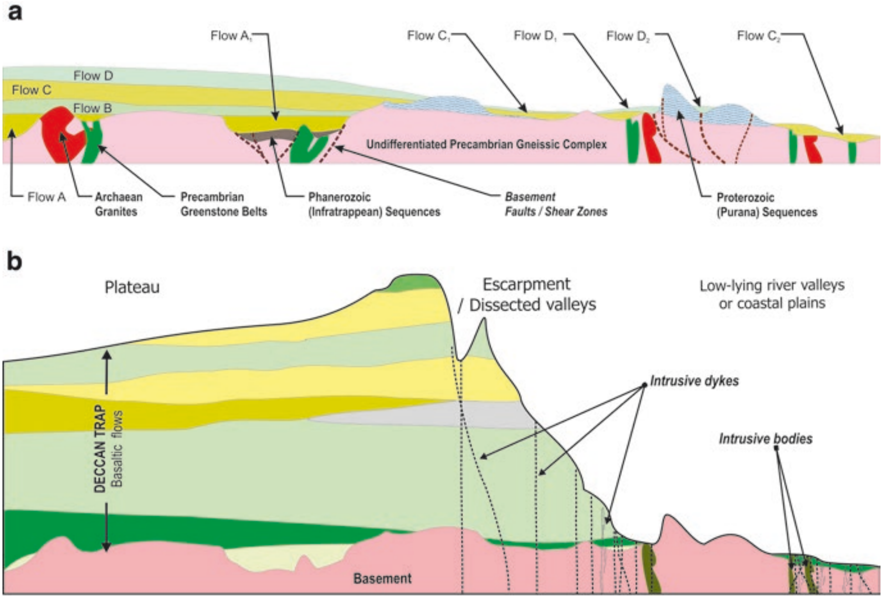


**Fig. 8.6** (**a**): Generalised sketch of the Trap—basement contact normally observed around the fringes of the DVP. Note the basaltic flows that have been emplaced as disconnected outcrops (marked as Flow A1, C1, C2, D1, D2) may or may not be the same as the main sequence (Flows A to D) on the left of sketch, and proving their continuity required field mapping of the entire flow field. The pre-trappean topography displays undulations with amplitudes of up to 250 m at places. (**b**): Generalised sketch of the Trap—basement contact and the cross-sectional profile encountered along the fringes of the plateaux in the DVP. The basement is collectively shown in pink colour. Pre-trappean topographic undulations can be observed at the lower reaches but may only be inferred below thick sequences where the basement is not exposed. Intrusives and dykes are commonly exposed in the river valleys (such as the Narmada, Tapi, and Godavari) and the western coastal belt (KCB) of the province. Their persistence below the thicker sequence of the flows cannot be ascertained. The variations in thicknesses of the successive flows as well as their pinching out geometry are schematic, but factual

Rajasthan, Sagar in Madhya Pradesh and Azra and Phondaghat in Maharashtra. Wherever the Deccan Traps rest directly on the Archean crystalline basement, the contact is relatively more peneplained. Drilling in the Koyna–Warna seismic zone (Gupta et al. 2017) has shown that there are variations of the magnitude of +200 m in the altitudes of the Trap—basement contact. Taken together, it is possible to generalise that the Deccan Traps erupted on a mature peneplained basement except where relict hills of resistant rocks punctuated the topography.

The regional trends and shear zones in the basement (Fig. 8.7) can be shown to have exerted control on the eruptive history of this continental flood basalt province (Peshwa and Kale 1997; Radhakrishna and Mahadevan 2000) and may have added to the complexities in the paleotopographic configuration of the basement on which the basalts were erupted. This has major implications on the lateral correlation of the stratigraphic units of the Deccan Traps as discussed below.

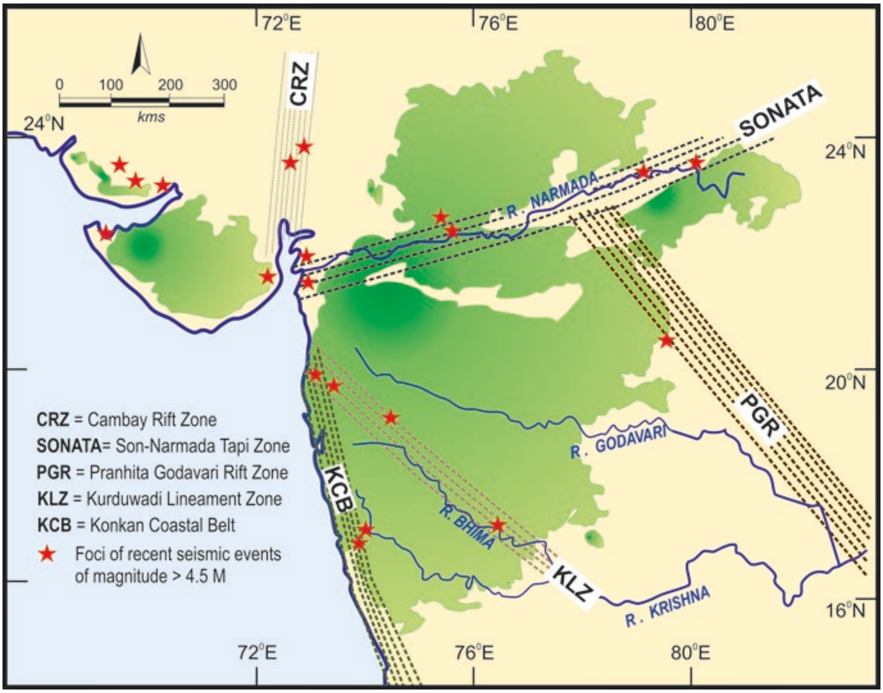


**Fig. 8.7** Zones of major structural deformation in the DVP (in green shades) that correspond with Precambrian trends in the basement of the basalts (after Peshwa and Kale 1997). These zones have evidence of having been active during the Precambrian times, have geophysical signatures in terms of anomalies and appear to be locales of recent seismic activity (of which the larger events are represented by red stars), besides exposing dislocations and disruptions in the lateral continuity of the basaltic flows

#### 8.3.1.2 Geophysics

Geophysical studies across the province have concluded that the thickest basaltic pile is found in the Western DVP, followed by the Mandla, Central, Malwa and Saurashtra subprovinces with successively reduced thickness (Kailasam et al. 1972; Brahmam and Negi 1973; Kaila 1988). The projected thinning of the Trap cover towards the fringes of the province is validated by field studies and drilling (Godbole and Chatterjee 1996; Sengupta and Deshmukh 1996). The smooth sub-trappean basement profile (inferred by geophysical studies) and thinning towards fringes were used in support of the assumption of a peneplained sub-trappean basement that was used in the eruptive models (Jay and Widdowson 2008; Richards et al. 2015) and the projected dispersal of lavas (Self et al. 2008b; Schoene et al. 2019). The segmented and uneven nature of the sub-trappean basement is now established unambiguously (Ramachandran and Kesavamani 1998; Mahadevan and Subbarao 1999; Tiwari et al. 2001b; Harinarayana et al. 2007; Rajaram et al. 2017).

#### 8.3.1.3 Structural Zones/Regional Lineaments

The ENE-WSW trending Son–Narmada–Tapi (SONATA) zone is the most prominent of the regional lineaments transecting the DVP (West, 1962; Ravi Shanker 1991). It hosts the Late Archean–Paleoproterozoic Central Indian Suture between the southern and northern blocks of the Peninsular Indian shield (Valdiya 2016 and citations therein). Evidence of post-trappean deformation along it is compelling (Tiwari 1985; Peshwa et al. 1987). The Pranhita–Godavari rift (PGR) zone that separates the Bhandara and Dharwar cratons was an active rift during the Mesoproterozoic times as well as the Gondwana times. They together separate the Malwa subprovince (north of SONATA) and the Mandla Lobe (east of the PGR zone).

The Cambay Rift Zone (CRZ) that is known to have suffered Tertiary faulting and folding separates the Saurashtra Subprovince from the contiguous exposures of the Deccan Traps. It is collinear with the trends of foliation in the southern parts of the Precambrian Aravalli–Delhi belt. The Kurduwadi Lineament Zone (KLZ) with a NW-SE trend cutting across the Deccan Plateau (Brahmam and Negi 1973; Kale and Peshwa 1988) has been shown to control the evolution of the Proterozoic Bhima basin and displays fracturing and faulting of the Deccan Traps along its length (Peshwa and Kale 1997; Kale et al. 2017), besides neotectonic deformation of the Quaternary sediments resting on the basalts (Dole et al. 2000).

The Konkan Coastal Belt (KCB) on the western edge of the continental exposures of the DVP is characterised by westerly monoclinal dips of the Deccan Traps and numerous N-S to NNW-SSE trending dykes and other intrusive bodies. The sills and dykes recorded from Thana and Raigad districts (e.g. Auden 1949b; Mulay and Peshwa 1980; Godbole et al. 1996; Sheth and Pande 2014) appear to be part of late magmatic activity in the DVP. The parallel alignment of the dykes in this zone with the West Coast fault system in the Bombay offshore region and the evidence of faulting and fracturing along this zone are significant. The Panvel Flexure (Rajurkar et al. 1990; Dessai and Bertrand 1995; GSI 2000; Hooper et al. 2010; Samant et al. 2017;

Pande et al. 2017b), NW-SE trending strike-slip faults and numerous regional fracture zones superimposed on the basalts along this belt (Peshwa and Kale 1997; Kundu and Matam 2000; Misra and Mukherjee 2015) are evidence of post-trappean deformational events along this zone. Several hot springs are present in this zone (Pitale et al. 1987; Minissale et al. 2000; Kumar et al. 2011; Reddy et al. 2013).

### *8.3.2 Subprovinces*

Using these basement zones and the flow-by-flow mapping undertaken by the Geological Survey of India (published as a series of District Geology maps between 1999 and 2005: GSI 2001), it is possible to subdivide the DVP into subprovinces (Fig. 8.8) that are structurally and stratigraphically coherent within themselves. The

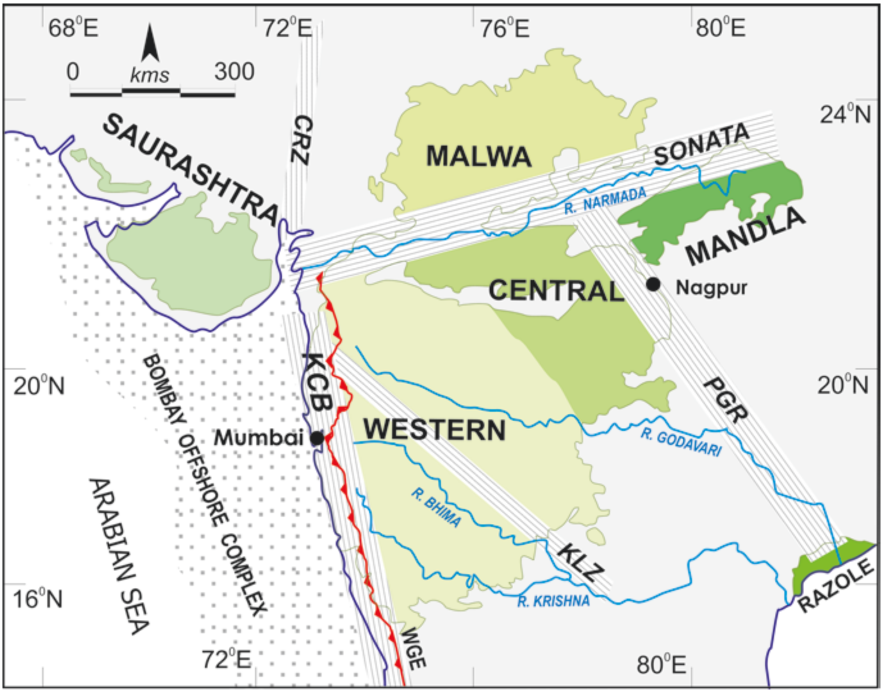


**Fig. 8.8** Subprovinces of the DVP based on basement structures and contiguity of flows (enabling establishment of a stratigraphic column). The Konkan Coastal Belt (KCB) is a part of the Western subprovince (often referred to as the Main Deccan Plateau: Krishnamurthy 2008). The Razole Subprovince on the eastern coast (around Rajahmundry) has limited exposures on land but has been traced further eastwards in the offshore Krishna Godavari basin to extend across not less than 50,000 km$^2$. It is likely that each of these subprovinces had an independent (but interlinked) eruptive history and that the lavas were fed by different eruptive foci in each of them. The existing popular model (after Cox and Hawkesworth 1985; Richards et al. 2015) assumes a monocentric eruptive history of the entire province

SONATA zone separates the Malwa from the Deccan Plateau. The narrow (<100 km wide) western coastal KCB (see Fig. 8.5) is separated from the Deccan Plateau by the spectacular N-S trending Western Ghats (Sahyadri ranges) with maximum elevations of more than 1600 m. The Sabarmati and Mahi valleys (along the CRZ) separate Saurashtra from the rest of the DVP. The Mandla lobe is detached from the rest of the DVP by the PGR. Stratigraphic correlations of the lava piles based on chemostratigraphic parameters across the subprovinces fail the test of field mapping of flow continuity (Deshmukh and Nair 1996: p. 14; GSI 2001; Kale and Pande 2017).

### *8.3.3 Constituents*

The earliest descriptions of the Deccan Basalts through the nineteenth and early part of the twentieth centuries (Newbold 1844; Blanford, 1867a, b, 1869; Bose 1884; Fermor and Fox 1916) laid the foundations of the present understanding of the DVP. Washington (1922) gave the earliest petrochemical analyses of the Deccan basalts. Subsequent work between the 1940s and 1970s focused on the physical description of the flows and dykes (e.g. Auden 1949b) and the petrochemical studies of the alkaline and acidic rocks found in different parts of the province (see Wadia 1975; Bose 1980; Krishnan 1982; Krishnamurthy 2008 and citations therein). The work of West (1959) and Walker (1971) provided the foundations for the physical volcanological classification of the lava flows. The geochemical characterisation and chemostratigraphic classification evolved in the last half of the 1980s (Sreenivasa Rao et al. 1985; Cox and Hawkesworth 1985; Devey and Lightfoot 1986) leading to the compilations in Subbarao (1988, 1999).

Petrologically, the DVP is dominated by subalkaline tholeiitic basalt flows, which account for more than 85% of its exposed area. Picritic, potassic, low-Ti and high-Ti varieties have been recorded along with rhyolitic and alkaline basalts, gabbroic and lamprophyric intrusive bodies and other transitional varieties (see Subbarao and Sukheswala 1981; Subbarao 1988, 1999; Deshmukh and Nair 1996) representing a minor component of this province. The flows of mega-porphyritic (plagioclase phenocrysts bearing) basalts, also called 'giant phenocryst basalts (GPBs)' that occur at multiple levels in the sequences of flows (Karmarkar et al. 1971; Sheth 2016), are significant from the petrogenetic as well as stratigraphic perspective.

The tholeiitic basalts are constituted of plagioclase, augitic clinopyroxene, olivine and magnetite with minor proportions of ilmenite, apatite and glass. They typically display porphyritic textures (with >20% phenocrysts), the groundmass exhibiting an aphyric to phyric texture. A large variety of secondary minerals including zeolites, (cryptocrystalline and crystalline) silica and calcite with palagonite, iddingsite and chlorophaeite are recorded from them. Picritic basalts have been recorded in the Western Deccan and Saurashtra subprovinces. They contain larger portions of magnesian olivine and pyroxene than the plagioclase. Alkali basalt flows and intrusives have been recorded from Kutch, Narmada valley and CRZ, often associated with felsic igneous rocks and carbonatites. They are composed of fosteritic olivine, diopsidic and titan–augitic pyroxenes, spinels, labradoritic plagioclase and occasionally sanidine and albite. They have been reported to host mantle nodules of dunite and spinel peridotite (Karmalkar et al. 2005; Ray et al. 2008). Doleritic dyke swarms are reported from the KCB and SONATA zones in the DVP (Auden 1949a; Peshwa et al. 1987; Deshmukh and Sehgal 1988; Ray et al. 2007; Vanderkluysen et al. 2011), although a feeder relationship between them and the flows is ambiguous. Such dykes are not often encountered in the upper flows in various sequences (as shown in Fig. 8.6b) of the Western, Malwa or Mandla subprovinces, except in the Nasik–Sangamner–Aurangabad tract and Lonavala areas on the crest of the Western Ghats (Peshwa et al. 1987; Bondre et al. 2006; Babar et al. 2017). Several other volcano-plutonic complexes are present within the DVP (Vaidyanadhan and Ramakrishan 2008, p. 757–767), particularly in the Saurashtra subprovince (e.g. Barda hills, Girnar complex, Osham hills and other alkali rocks of Kutch), CRZ (e.g. Mundwara complex, Pavagadh hill, Dandali complex), Narmada valley (e.g. Ambadongar complex, Rajpipla hills, Phenai Mata complex) and the KCB (e.g. Jawahar, Malabar, Worli hills, Murud–Janjira complex, St. Mary's Island). They host a variety of alkaline, lamprophyric, felsic and carbonatitic rocks. They have yielded mantle and lower lithospheric xenoliths of various sizes that enable understanding the sub-trappean lithosphere and the magmatic processes leading to the primary partial melting of the magmas that eventually fed the voluminous eruptions in the DVP. The overall petrochemical characters and ages (discussed later) appear to indicate that the Deccan magmatism passed through three phases as the Indian plate passed over the Reunion hotspot. The ultra-alkaline to alkaline magmatism preceded the main phase of voluminous tholeiitic eruptions. The alkaline to acidic magmatism that included remobilised upper crustal components manifested as carbonatites and lamprophyres (Krishnamurthy 2008), represented in the late magmatic phase. This is broadly consistent with the magmatic sequences observed in other continental flood basalt provinces of the world, including that in the Columbia, Karoo and RBS provinces.

The distribution patterns (geographically and stratigraphically) and compositional characters (including major, minor and trace-elemental compositions and isotopic characters) of the tholeiitic lavas have been generally ascribed to primary derivation as partial melts from a hot upwelling mantle source (possibly at the Reunion hotspot), emplaced in sub-lithospheric magma chambers where they underwent further modifications through variable differentiation and crustal contaminations. In most of the vertical sequences exposed in parts of the DVP, systematic variations have been recorded in the petrochemical characters of the flows. These variations have enabled elucidate a chemostratigraphic classification of the Deccan lavas in the western parts of the province in particular (see Subbarao 1988) that has been subsequently extended to other parts of the province (Mitchell and Widdowson 1991; Subbarao 1999; Jay and Widdowson 2008; etc.) and propose long-distance correlations of the flows (e.g. Self et al. 2008b; Shrivastava et al. 2014, 2017).

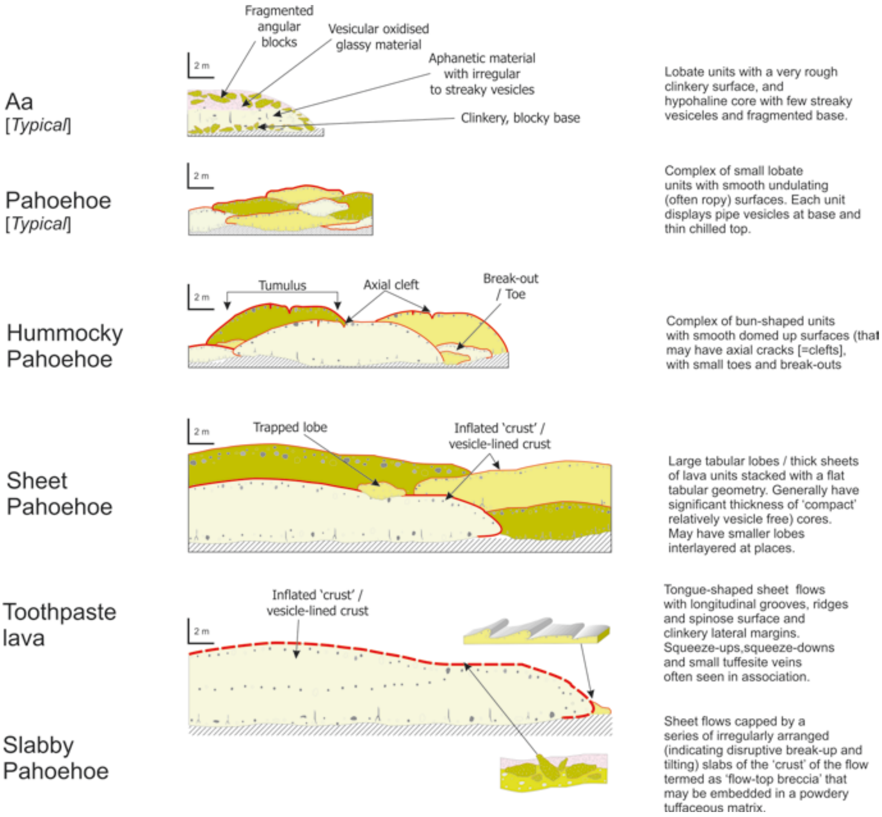
### 8.3.4 Flow Geometry and Types

The recognition of the subhorizontal sheeted geometry of the lava flows in the DVP has been noted even in the earliest descriptions of the Deccan Traps, named after the steplike topographic profiles that develop on them. To a large extent, the volcanological description of the Deccan flows (flow fields) are modelled on the lines of Hawaiian lava flows following the initial comparisons by Walker (1971), modified by Deshmukh (1988). They are essentially classified as (1) compound pāhoehoe flows, comprising multiple lobes with chilled margins that are fused together; (2) simple flows 'representing a single volcanic episode' with chilled, vesicular top and basal margins of variable thicknesses and having a compact crystalline core sandwiched between vesicular layers, but without a'ā characters; or (3) a'ā flows with clinkery or blocky (brecciated) tops (Godbole et al. 1996: p.126).

Recognition of features such as inflated crusts, tumuli, lateral transition from pāhoehoe to a'ā within a single flow unit provided a better understanding of the volcanological characters of these flows in the last two decades (Bondre et al. 2000, 2004; Duraiswami et al. 2001, 2003, 2004, 2014; Brown et al. 2011; Sheth et al. 2011, 2017; Sen et al. 2012; Sen 2017). Broadly, in terms of their primary volcanological geometry, using the Hawaiian analogues, the flows in the DVP can be categorised into about six types depicted in Fig. 8.9. Of these, there are doubts as to whether typical a'ā lavas as encountered in Hawaii (sensu Walker 1971) are present in the DVP at all (Keszthelyi et al. 1999). The slabby pāhoehoe type can be easily mistaken for the typical a'ā flows in vertical sections, unless their overall geometry and spread are appropriately mapped. The slabby pāhoehoe type has also been described as rubbly pāhoehoe flows in cases where the disrupted crust is thick and prominent by Duraiswami et al. (2008), who consider most of the 'simple' flows in the DVP to belong to this category.

The morphology of the lava flow is primarily determined by its composition (with respect to crustal contamination and differentiation indices), viscosity (that is critically dependent upon when and how it loses its vapour phase), emplacement temperatures and volumetric rate of effusion (in each pulse of emplacement). These parameters respond to the local gradient of the substrate on which the lava flows, rate and nature of vapour escape from the cooling lava and the available space in which it can spread. The preserved internal structure and morphology of a lava flow is a manifestation of the end result of each of these parameters working in tandem (see Walker 1971; Long and Wood 1986; Rowland and Walker 1987; Wilmoth and Walker 1993; Hon et al. 1994; Keszthelyi and Denlinger 1996; Cashman et al. 1999; Harris et al. 2007; Katterhorn and Schaefer 2008; Anderson et al. 2012; Glaze and Baloga 2013; Marshall et al. 2016; and citations therein).

Against this background, taking all the recorded observations (including by this author), it may be concluded that more than 95% of the flows in the Deccan qualify as compound pāhoehoe type flows. Typical a'ā flows (sensu Hawaiian analogues) only occur with limited aerial extent in the close proximity (a few kms) of eruptive vents. The primary mechanism of lava transfer across large distances is of emplace-



Lobate units with a very rough clinkery surface, and hypohaline core with few streaky vesiceles and fragmented base.

Complex of small lobate units with smooth undulating (often ropy) surfaces. Each unit displays pipe vesicles at base and thin chilled top.

Complex of bun-shaped units with smooth domed up surfaces (that may have axial cracks [=clefts], with small toes and break-outs

Large tabular lobes / thick sheets of lava units stacked with a flat tabular geometry. Generally have significant thickness of 'compact' relatively vesicle free) cores. May have smaller lobes interlayered at places.

Tongue-shaped sheet flows with longitudinal grooves, ridges and spinose surface and clinkery lateral margins. Squeeze-ups,squeeze-downs and small tuffesite veins often seen in association.

Sheet flows capped by a series of irregularly arranged (indicating disruptive break-up and tilting) slabs of the 'crust' of the flow termed as 'flow-top breccia' that may be embedded in a powdery tuffaceous matrix.

**Fig. 8.9** Cross sections and relative sizes of typical flow types recognised from the DVP. The figure is modified from the compilations of Bondre et al. (2000, 2004), Duraiswami et al. (2008, 2014): Table 8.1, Sen (2017) and this author's field observations. Note that the vertical and horizontal scales are identical but only representative to show relative sizes of thickness and horizontal spread of the different types and the constituent lobes within them. Lateral transitions from one type to another have been recorded in different parts of the DVP. Jointing patterns within the core have not been depicted here to retain clarity of the figures

ment in multiple successive pulses and endogenous transfer across their length and breadth, with inflated and/or disrupted crusts. Based on these principles, it is now possible to revise the physical volcanological classification of the basaltic flows found in the DVP to a continuous, transitional suite of morphologies, with two end-members described by Kale (2016) as 'type-A' and 'type-B' flows.

The 'type-A' flows (Fig. 8.10a) are lobate, inflated compound pāhoehoe flows that are made up of numerous small lobes. Tumuli, hummocky surfaces and reddened, chilled glassy rinds of individual lobes are common in them. Individual lobes may not spread more than a few km$^2$, while a flow field may be traced over distances of a few tens of km laterally. This type usually displays a lateral spread to thickness ratio in the range of 1:10–1:100. Due to their high vesicularity, they often

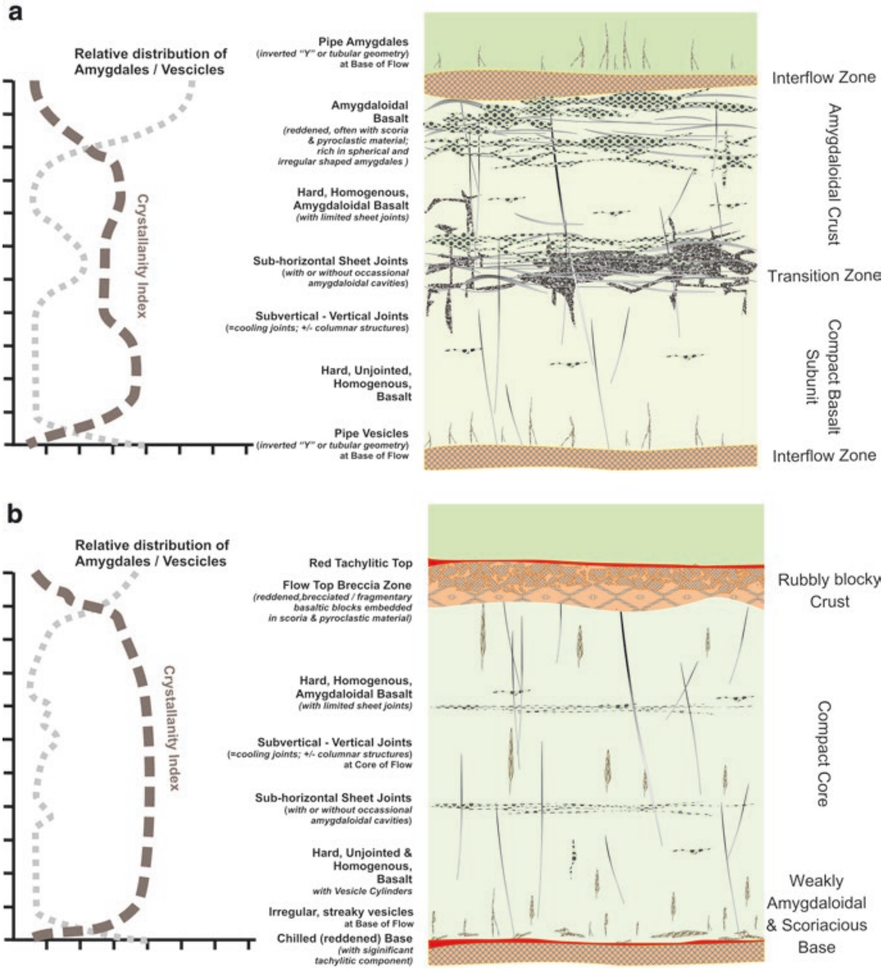


**Fig. 8.10** (**a**): Generalised vertical cross sections of the type-A flows from the DVP (modified after Kale 2016). This endmember of the continuous series of internal flow geometries in the Deccan lavas represents the product of eruption of relatively small volumes of individual pulses of emplacement but in brisk succession. The cooling history suggests a rapid loss of the vapour phase on emplacement, leaving a more viscous lava that is unable to move across long distances, resulting in a lobate geometry. (**b**): Generalised vertical cross sections of the type-B flows from the DVP (modified after Kale 2016). This endmember of the continuous series of internal flow geometries in the Deccan lavas represents emplacement of large volume batches of lava that were transferred endogenously within the chilled crust of the flow. The chilled crust trapped the vapour phase for a longer duration, providing the necessary fluidity to the lava to spread across larger distances laterally. The vapour phase was eventually lost by cracking through the crust, producing the flow-top breccias, leaving behind a relatively vesicle-deficient core. Vesicle banding and flattened irregular cavities along with subhorizontal cooling joints at more than one level within the compact core testify to the multiple batches that eventually crystallised within the (crust-)enclosed system

are easily weathered. Their core is depleted of vesicles as compared to the base or top. The relative proportions of the thickness of the core to vesicular (amygdaloidal) crust in these flows is less than or equal to 1. Inter-lobe contacts are sharp and clearly marked by chilled glassy rinds of reddish brown tachylitic material. Multiple lobes of this type, welded together into thick compound flows, occur in the northern and central parts of the Deccan Plateau and in the Konkan Coastal Belt as subvertical cliffs with smooth rounded surfaces. They indicate an emplacement of successive lobes (that quickly fuse together) without significant breaks between them. Interflow horizons between such flows (if present) are normally very thin and impersistent. Rare (1–5 m thick) intertrappean sedimentary beds have been recorded around Mumbai and in the Malwa Subprovince from them.

The 'type-B' flows (Fig. 8.10b) on the other hand may be described as sheet pāhoehoe lobes/flows that extend across many tens (sometimes a few hundreds) of km laterally. Without exception, they are capped and floored by interflow horizons that can be traced across several tens of km. Flow-top breccias, thick inflated vesicular crusts (that testify to significant endogenous emplacement of the lava), vesicle cylinders and entablature and (often multi-tiered) columnar joint patterns in their compact portions are commonly observed in these flows. The core of such flows is thicker than the crust (including the flow-top breccia and chilled rinds where present). Such flows are normally more crystalline than the 'type-A' flows. Many of them were classified as 'simple flows' by earlier workers, signifying their development by a solitary pulse of lava emplacement (as against multiple pulses in 'compound' flows) that spread over considerable distance. Detailed examination shows that they are constituted of crusts (often with multilayered inflated crustal slabs) that are disrupted along their length in variable degrees and almost nonvesicular cores with more than one cooling fronts resting on a vesicular base that has streaky vesicles, large amygdaloidal cavities with flat base and curved tops and prolific vesicle cylinders. The core segments often display subhorizontal bands of vesicles suggesting that it grew from multiple batches of lava. Calling them 'simple' flows thus is a misnomer. They are best analogous to the sheet pāhoehoe flows (sensu Self et al. 1998) that have spread over large areas and were fed by several batches of endogenous lava emplacement (enveloped within the chilled crust) enabling efficient transfer of large volumes of lava laterally across long distances.

It can be shown in case of several flow fields of the DVP that flow lobes at stratigraphically same levels change their character from 'type-A' to 'type-B' laterally. It can also be demonstrated that the typical a'ā flows are present only as local transitional variants of the sheet (≅type-B) flows (e.g. Duraiswami et al. 2008). Given the overall compositional homogeneity of the lava flows across the DVP, it seems logical that such changes are the result of variations suffered in the near-surface and post-eruptive crystallisation and transportation history of the individual flow fields. The different lava morphologies do not suggest primary differences in the lava constitution but are a manifestation of variations resulting from diversity in their emplacement, vapour loss and cooling processes.

Deshmukh (1988) was the first to compile a province-wide map of the distribution of the flow types (see Inset- Fig. 8.11), based on the classification of the flows

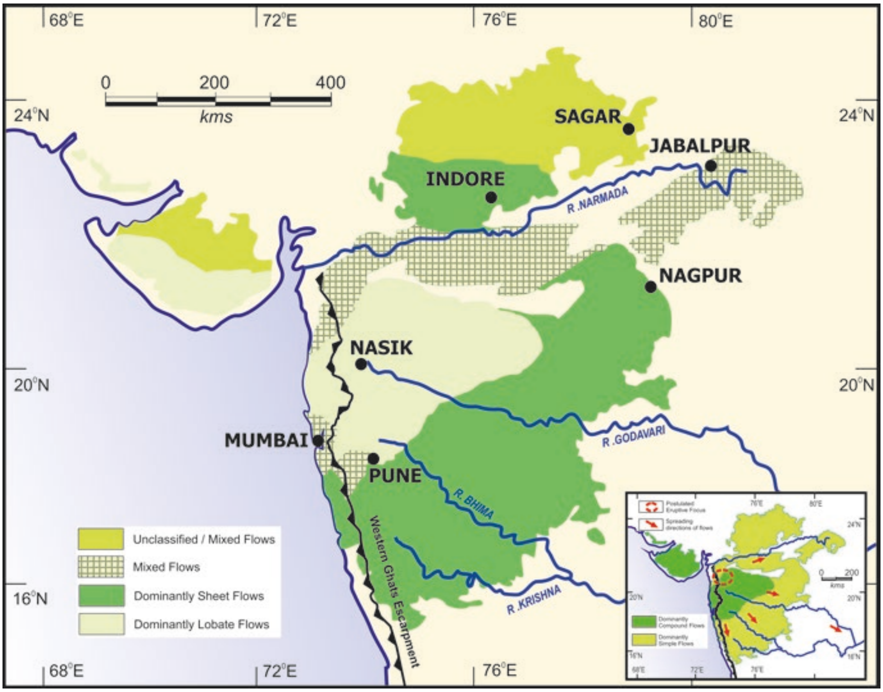


**Fig. 8.11** Distribution of flow types across the DVP (from Kale et al. – in review). The lobate flows are dominantly of the type-A endmember and were earlier clubbed as 'compound flows', while the sheet flows are more of the type-B endmember. Mixed flows include areas where the vertical sequence displays a mixture of intermediate variations between these two endmember types. Some parts of the Saurashtra Subprovince and northern Malwa province may be of the mixed type, although their exact typology is yet uncertain and hence are shown as unclassified. It is interesting that the distribution of mixed flows corresponds with the incidence of dyke swarms in the Western and Central subprovinces. Inset depicts the compilation by Deshmukh (1988) of the distribution of simple and compound flows along with the postulated primary edifice of Deccan volcanism (modelled by Cox and Hawkesworth 1985, Subbarao and Hooper 1988; Mitchell and Widdowson 1991; Jay and Widdowson 2008 amongst others) and the projected directions of the dispersal of the lavas, including the possible linkage with the Razole Province postulated by Baksi et al. 1994; Self et al. 2008b; Jay et al. 2009; Richards et al. 2015)

into 'simple' and 'compound' types. This figure was used in subsequent works to extend the correlations of the chemostratigraphic units across the province and postulate a monocentric shield-type volcanic model for the DVP. If the revised classification of endmember types (A & B) of the flows is used, a very different picture of the distribution of flow types in the province emerges (Fig. 8.11).

Although the Deccan flows do display many features analogous to the Hawaiian flows, as also has been recorded from other flood basalt provinces (e.g. Self et al. 1998; Thordarson and Self 1998; Bondre et al. 2004; Sheth 2006), several obvious differences exist between the Hawaiian and Deccan basaltic flows. The presence of a thick, cold continental crust (that may have suffered limited localised heating due to magmatic upwelling during the volcanism) in the Deccan as against its absence in Hawaii perhaps is the most significant of the differences that would have substantial impact on the composition (particularly in crustal contamination levels), viscosity, emplacement temperatures and rate of effusion. How these translate into the physical volcanological features preserved in the Deccan lavas is an aspect that cannot be disregarded when comparing them with the Hawaiian analogues. In that sense, the Icelandic analogue of flood basalts may provide a better point of comparison both in terms of physical volcanological features and the lava architecture that results (e.g. Òskarsson and Riishuus 2014) in a continental flood basalt province.

Early interpretations (Auden 1949b; West 1959; Krishnan 1982: p. 405) of the DVP indicated that it may represent a fissure-type eruption. The lack of specific exposures of feeder dykes—flow relations were pointed out across the province in subsequent times as a limiting factor for this model. The monocentric eruptive model for the DVP (Cox and Hawkesworth 1984, 1985) with the eruptive edifice in the north-western corner of the Western DVP near Nasik (as depicted in Inset Fig. 8.11) gained more acceptance with the increasing contributions on the chemostratigraphy and chemical parameter-based correlations across the province (Mitchell and Widdowson 1991; Self et al. 2008b; Richards et al. 2015; Renne et al. 2015). The need for a reassessment of this model has emerged based on the severe limitations of the chemistry-based approach versus field-mapping-based approach in recent times. A dyke-fed fissure-type eruptive model (e.g. Ju et al. 2017) as demonstrated in Iceland (Eibl et al. 2017) with polycentric eruptive foci provides a better explanation of the observed features and flow sequences in the DVP.

### *8.3.5 Stratigraphy of DVP*

The traditional classification of the Deccan Traps (Pascoe 1956; Krishnan 1982) was into the Lower, Middle and Upper Traps (from east to west successively), based on the fossil ages interpreted from intertrappean beds (Fig. 8.12). The infratrappean sediments (Bagh Group and Lameta Formation) exposed along the Narmada valley and in the eastern parts of the DVP showed affinities to Late Cretaceous flora and fauna, suggesting that the earliest flows were erupted close to the terminal Cretaceous times (Sahni and Bajpai 1988). On the other hand, the intertrappeans exposed around Mumbai and in the Saurashtra Subprovince were distinctly of lower Tertiary age. This appeared to validate the earlier postulated westward younging of the Deccan lavas.

The primary limitation in trying to stratigraphically subdivide this large volume of basaltic lava sequence is its compositional monotony that does not allow an easy recognition of a marker horizon within the sequence. The lateral tracing of individual flow fields is limited by their (pinch-and-swell and lobate) geometry (Fig. 6) and changes in internal structure from one type of flow to another (e.g. Duraiswami et al. 2003, 2014). This is compounded by the Tertiary–Quaternary erosional cycles and morphotectonic events that have created topographic profiles that impede tracing of the flows across larger distances. Although the spectacular ‘ghat’ sections

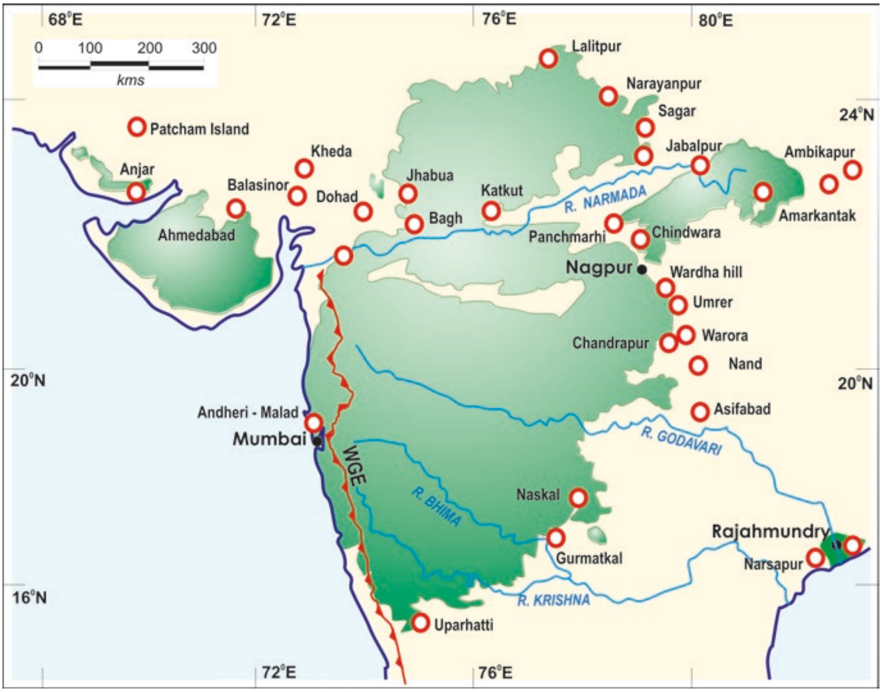


**Fig. 8.12** Locations of fossiliferous Cretaceous infratrappean (Bagh Group & Lameta Formation and their equivalents) and intertrappean sediments from the DVP. The locations are taken from various references cited in the text. Some of these locations appear to be away from the limits of the DVP (e.g. Asifabad, Ambikapur) but do have exposures of the trap-related sediments and associated outliers of basaltic flows. The detailed fossil assemblages have been compiled by Vaidyanadhan and Ramakrishan (2008: p. 777–784). The Rajahmundry (Razole) Traps are included since significant paleontological data related to the K-Pg Boundary also is derived from that sequence

give an impression of long distance persistence of the subhorizontal stacks of flows, also established in some parts (West 1958; Choubey 1973), there are doubts expressed regarding the same based on the inherent geometry of the individual flows/flow fields (see Gupte et al. 1974; Kale et al. 1992; Sheth 2000.

#### 8.3.5.1 Chemostratigraphy

The detailed chemical analyses of successive flows from vertical sections indicate that some systematic variations in the major elemental ratios (MgO number, differentiation index) and in the trace element and isotopic compositions may enable grouping of flow packages. This was demonstrated first in the Narmada region (Sreenivasa Rao et al. 1985) and the Mahabaleshwar section (Cox and Hawkesworth 1985). The recurrent occurrence of GPBs and picritic basalts provided another potential feature for subdividing the flows into packages. Beane et al. (1986)

proposed the chemical stratigraphic classification for the Traps exposed along the Western Ghats into ten formations, clubbed into three subgroups using these parameters. The uppermost Panhala and Desur Formations were added subsequently (Subbarao and Hooper 1988) when the stratigraphy was further extended to the southern and eastern parts of the Deccan Plateau by Mitchell and Widdowson (1991), Khadri et al. (1999a), Bilgrami (1999) and Jay and Widdowson (2008) in subsequent years. This eventually became the standard framework for describing the Deccan Traps Group (e.g. Chenet et al. 2009; Hooper et al. 2010; Renne et al. 2015; Richards et al. 2015; Schoene et al. 2015; Font et al. 2016). The average thicknesses, flow types and magnetic polarity of the compiled stratigraphic column of the DVP established in the Western subprovince through these studies are given in Fig. 8.13. The broad parameters that chemically characterise these stratigraphic divisions defined along the Western Ghats and KCB are listed in Table 8.1.

The Kalsubai Subgroup that hosts the oldest five formations is characterised by amygdaloidal compound flows, picrites and picritic basalts (MgO > 10%) at their base and is capped by evolved basaltic flows with megacrysts of plagioclase (GPBs). Thakurwadi Formation includes nine chemical types with compositional range of

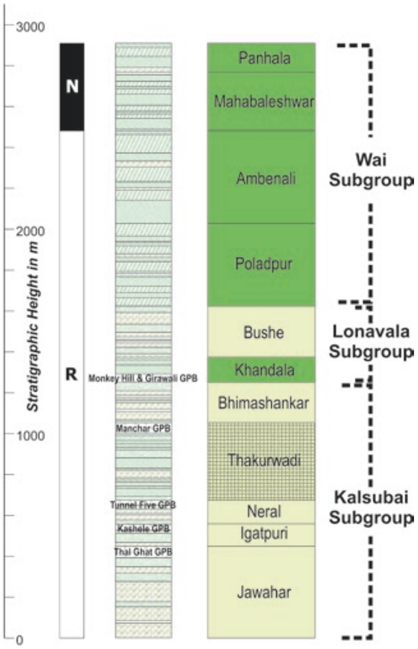


**Fig. 8.13** Chemostratigraphy of the Deccan Traps (as established in Western DVP). The pale green and deep green colours denote that the relevant formation contains dominantly type-A or type- B flows, respectively. Thakurwadi Formation has mixed flow types. The paleomagnetic polarity of the various units is given (based on Jay et al. 2009; Richards et al. 2015). The positions of the GPB horizons included in this classification to define Formation boundaries are given with the names of the GPB horizons (after Bodas et al. 1988, Khadri et al. 1988). See text for detailed description and discussion

**Table 8.1** Chemical characters of chemostratigraphic units from the Western DVP (after Vanderkluysen et al. 2011; Sheth 2016)

| Formation | Member/Chemical type | $(^{87}Sr/^{86}Sr)_t$ | Average Mg-no. | $TiO_2$ wt% | Average Zr/Nb |
|---|---|---|---|---|---|
| *Wai subgroup* | | | | | |
| Panhala | Desur | 0.7072–0.7080 | 48 | 1.6–1.9 | 11.4 |
| | Panhala | 0.7046–0.7055 | 52 | 1.6–2.3 | 14.8 |
| Mahabaleshwar | | 0.7040–0.7055 | 47 | 2.5–4.3 | 11.4 |
| Ambenali | Ambenali | 0.7038–0.7044 | 49 | 1.9–3.1 | 14.4 |
| Poladpur | Upper | 0.7061–0.7088 | 52 | 1.8–2.3 | 12.7 |
| | Lower | 0.7053–0.7110 | 56 | 1.5–2.0 | 14.0 |
| *Lonavala subgroup* | | | | | |
| Bushe | Bushe | 0.713–0.720 | 55 | 1.0–1.3 | 15.3 |
| | Shingi hill | 0.718–0.7181 | 49 | 1.3–1.4 | 16.2 |
| | Harishchandragad | 0.712–0.7164 | 58 | 2.0–2.1 | 12.9 |
| | Karla caves | 0.7147–0.7150 | 68 | 1.1–1.2 | 19.7 |
| | Bhaja | 0.7040–0.7055 | 47 | 1.3–1.5 | 18.2 |
| Khandala | Rajmachi | 0.7093–0.7102 | 44 | 2.1–2.5 | 14.6 |
| | Khandala Phyric | 0.7077–0.7085 | 41 | 2.4–2.8 | 13.6 |
| | Dhak Dongar | 0.7071–0.7072 | 40 | 2.9–3.1 | 13.1 |
| *Kalsubai subgroup* | | | | | |
| Bhimashankar | Monkey Hill GPB | 0.7073–0.7075 | 41 | 3.1–3.4 | 12.2 |
| | Giravali GPB | 0.7068–0.7074 | 45 | 2.8–3.1 | 12.1 |
| | Bhimashankar | 0.7067–0.7077 | 47 | 1.9–2.6 | 11.7 |
| Thakurvadi | Manchar GPB | 0.7075–0.7077 | 42 | 2.9–3.1 | 13.2 |
| | Thakurvadi | 0.7067–0.7088 | 58 | 1.8–2.2 | 12.0 |
| | Water pipe | 0.7099–0.7112 | 59 | 1.4–1.6 | 12.3 |
| | Jammu Patti | 0.7066–0.7077 | 34–56 | 1.7–2.7 | 8.4–11.2 |
| Neral | Tunnel five GPB | 0.7082–0.7083 | 36 | 3.3–3.5 | 10.8 |
| | Neral | 0.7062–0.7073 | 62 | 1.5–1.7 | 12.3 |
| | Ambivli Picrite | 0.7104 | 67 | 1.4–1.5 | 18.6 |
| Igatpuri | Kashele GPB | 0.7102–0.7122 | 40 | 2.6–3.1 | 11.5 |
| | Igatpuri Phyric | 0.7107–0.7124 | 49 | 1.9–2.2 | 14.3 |
| Jawahar | Thal Ghat GPB | 0.7108 | 36 | 3.6 | 10.7 |
| | Jawahar | 0.7085–0.7128 | 38–59 | 1.3–3.0 | 10.8–13.0 |

MgO 3.5–1.7%, $TiO_2$ 1.3–3.3%, $P_2O_5$ 0.12–0.30% and CaO 7.47–12.5%. The recurrence of similar chemical types at multiple levels indicates the cyclic nature of eruptions in this formation which has the Manchar GPB at the top (Beane et al. 1986; Bodas et al. 1988; Khadri et al. 1988). The succeeding Lonavala Subgroup consists of Khandala and Bushe Formations and is characterised by Ba/Ti and Ba/Sr ratios and lower MgO content. Khandala Formation dominantly consists of simple flows and has a wide range of compositions, whereas Bushe Formation has coarse-grained, aphyric compound flows with narrow abundance range for most of the elements. It is characterised by conspicuously low $TiO_2$ content and the low concentration of some of the incompatible trace elements (Cox and Hawkesworth 1985).

The youngest Wai Subgroup is characterised by thick, easily traceable 'simple' flows. The flows belonging to it are more evolved, although the GPB horizons are lacking. The picritic basalts though rare in this Subgroup tend to occur at the base of the Formations. The lower Poladpur is distinguished from the Bushe Formation based on the sharp changes in $^{86}Sr/^{87}Sr$ (0.7053 to 0.7060 to ~0.716 respectively) and $TiO_2$ concentrations. The boundary between the Poladpur and Ambenali Formations is a chemically diffuse one, notionally placed at the point when the value of Ba becomes <100 ppm (Cox and Hawkesworth 1985), without any natural break. A similar gradational contact is defined between the Ambenali and Mahabaleshwar Formations, marked by enriched values of Sr, Ba, Nb, Rb and $K_2O$ in the latter as compared to the former in this scheme of classification of the Deccan Basalts.

The exposures around Mumbai (Bombay) with acidic differentiates and dykes (earlier classified as the Upper Traps) were designated as the Salsette Subgroup (Sethna 1999). They represent a distinctly younger phase of eruptive history and have chemical differences with the Western Ghats stratigraphic types (Sheth and Pande 2014; Sheth et al. 2014; Pande et al. 2017b).

This chemostratigraphic sequence relies on variations in the geochemical parameters plotted against stratigraphic heights of the sampled units in different sections (Devey and Lightfoot 1986). Only the initial Sr isotopic ratios display sharp breaks, while boundaries defined by other trace element criteria tend to be diffused or transitional (Mitchell and Widdowson 1991). Peng et al. (1994) opined that the isotopic data falling in or near the common signature region, where several Western Ghats arrays converge, reflects a large-scale open system—low crustal contamination process operating during their emplacement. Recognising the non-discriminant overlapping fields of compositional ranges, Mahoney et al. (2000) proposed multivariate statistical parameters to discriminate between the Formations. This was further refined by Sheth et al. (2004, 2014), Duraiswami et al. (2014) and Peng et al. (2014). Attempts to use the chemical signatures for correlating the dykes and flows from other parts of the DVP (Khadri et al. 1999a, b; Knight et al. 2003; Bondre et al. 2006; Jay and Widdowson 2008; Vanderkluysen et al. 2011; Shrivastava et al. 2014; Sheth et al. 2018) have met with limited success.

#### 8.3.5.2 Lithostratigraphy

Between 1998 and 2004, the GSI released a series of indexed maps named as the District Resources Maps (DRMs) for the entire country as a part of the celebrations of 125 years of its foundation. The parts of Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh and Karnataka where the Deccan Traps are exposed (cited as GSI 2001 in the ensuing pages) provide a view of the stratigraphic classification adopted by the Geological Survey of India. However, barring most of Maharashtra and Madhya Pradesh, the DRMs from other states do not provide the desired clarity on the stratigraphic classification of these basaltic flows. This classification (although largely documented in unpublished or abstracted annual reports of GSI) scores over the chemical classification because it is based on exhaustive field mapping as evidenced by the DRMs.

This classification is largely based on the physical characterisation of the flows into simple or compound types as proposed by Deshmukh (1988) with minor modifications and also provides the chemical characters of the formal stratigraphic units where identified (e.g.: Godbole et al. 1996; Solanki et al. 1996). In some regions formal 'Formations' were only tagged alphanumerically, without formal names (e.g. Yedekar et al. 1996; Deshmukh et al. 1996), leading to a degree of uncertainty regarding their equivalences across the province. This shortcoming was partly overcome in the compilations of the DRMs (GSI 2001). Besides following the standard stratigraphic codes in terms of nomenclature and classification, this lithostratigraphic classification acknowledges the inherent difficulties in extending Formations across the subprovinces in the DVP and proposes independent nomenclature for each of the subprovinces. Table 8.2 gives the subprovince-wise lithostratigraphy of the Deccan Traps defined by GSI (2001) and compares it with the chemostratigraphic classification elucidated in the Western DVP (shown in Fig. 8.13 and Table 8.1).

#### 8.3.5.3 Comparison

The zonal stratigraphy is more unambiguous than the chemostratigraphic classification that attempts to club the entire province into a single volcanic system. It relies on physical tracing of flow fields across large areas and establishing the order of superposition regionally across multiple sections. The plus point in this is that this scheme acknowledges the chemical types (as defined in the chemostratigraphy) but overcomes the ambiguous overlapping criteria by demonstrating the lateral continuity of the flow fields. The paleomagnetic signatures of the flow sequences and their ages (discussed below) also support this zonal classification of the Deccan Traps rather than a unified approach across the province. The GSI (2001) classification is consistent with four major subprovinces of the DVP (Fig. 8.8) each having an independent grouping of formations as listed in Table 8.2 and raises the entire province to a Supergroup status. Godbole et al. (1996), Deshmukh et al. (1996) and Vaidyanadhan and Ramakrishan (2008: p. 754–757) have discussed aspects of the comparability of the lithostratigraphic and chemostratigraphic classifications of the DVP. The general comparison between chemo- and lithostratigraphic classifications of the Western DVP are fairly valid, but they are definitely not mutually replicable, both in concept, extent and thickness. The Kalsubai and Khandala subgroups are consistent in contents in both these classifications. The Jawahar, Neral and Igatpuri Formations (chemostratigraphic) are clubbed into the Salher Formation (lithostratigraphic) with cycles of picritic–tholeiitic–plagioclase–phyric basalts (GPBs) having a lobate compound geometry but are limited to the north-western parts of the Western DVP.

The Ajanta and Karla Formations (≅Bushe), characterised by welded compound pāhoehoe lobes, are correlatable on the basis of their physical characters and their position over the Upper Ratangad Formation. Other equivalences between the western sequence and the other parts of the DVP are ambiguous. For example, the overall characters of the Indore Formation (from Malwa) and the Chikhali–Buldhana Formations (from Central DVP) have been shown to be comparable both in terms of physical vol-

**Table 8.2** Chemostratigraphic and lithostratigraphic classifications of the DVP. No equivalences between the two or between different subprovinces of the DVP is either indicated or suggested in this compilation, except some that are discussed in the text. Stratigraphy of the Saurashtra subprovince is not yet formally defined

| **Chemostratigraphy** (after Subbarao and Hooper, 1988) | | | **Lithostratigraphy** (modified after Godbole, et al, 1996; GSI 2001) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Western** (= W Deccan Plateau, Western Ghats & Konkan Coastal Belt) | | | **Central** (= E Deccan Plateau, Satpura, & Tapi Valleys) | | **Northern** (Malwa Plateau & N Narmada Valley) | | **Eastern** (Mandla Lobe) | |
| **Group** | **Subgroup** | **Formation** | **Group** | **Subgroup** | **Formation** | **Group** | **Formation** | **Group** | **Formation** | **Group** | **Formation** |
| **Deccan Traps** | | | **Sahyadri** | Bombay | Borivali<br>Elephanta | | | | | | |
| | Wai | Desur | | Mahabal-eshwar | Mahabaleshwar | **Satpura** | Karanja | **Malwa** | Singarchori | | |
| | | Panhala | | | | | | | Bargonda | | |
| | | Mahabaleshwar | | Diveghat | M4 (GPB)<br>Purandargad | | Buldana | | Indore | **Amarkantak** | Kuleru |
| | | Ambenali | | | | | | | | | Khamla / Khampla |
| | | Poladpur | | | Diveghat | | Chikhali | | Kankaria - Pirukheri | | |
| | Lonavala | Bushe | | Lonavala | Karla | | Ajanta | | Kalisindh | | Amarwara |
| | | Khandala | | | Indrayani | | | | Mandleshwar | | Multai |
| | Kalsubai | ------ GPB ------<br>Bhimashankar | | Kalsubai | M3 (GPB)<br>Upper Ratangarh | | Upper Ratangarh | | Gaganwara | | Linga<br>Pipardehi |
| | | ------ GPB ------<br>Thakurwadi | | | M2 (GPB)<br>Lower Ratangarh | | | | | | Dhuma<br>Mandla |
| | | ------ GPB ------<br>Neral | | | M1(GPB)<br>Salher | | | | | | |
| | | ------ GPB ------<br>Igatpuri | | | | | | | | | |
| | | ------ GPB ------<br>Jawhar | | | | | | | | | |
| Trappean Basement *(undifferentiated)* | | | | | | Cretaceous Lameta Formation & Bagh Group | | | | | |
| | | | | | | Gondwana Supergroup | | | | Gondwana Supergroup | |
| | | | Proterozoic Kaladgi Supergroup / Bhima Group | | | Mahakoshal Group | | Vindhyan Supergroup | | Mahakoshal, Sausar, Sakoli Groups | |
| | | | Archaean Basement Complex | | | | | | | | |

canological features as well as chemical parameters (see Deshmukh et al. 1996; Khadri et al. 1999b) with the Bushe–Poladpur–Ambenali chemical types. It is, however, relevant that while the latter sequence from Western DVP has a distinctly reverse paleomagnetic polarity, the Malwa sequence shows a normal polarity. Correlating them would therefore be untenable, since they were obviously erupted at different times and perhaps from differing sources as well (e.g. Peng et al. 1998; Ju et al. 2017).

The lithostratigraphic classification (GSI 2001) recognises multiple horizons of GPBs (also termed megaporphyritic basalts) as regional marker horizons that help subdivide the sequence. Their widespread occurrence and petrogenetic significance has been recognised (see Hooper et al. 1988; Higgins and Chandrasekharam 2007; Sheth 2016) since the early descriptions by Karmarkar et al. (1971). While three separate GPB horizons are recognised in the lowermost chemostratigraphic formations, Godbole et al. (1996) recognise only a single GPB horizon (named by them as M1) at the top of the Salher Formation. The horizon M2 (equivalent of the Manchar GBP) separates the Lower and Upper Ratangad Formations, while M3 occurs at the top of the latter. The GPB exposed in the Purandar Fort (Karmarkar et al. 1971) is recognised in the lithostratigraphy as M4 and has been mapped as a clear marker horizon at the top of the Purandargad Formation across a wide area of ~ 5000 km$^2$ in the Western DVP. It is significant that this horizon finds no mention in the chemostratigraphic literature, but is distinctly present throughout the southern parts of the Western DVP. Similar GPB horizons have been mapped from several lithostratigraphic formations in the Central and Malwa subprovinces and serve as excellent marker horizons during field mapping.

The chemical stratigraphy is based on chemical types that may occur at multiple levels during the eruptive sequence and has several overlapping compositional ranges that are not sharp enough to justify a robust correlation. The magnetic polarity and geochronological data bring out the additional complications in the models based on the chemostratigraphic correlations that tend to unite the DVP into a single volcanic province (Kale et al., 2019), but do not create a conflict in the zonal stratigraphy. The latter therefore appears more robust and consistent (Kale et al. 2019).

### 8.3.6 Magnetostratigraphy

Fe-oxides in free state and the undeformed nature of the basalts provided an ideal setting for paleomagnetic studies in the DVP that focused on determination of the paleolatitudes of the Indian subcontinent (Deutsch et al. 1959). Although Athavale (1970) had recorded only an R-N sequence along the Amarkantak–Dindori traverse, subsequent studies (Verma and Pullaiah 1971; Verma et al. 1973) suggested a more complex history for the Mandla lobe. Shrivastava et al. (2015) have identified no less than 5 normal flows interbedded with other flows of reverse or mixed polarity in the 37 flow sequence in the Mandla lobe. The proposed correlation of this sequence with the Western DVP sequence positioned in 29 R-29 N is not consistent with the age range of 63–66 Ma of these flows. The geochronology of these flows indicates that they perhaps are better correlated with chrons 27 R-28 N (see Fig. 8 in Pathak et al. 2017).

The Western DVP is characterised by an exceptionally continuous reverse polarity (Fig. 8.13), with a normal sequence occurring at its top, around Mahabaleshwar (Wensink 1973; Pal 1975; Courtillot et al. 1986; Khadri et al. 1988; Jay et al. 2009). This has been correlated with magnetic chrons 29R - 29N based on the available ages of this sequence and is the cornerstone of the linkage of the Deccan volcanism with the K-Pg Boundary that is placed within 29R (Renne et al. 2013). Hence the entire sequence of flows including the Kalsubai and Lonavala subgroups and the Poladpur and Ambenali Formations of Wai Subgroup can be considered one unit for chronological and magnetostratigraphic considerations, with well-constrained data. The Mahabaleshwar Formation belongs to the younger magnetic chron with a normal polarity (29N).

The relatively thin sequence in Kutch has a mixed polarity. Courtillot et al. (2000) measured an R-N-R paleomagnetic sequence for the middle part of the Anjar section that is iridium enriched (Bhandari et al. 1995, 1996; Bajpai and Prasad 2000). If the uppermost reverse polarity corresponds with 29R that hosts the K-Pg Boundary, the lower normal–reverse sequence may correspond with 30N - 30R. Central Deccan sequences were recorded with multiple (R-N-R-N) polarity chrons by Venkata Rao et al. (1996), which were later attributed to repetition of strata resulting from structural complexity or due to the possibility of mixed polarity being identified as a polarity chron. Subsequent studies suggested that the Narmada and Malwa sequence has only the N-R-N sequence, which was correlated with 30N - 29R - 29N (Dhandapani and Subbarao 1992; Khadri 2003; Chenet et al. 2009; Schöbel et al. 2014).

The contemporary paleolatitudes of the Indian subcontinent derived from geomagnetic studies unambiguously coincide with the location of the Reunion hotspot in the Indian Ocean. This is consistent with the growth history of the Indian Ocean floor as well as that of the northward flight of the Indian plate (see Fig. 8.20). The presence of not less than two and often three magnetic chrons, of which the middle reverse magnetic chron is sandwiched between flows with normal polarity, is unequivocal. What is contentious is whether the N-R-N polarity recorded in different sections can be correlated with each other across the province or not. The geochronological data does not support such integration.

### *8.3.7 Age and Duration*

Even the earliest texts on the DVP did not question its close association with the Cretaceous–Tertiary transition (Wadia 1975; Krishnan 1982), although more accurate information and robust data on the age and duration of this continental flood basalt province have emerged only in the last few decades. The earlier estimates of the duration assumed that such a large province would require 20 million years or more to be erupted across such a large area. Some estimates, that included the Rajmahal Traps as a part of the Deccan, suggested that the volcanism in this province occurred between about 80 Ma and 30 Ma (Kaneoka 1980; Alexander 1981).

#### 8.3.7.1 Paleontological Evidence

The Tertiary sequences resting on top of the basaltic flows (in Saurashtra, Cambay Graben, Bombay offshore shelf region) are informally termed as Supratrappeans. Some of the intertrappeans (Fig. 8.12), including the ones near Anjar and the Rajahmundry sequence (as sampled in 10 wells from the petroliferous Krishna–Godavari basin and in its exposed outcrops), are considered to host the K-Pg Boundary based on paleontological and geochemical (particularly iridium and mercury concentrations) data (Bajpai and Prasad 2000; Bhandari et al. 1996; Venkatesan et al. 1996; Prasad and Sahni 2014; Keller et al. 2011, 2012, 2016a; Kapur and Khosla 2018). This shows that the Deccan volcanism was closely associated in time with the K-Pg Boundary, and this large volcanic event had a role to play in creating an environmental crisis that led to the terminal Cretaceous mass extinction event (Self et al. 2008a; Richards et al. 2015; Renne et al. 2015). Punekar et al. (2014) and Font et al. (2016) argued that the early Danian (29 N) phase of Deccan volcanism was responsible for the delayed biotic recovery of marine planktons.

#### 8.3.7.2 Geochronology

Courtillot et al. (1986) and later Jaeger et al. (1989) argued for the Maastrichtian age (~73–69 Ma) of the Deccan Traps on the basis of shark fossils from the upper Lameta beds of Jabalpur and the paleontological data of the infratrappean, intertrappean and supratrappean sediments. Ar-Ar dating and the Normal–Reverse magnetic polarity of the Western Ghats succession were used by Courtillot et al. (1988), Duncan and Pyle (1988) and Hofmann et al. (2000) to suggest that the Deccan eruptions spanned a short duration of only about 1 million years straddling the K-Pg Boundary. Venkatesan et al. (1993) and Venkatesan and Pande (1996) advocated an extended duration of about 5–7 million years on the basis of Ar-Ar dates centred around 66 ± 3 Ma. Pande (2002) demonstrated that several earlier age determinations had differences in the monitor samples used in different laboratories and that recoil effects had not been factored into the computations. Widdowson et al. (2000) reported an age of 62.8 ± 0.2 Ma for dykes from Goa in the southern coastal part of the DVP. Although no direct ages of the basaltic flows from Saurashtra are available, Cucciniello et al. (2015) reported ages of 66.6 ± 0.3 Ma, 65.6 ± 0.2 Ma and 62.4 ± 0.3 Ma for three dykes intruded into them. This indicates that the flows should have erupted before the K-Pg Boundary. Sheth et al. (2001) reported Bombay trachytic Ar-Ar ages between 60 Ma and 61 Ma, while Sheth and Pande (2014) gave ages of 62.6 ± 0.6 Ma for rhyolites from Dongri, thereby providing additional evidence for a Late Danian (Paleocene) phase of late Deccan volcanism. This pulse of volcanism has been linked with the India–Seychelles breakup and evolution of the Laxmi ridge in the offshore region (Pande et al. 2017a, b). Samant et al. (2019) have shown that the tholeiites from the Elephanta Island belong to the older (66–65 Ma) pulse but have been intruded by dykes that are contemporaneous to the Bombay volcanics.

Renne et al. (2015), Schoene et al. (2015) and Parisio et al. (2016) suggest that the Deccan lavas were emplaced in not less than two pulses. The first pulse straddles the K-Pg Boundary and was erupted during the magnetic chron 29R between 67.5 Ma and 65.8 Ma, while the second (which had larger volumes, represented by the Wai Subgroup, emplaced in quicker succession according to Richards et al. 2015) is of Danian age covering the transition between the chrons 29R and 29N. This has been reaffirmed by subsequent precision dating by Schoene et al. (2019) and Sprain et al. (2019). Schöbel et al. (2014) interpreted that the Malwa flows erupted dominantly during chron 30N on the basis of the $^{40}$Ar-$^{39}$Ar age of 67.12 ± 0.44 Ma. The age of flows from the Mandla Traps and the dykes from the Malwa region (Bhattacharjee et al. 1996; Pathak et al. 2017; Shrivastava et al. 2017) suggests that the volcanism straddled the K-Pg Boundary. The ages from the KCB (around Mumbai and Goa) suggest that a third, late phase of activity (around 62 Ma) may have included several intrusives and late magmatic differentiates exposed in the westernmost part of the DVP.

#### 8.3.7.3 Synthesis

A critical analysis of the available age data from the DVP (Kale et al. 2019) is summarised based on recomputed $^{40}$Ar–$^{39}$Ar ages in Fig. 8.14. This shows that the lava flows in Kutch (Saurashtra), Malwa and the lower flows in the Western and subprovinces have Maastrichtian ages (68–66 Ma) older than the K-Pg Boundary (Fig. 8.14b). However, the upper flows (notably in the Western Ghats sequences: Fig. 8.14a) in these subprovinces are younger by 3–4 million years. Although no unconformity or recognisable gap is observed within the lava sequences, their magnetic orientations are distinctly different, further validating the difference in their ages. The intrusive dykes from the Malwa Subprovince (Narmada valley) have ages of 66 Ma–64 Ma (Ju et al. 2017) suggesting that the last phase of igneous activity in these parts continued beyond the K-Pg Boundary.

The Mandla Subprovince (Amarkantak Group), with a N-R-N sequence (Fig. 8.14d), is in all likelihood a post-K-Pg sequence, and the correlation with the R-N sequence in the Western DVP is not justified, as was also argued by Pathak et al. (2017). This probably also explains why the chemostratigraphic comparison of the sequence in the Mandla lobe yields untenable combinations of younger (? Mahabaleshwar chemical type) flows occurring at lower levels or between older (Poladpur and Bushe type) flows (Shrivastava et al. 2014). Shrivastava et al. (2017) proposed that terminal igneous activity in the Mandla Subprovince may have extended up to ~56 Ma based on the Ar-Ar dating of a dyke. However, the plateau age and the isochron age determined for the sample (Fig. 8.5- *op cit*) differ more than the acceptable limits in this technique.

This review of the chronological data shows that a large volume of Deccan lava was erupted in the Maastrichtian (prior to the K-Pg) and may have contributed to the environmental crisis leading to mass extinctions (e.g. Sahni and Bajpai 1988; Self et al. 2008a; Keller et al. 2012). An equal (or perhaps larger according to Renne et al.

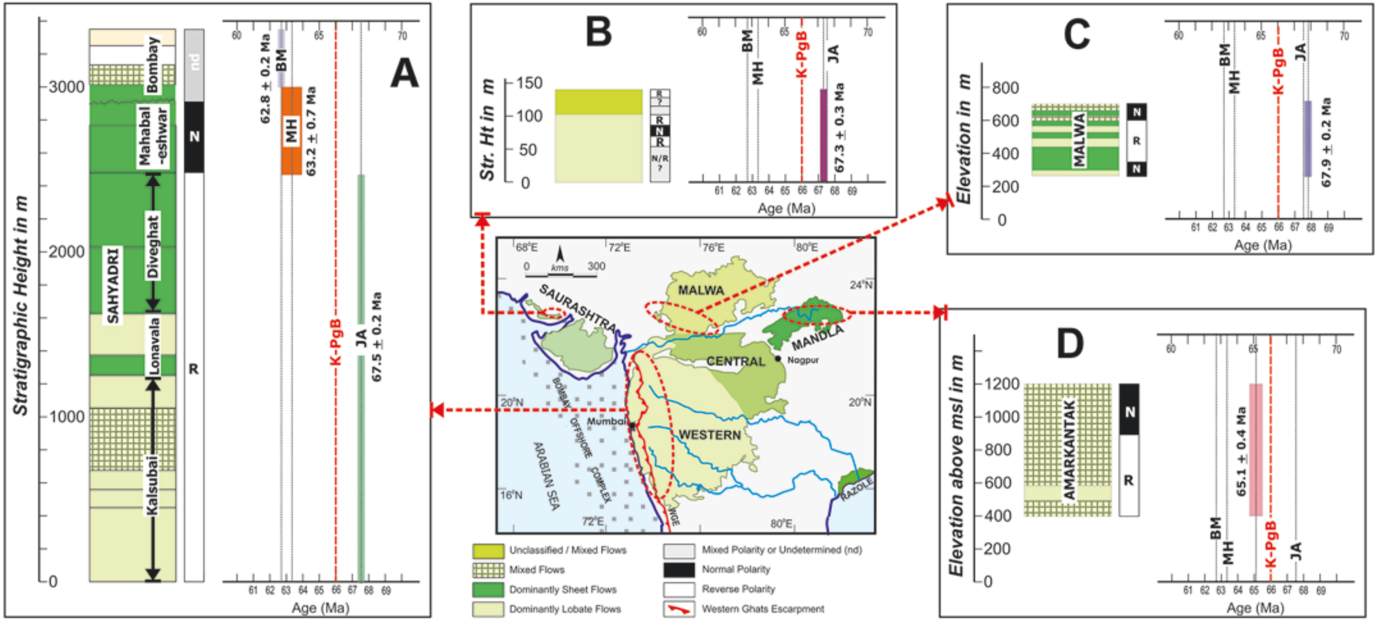


**Fig. 8.14** Compilation of weighted mean of recomputed $^{40}Ar$-$^{39}Ar$ ages for the Western and Central DVP (**a**), Saurashtra (**b**), Malwa (**c**) and Mandla (**d**) subprovinces (after Kale et al. in prep.) plotted against the respective lithostratigraphic columns. The red ellipses superimposed on the subprovinces map of the DVP mark the approximate sampling areas in each of the subprovinces. The lithostratigraphic columns depict the major flow types present in the constituent Formations of the Groups (Table 8.2) of respective subprovinces. The paleomagnetic polarity of the respective columns determined by various authors (as discussed in the text) is given for reference. Note that the Saurashtra Subprovince column is plotted against an expanded vertical scale since the sequence is relatively very thin. For the Malwa and Mandla subprovinces, the columns are plotted against the mean sea level elevations, while for the other two the stratigraphic heights are plotted. Note that three pulses (JA, representing the Jawahar to Ambenali reverse polarised sequence; MH, representing the normal polarised Mahabaleshwar sequence; and BM, representing the Bombay and western coastal volcanics, volcaniclastics and intrusives) at 67.5 ± 0.2 Ma, 63.2 ± 0.7 Ma and 62.8 ± 0.2 Ma, respectively, emerge from the weighted mean ages for the Western DVP. They are replicated along with the K-Pg Boundary (at 66 Ma: Gradstein et al. 2012; Renne et al. 2013) for reference in the other subprovinces. The weighted mean ages for the Saurashtra and Malwa subprovinces precede the K-Pg Boundary, but the Mandla Subprovince is distinctly younger and has a different age altogether

2015; Sprain et al. 2019) volume of lava in this province was erupted in the Danian. This may have retarded the biotic recovery during the Paleocene times across the world (Punekar et al. 2014; Font et al. 2016; Schoene et al. 2019). The last phase of volcanism in the Deccan was significantly younger than 64 Ma and included significantly larger portions of acidic differentiates, alkaline magmas (yielding the lamprophyres and ultra-alkaline intrusives) and other contaminated crustal melts that were emplaced only in the western edge of the DVP and along the SONATA zone.

The lop-sided concentrations of geochronology from only a few sections (mostly located along the Western Ghats) with sparse comparably accurate data from the other parts of the DVP, uncertainties regarding (a) the correlations based on chemical parameters, (b) magnetic polarity groupings and (c) lateral continuity of flows (Kale et al. 1992, 2017, 2019) are major arguments that stand against a unification of the entire province into a singular volcanic system. Several authors (Lightfoot et al. 1990; Deshmukh et al. 1996: p. 14; Jay et al. 2009; Peng et al. 2014) have time and again cautioned against long-distance correlations of flows based on chemical criteria alone. The structural discontinuities that cut across the province (Fig. 8.9) and the differences in their basement constitution endorse the fact that the different subprovinces of the DVP had temporally differing eruptive histories.

### *8.3.8 Eruptive Models*

The last few decades have produced a large volume of data on the DVP (see edited volumes: Subbarao and Sukheswala 1981; Subbarao 1988, 1999; Deshmukh and Nair 1996) that has been largely adding to its chemical characterisation, magnetic properties and geochronology. The physical volcanological aspects of this province received relatively lesser attention as did its structural configuration. These aspects have an important bearing on the eruptive style and history of the province. Although earlier workers proposed that the Deccan basalts represent fissure-type eruptions, modern studies tend to support a central shield-type volcano model akin to the Hawaiian model.

Using the latter model, two configurations (Fig. 8.15) of the eruptive sequence and the development of the Deccan Plateau emerged in the ensuing period (Watts and Cox 1989; Mitchell and Widdowson 1991). Both essentially justify the southward and eastward overstepping and stacking of successive chemostratigraphic formations from a primary eruptive edifice located northeast of Mumbai in the Nasik-Igatpuri sector. The overstepping of successive formations (both litho- and chemostratigraphic) towards the south is validated in Western DVP since the younger formations (Diveghat–Mahabaleshwar Subgroups ≅Wai Subgroup) rest directly upon the Precambrian basement all along the southern fringe of the DVP. The absence of the older formations in this sector south of Pune has also been reconfirmed by the drilling near Koyna (Gupta et al. 2017). The absence of oldest Formations in the Central DVP and along the south-eastern margin of the province around Gulbarga and Bidar (see Bilgrami 1999; GSI 2001–DRMs of Buldhana, Latur and Nanded districts; Jay and Widdowson 2008) also appears to bear out the

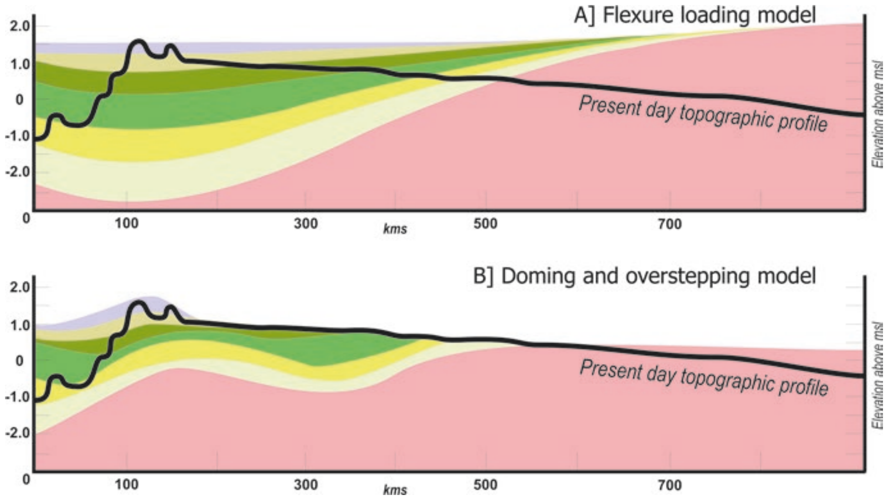


**Fig. 8.15** Inferred stratigraphic E-W cross sections across the DVP for two alternative models of the eruptive configuration and resulting distribution of the chemostratigraphic units. Model A (after Watts and Cox 1989) invokes the loading of the crustal segment and its consequential (down-)flexuring along the western coast, creating a stack of the lavas. Model B (after Mitchell and Widdowson 1991) assumes that the crust dome upwards above the upwelling magma chamber and the formations successively overstepped older flows both southwards and eastwards, resulting in the (Panvel) monoclinal flexure along the western coastal region but an antiformal structure that plunges southeastwards across rest of the province

overstepping model. The central edifice model (monocentric eruptive history) is also argued in absence of widespread occurrences of feeder-dykes across much of the province (e.g. Vanderkluysen et al. 2011), and the restrictive exposures of intrusive dykes only in the lower flows exposed along the western coastal tracts and in the eroded valleys of Narmada and Tapi rivers (Fig. 8.6b).

This monocentric shield volcano model of the eruptive history does not give sufficient weightage to the undulating nature of the Trap–Basement contact as well as the sub-trappean heterogeneities of the crustal blocks. The recognition of subprovinces (with their own stratigraphy) that may be linked together by a common magma source has the capacity to address these issues more logically. The chemical variations are essentially the result of variations induced in the magmatic composition due to crustal contaminations and differentiation as it is transmitted from its primary chamber upwards before erupting on the surface.

Modelling the Deccan eruptive history also benefits largely from emerging new research on physical volcanological aspects of compound pāhoehoe flow fields (Guest et al. 2012; Sehlke et al. 2014; Maeino et al. 2016), the nature and controls on inflation mechanisms (Katterhorn and Schaefer 2008; Deschamps et al. 2014) and how effusion rates control the geometry and nature of the flow field developed (Keszthelyi and Denlinger 1996; Gregg and Keszthelyi 2004; Harris et al. 2007) amongst other studies and reports from this province itself (e.g. Bondre et al. 2000; Duraiswami et al. 2003, 2004, 2008, 2014; Sen 2017). The recognition of the facies architecture of basaltic flow fields in flood basalt provinces around the world (Waichel et al. 2012; Barreto et al. 2014; Òskarsson and Riishuus 2014; Single and Jerram 2014; Bernardi et al. 2015; Marshall et al. 2016) has several parallels in the DVP but still await documentation. Against this background, the modelling of the Deccan volcanism on lines of the continental fissure-type eruptions (as had been the earlier postulation) has several supporting arguments. The recent work on active volcanic fields in Iceland (Eibl et al. 2017) provides a working hypothesis for explaining the eruptive style and spread of the Deccan flood basalts.

This is conceptualised in Fig. 8.16 where the magma is initially emplaced at shallow crustal levels as a sheet-dyke along a fracture, following the path of least resis-

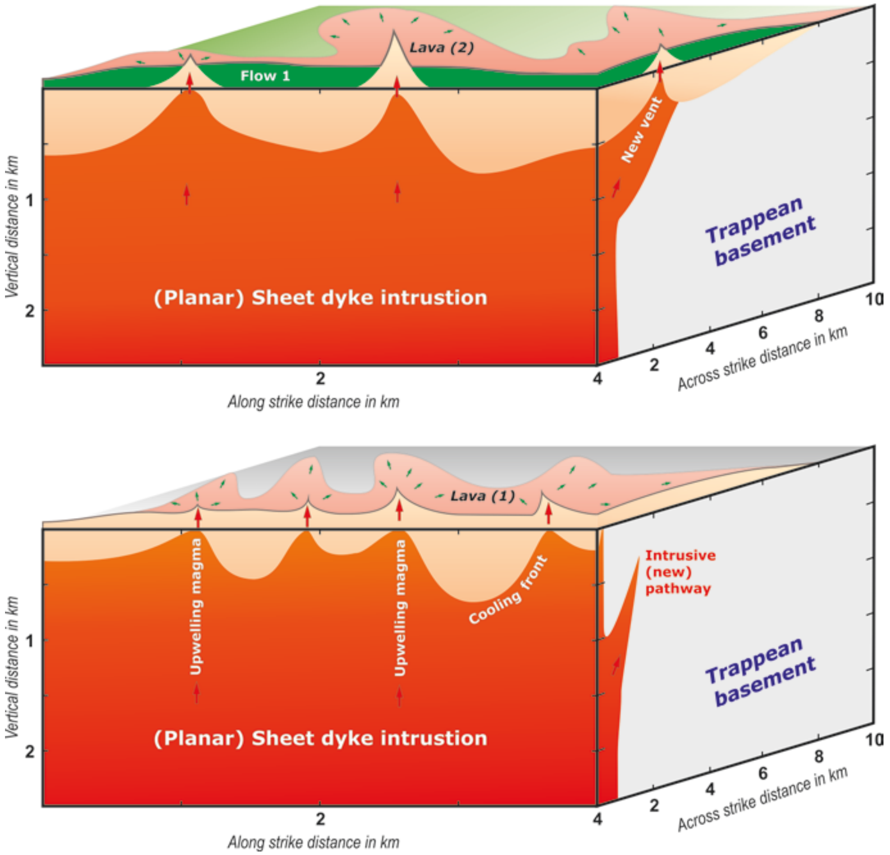


**Fig. 8.16** Model of upward emplacement of magma at shallow crustal levels (modified after Eibl et al. 2017: Fig. 8) and emplacement of successive flows that may explain the mode of eruptive emplacement of the Deccan flood basalts. The surface emplacement of the lava occurs through a series of vents from which the lava flows out as lobes on the surface (lower sketch). With the initial venting (yielding Flow 1), the cooling front moves to deeper levels, and some of the vents may shut down, while others remain open during the succeeding emplacement. Also, with additional influx of magma, new vents may open up sideways at horizontal distance away from the axis of the 'feeder' dyke, at the time of emplacement of the succeeding flow(s) as shown in the upper sketch

tance. The shallow crustal fissure may have been created due to the upward pressure of the magma or (equally probably) be a pre-existing fracture/shear in the basement that was reopened and became a channel for the upwelling magma. This mode of magma emplacement and dispersal through the upper continental crust was also hypothesised for Late Cretaceous basic intrusives in parts of the Central Indian Shield (Lala et al. 2011; Chalapathi Rao et al. 2014). The examples of dykes occupying ancient fault planes in the basement rocks (Peshwa et al. 1987) bear out the postulation that such pre-existing planar openings in the basement of the Deccan Traps provided inherent channels for the upward movement of the magma at shallow crustal levels.

As shown in Fig. 8.16, venting points for the lavas may be initially aligned parallel to the main 'feeder' dyke (somewhat akin to the Laki volcanic field in Iceland) but eventually may shift away from its axis. This progressive shifting will be primarily determined by the net push and volume of upwelling magma, extrusion volumetric rates and the rheological resistance of the pre-trappean crustal segments through which it is venting, besides the nature of the pre-existing structural discontinuities in the crustal segments. Intrusive relation of the feeder channels cutting through the earlier flows during emplacement of the younger flows will show up as intrusive dykes (see Fig. 8.6), while the main 'feeder channel' remains concealed below the surface. This may explain why it becomes difficult to trace the 'feeder' dykes (as noted by Sheth 2000; Ray et al. 2007; Vanderkluysen et al. 2011). With the initial venting, the cooling front moves to deeper levels, and some of the vents may shut down, while others remain open during the succeeding emplacement. Also, with additional influx of magma, new vents may open up sideways at horizontal distance away from the axis of the 'feeder' dyke, at the time of emplacement of the succeeding flow(s) as shown in the upper sketch of Fig. 8.16.

This model assumes that the on-surface discharge of the lava occurs through a series of vents from which the lava flows out as lobes on the surface (Fig. 8.16). This explains why several features (such as lava channels and volcanic cones and breccias (e.g. Sharma and Vadadi 1996; Duraiswami et al. 2004) akin to central cone-type eruption are prolific in the Deccan. Once emplaced on the surface, the lava geometry and dispersal is determined by volumetric rate of effusion. The lava spreads in the available area and starts to cool. Endogenous transfer of hot lava encased within a rapidly chilled crust enables an efficient way of lateral spreading across significant distances as depicted in the cartoon (Fig. 8.17). This model also demonstrates how different morphological types recorded in the DVP (Fig. 8.9) may develop in different stages of pulsed emplacement of the lava (as marked in Fig. 8.17). It validates the suggestion (Kale 2016) that the morphological types can be attributed to a continuous variation series between the two endmember types names the lobate ('type-A') and sheet ('type-B') morphologies. The morphologies observed are not different types of lava, but reflect the form achieved by the same lava in progressive stages of its lateral spreading.

This model of progressive growth in a pulsed emplacement provides a logical explanation of how long sheet flows ('type-B' discussed above) would efficiently spread across long distances with each pulse pushing the aerial extent occupied by the flow further and further while replicating the process with each new batch of

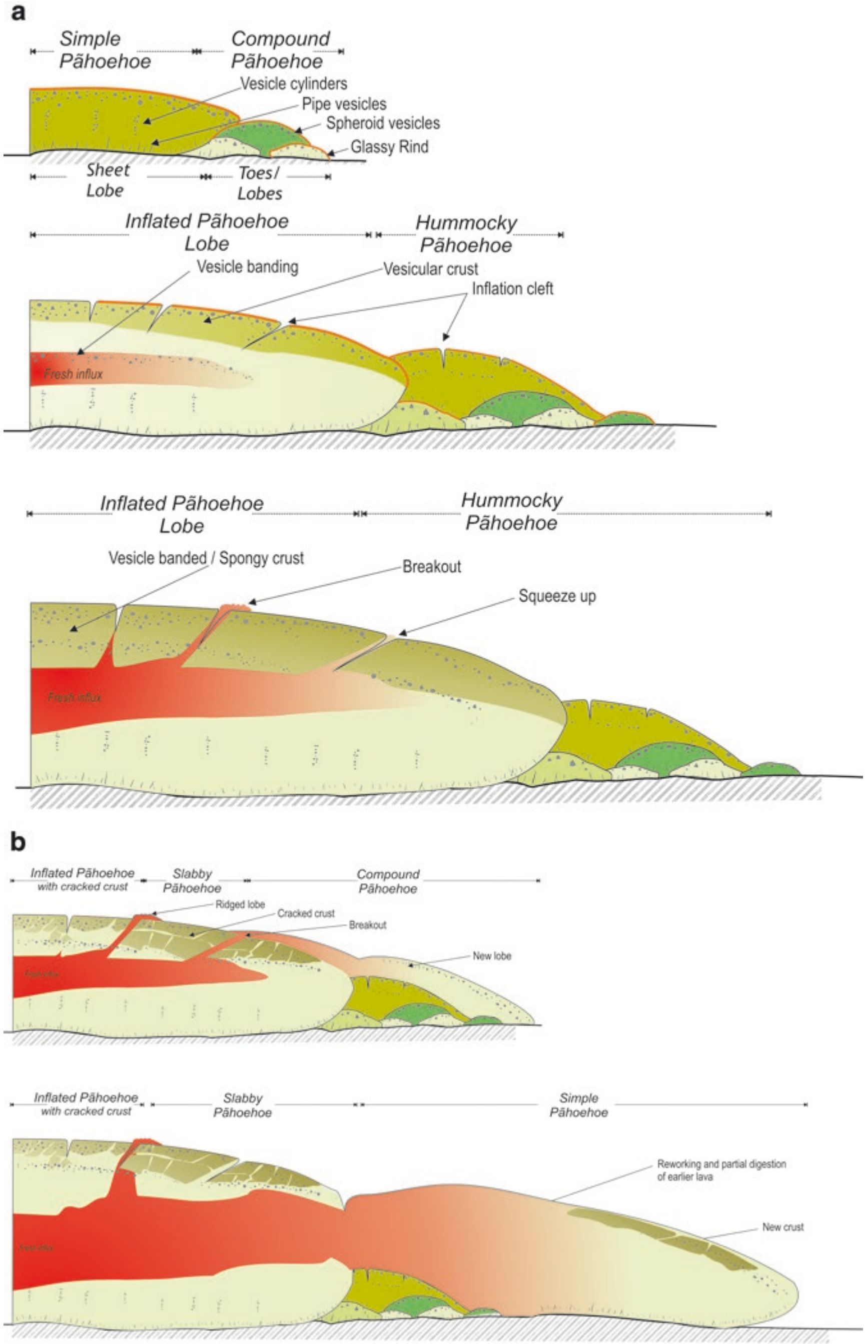


**Fig. 8.17** (**a**) Model of progressive spread and growth of lava once emplaced on the surface (integrating models of Thordarson and Self 1998; Duraiswami et al. 2014)—early phase. The red part represents hot unconsolidated lava, while the green parts represent crystallised/consolidated lava.

emplacement. Such rapid successive emplacement of lava batches is within the estimated rate of effusion predicted for the Deccan lavas from various studies cited above. In addition, this model explains the lateral transition of morphological types that are encountered in the Deccan Traps as discussed in the section on flow types. The smaller lobate flow units (type-A) would remain concentrated close to the vents of the lava, while the lava that has travelled farther away from the vent is more likely to display the sheet (type-B) geometry.

The combination of the upward transmission of magma along sheet dykes (Fig. 8.16) and the emplacement and endogenous lateral transfer of lava on the surface (Fig. 8.17) can explain most of the observed features in the Deccan lavas. The main centres of magma upwelling are postulated to be located along the Narmada–Tapti valleys and the KCB where the sheet dykes are profusely exposed in the lower flows. It may be pointed out that several studies in the Central, Malwa and Mandla subprovinces of the DVP (e.g.: (Deshmukh et al. 1996; Srinivasan et al. 1998; Khadri et al. 1999a; Chandrasekharam et al. 1999; Ju et al. 2017) have suggested that multiple eruptive foci may have been active across the DVP rather than the monocentric history propounded by the geochemical stratigraphic models.

While the source of the magma may have been common, its transfer to the surface along different trajectories would create minor (but significant and detectable) variations in its composition. The duration of the transfer would vary from one eruptive zone to another, as would the replenishment history. This has the capacity to explain why geochemically similar lava packets occur in dissimilar orders of superposition in different parts of the DVP (e.g. Shrivastava et al. 2014—Mandla lobe), since they erupted at different times, with differing transit periods through the underlying continental crust which was compositionally unlike the other subprovinces. This is a working hypothesis based on an understanding evolved from recent volcanological research in the Deccan and other continental flood basalt provinces across the world (cited above) but needs to be tested and refined in the days to come.

◄

**Fig. 8.17** (continued) Note that different types of flows are developed by the same process of progressive, pulsed endogenous transfer of lava. The early formed lobes (shown at the top) remain close to the vent of the lava. Inflation due to fresh influx within the core and development of breakouts/squeeze-ups is depicted in the lower sketch. **(b):** Model of progressive spread and growth of lava once emplaced on the surface—growth and enlargement phase. Other symbols and features same as in Fig. 8.17a. With the fresh batch of lava, the initial formed inflated crust may crack-up if the force of emplacement is significant, producing the slabby pāhoehoe sheets. The earlier breakup may provide an easy channel from which the lava starts overstepping the earlier lobes and spreads further. When the volume emplaced in the second batch is small, it may only form another set of overlying lobes (as in the upper sketch). When the volume is large, it will break through the crust and spread farther (carrying rafts of the brecciated crust along with it) resulting in the widespread sheet flows (type-B) with a significantly thick flow-top breccia. Such (erstwhile 'simple') flows are prolific in the vast expanse of the DVP (Fig. 8.11) . The key in this model is the fact that most of the lava types observed in the Deccan can be explained by this process of endogenous, sequential emplacement in batches (as has also been modelled by Thordarson and Self 1998; Gregg and Keszthelyi 2004; Katterhorn and Schaefer 2008). Note that the vertical and horizontal scale used in this fig (a & b) is the same

## 8.4 Relevance/Significance

### *8.4.1 Tectonics*

The Cretaceous volcanism in the Indian plate has several other representatives besides the RBS and Deccan provinces. Those located along the northern edge of the plate, like the Dras volcanics and its equivalents, are an integral part of the Tethyan sequences (Jain et al. 2003; Valdiya 2016) that suffered intense deformation, thrusting and metamorphism during the evolution of the Himalayan belt resulting from the Indo-Tibet collision. These tholeiitic rocks dated at around 104 Ma are considered to be part of the oceanic basalts from the Tethyan Ocean on the north of the Indian plate that are now obducted as ophiolites in the Himalayan belt.

Cretaceous tholeiitic basalts are also known from the Lakhra and Jalore areas of the Sindh basin (on the north-western part of the Indian subcontinent) but detected only during the drilling, where they occur at depths of more than 700 m below the surface. Lower Cretaceous volcanics encountered during drilling through younger sequences recorded in the RBS Province on the eastern part of the subcontinent have also been recorded from the Mahanadi offshore basin at depths exceeding 4000 m. Below the Arabian Sea, besides the Bombay High basin, Cretaceous volcanics have been recorded in the Kerala–Lakshadweep basin (offshore the south-western coast of India and the Mannar basin (between India and Sri Lanka). The acidic volcanics of St Mary’s Island (offshore Karnataka), dykes in Goa and several basic and alkaline intrusives in different Gondwana basins in central and eastern India have been dated to be of Cretaceous age (see Krishnamurthy 2008; Chalapathi Rao et al. 2014 and citations therein). The distribution of the ages of these different horizons and the ages of various segments of the oceanic basaltic systems in the Arabian Sea, Bay of Bengal and Indian Ocean provide direct evidence of the northward drift of the Indian plate from southern latitudes during the Early Cretaceous times. The Permo-Carboniferous rifting on the various Gondwana segments represent the onset of the extensional tectonics that eventually led to the breakup of this Paleozoic supercontinent. The breakup of the Indian plate from Eastern Gondwana assembly is postulated to have occurred during the Early Cretaceous times leading to the opening of the eastern Indian ocean. The Jurassic dykes in the Gondwana basins and RBS Province (Fig. 8.18) in eastern India represents the early continental volcanic activity that was succeeded by the rift-to-drift transition and opening of the Indian Ocean.

The ages of the ocean floor basalts and other igneous rocks across the Indian Ocean (validated by various ODP studies across the years) as depicted in Fig. 8.19 bring out the relationship between the Kerguelen and Reunion hotspots and the RBS and Deccan provinces, respectively. They are the products of the passage of the Indian plate over the hotspots in the Early and Late Cretaceous times, respectively (Duncan 1991; Sheth 2000; Krishnamurthy 2008; and citations therein). The paleomagnetic pole positions determined for the Indian plate at around 100 Ma and 66 Ma also place it above these hotspots at those times.

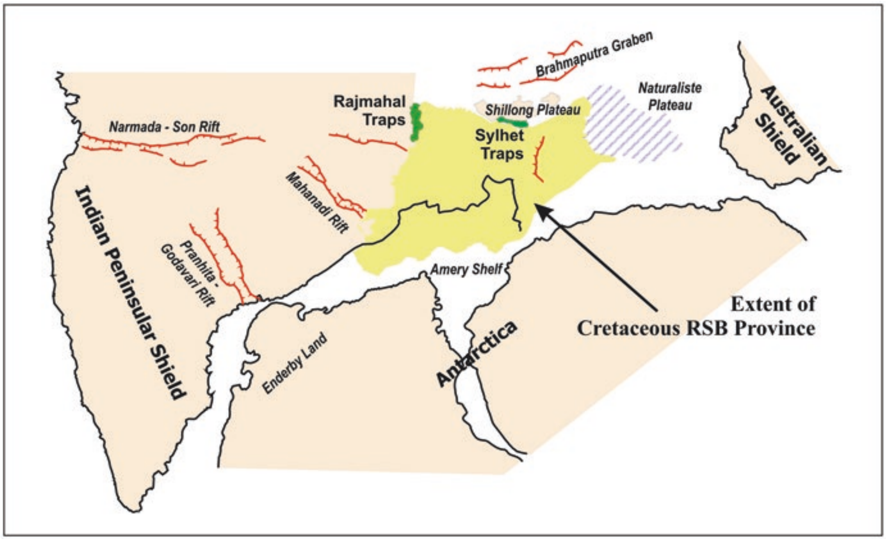


**Fig. 8.18** Reconstruction of Eastern Gondwana during the Early Cretaceous time, showing the various active rifts and the postulated extent of the RSB Province (after Kent 1991) shown in light green. The present exposures of the Sylhet and Rajmahal Traps (shown in dark green) represent only a small fraction of this province

Cox and Hawkesworth (1985) had used the northward passage of the Indian plate over the Reunion hotspot in support of their model of southward younging and overstepping of the chemical formations. Notwithstanding the arguments against the validity of the chemostratigraphic correlations, the fact remains that both these observations have been validated when traced along the Western Ghats Escarpment. In conjunction with the younger volcanics encountered further southwards and along the aseismic Lakshadweep–Chagos ridge, this appears to reiterate the linkage of the Deccan flood basalts with the Reunion hotspot postulated earlier (Duncan and Pyle 1988; Richards et al. 1989).

It is obvious that both the RBS and Deccan are flood basalt provinces closely linked with the breakup and separation of various segments of the Gondwana Supercontinent, initiated by mantle upwelling (? along discrete hotspots), continental rifting and development of spreading ocean floor basalts (Morgan 1981; Storey 1995). Available data appears to indicate that the RBS was related to the fragmentation of the Gondwanaland Supercontinent into eastern and western units during Early Cretaceous times, while the Deccan is connected to the rifting and drifting of India–Madagascar–Seychelles segments during the Late Cretaceous times that continued in the Paleogene period. It is likely that the RBS volcanism that marks the breakup of the Indian block from Australia–Antarctica (Kent 1991) also coincided with its separation (with Madagascar–Seychelles) from the African block around 120 Ma. The separation of Madagascar from India occurred around 88 Ma (Storey et al. 1995) leading to the rapid northward drift of the Indian subcontinent in the

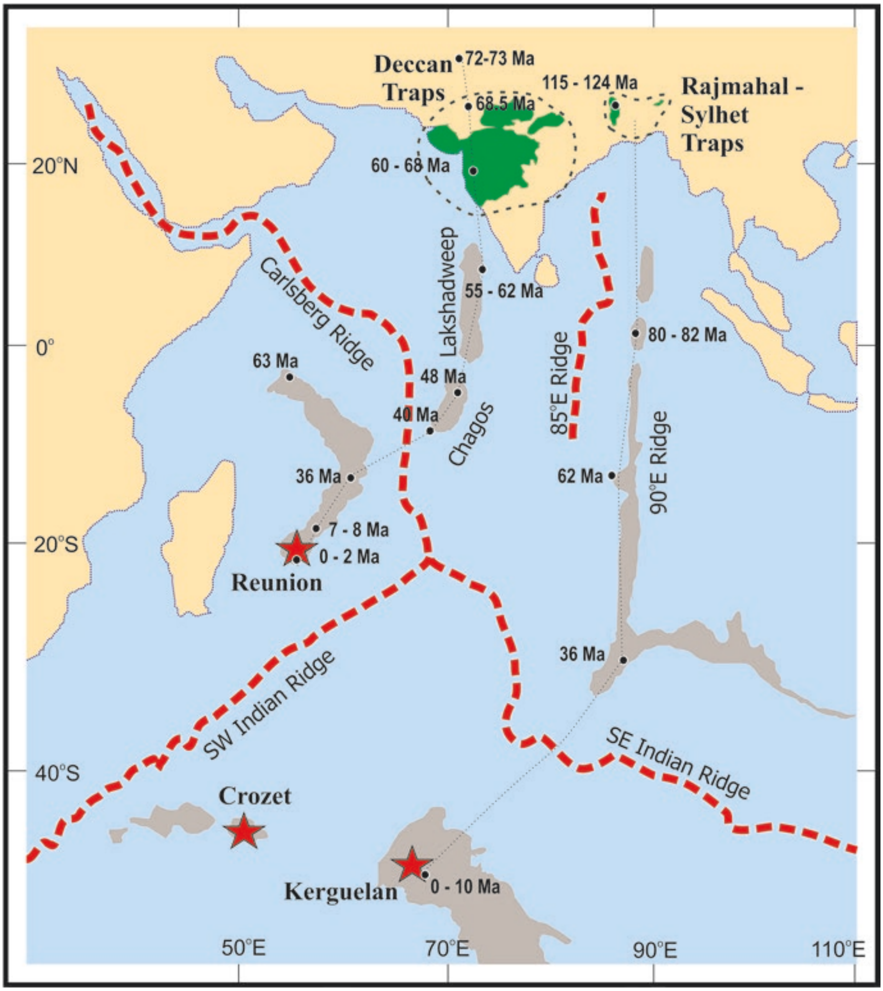


**Fig. 8.19** Ages of different segments of the Indian Ocean and its present day geometric configuration (modified after Duncan 1991 with updates from various authors discussed/cited in the text; Sheth 2000) and references cited in the text. The cream coloured areas are the landmasses surrounding this part of the Indian Ocean, while the grey shaded areas represent seamounts and small island chains in the Indian Ocean. The hotspots in the Indian Ocean are shown with red stars, while the spreading ridges in the Indian Ocean are shown with red dashed lines. The thin dotted lines denote the approximate tracks between the flood basalt provinces and their root hotspots

ensuing period. This was interrupted by the Indo-Seychelles breakup that occurred around the K-Pg Boundary (Nemčok and Rybar 2017) and coincides with the Deccan flood basalts. One may speculate that the SONATA zone and the Cambay Zone (see Fig. 8.8) suffered a degree of subsidence and faulting but failed to rift sufficiently to enable fragmentation of the continental crust. These zones did however provide channels for the magma (along with the rifted western edge of the Indian plate) to be emplaced as the Deccan flood basalts.

### *8.4.2 Environmental*

The age of the Deccan Traps makes it a prime candidate for linking it with the dramatic extinction of the dinosaurs and other fauna at the end of the Cretaceous. Several studies (see Sastry and Lahiri 1981; Courtillot et al. 1986; Duncan and Pyle 1988; Sahni and Bajpai 1988; Mahobey and Udhoji 1996; Keller et al. 2009, 2012, 2016b) have established this connection. Self et al. (2008a) provided a model for the volume of toxic gases that may have been released from DVP during its eruptive phase.

Mass extinctions have been attributed to such environmental crisis resulting from emanations of large igneous provinces or to extraterrestrial impacts. The Chicxulub crater is considered one of the prime candidates for the K-Pg extinction event in this context (Alvarez et al. 1980). Recently, Richards et al. (2015) attempted to link the Deccan basalts and the Chicxulub impact hypothesis in the context of the K-Pg extinction event. Anomalous iridium (Ir) concentrations at the K-Pg Boundary recorded across the world have been considered as the primary evidence for the extraterrestrial hypothesis of mass extinction since Ir is not normally present in terrestrial sources. Recent observations of mercury (Hg) concentration (see Font et al. 2016 and citations therein) in the K-Pg Boundary sequences across the world have been interpreted to be of volcanogenic origin.

The geochronological data (see Sect. 3.6) of the Deccan opens up certain questions that remain unanswered. There is no doubt that a larger volume of the Deccan lavas were erupted prior to the K-Pg Boundary (between 68 Ma and 66 Ma). However, equally sizeable volumes of lava were erupted in the DVP after the K-Pg Boundary (between 65 Ma and 62 Ma). What was their impact on the biosphere and the environmental toxicity remains to be appropriately answered.

### *8.4.3 Post-Eruptive Events*

The spectacular view of subhorizontal stacks of basaltic flows extending tens of kilometres in the Western Ghats Escarpment and other plateau edges of the DVP is largely responsible for the general opinion of their being structurally ‘undisturbed’ following their eruption. The landscape of wide plateaux stretching across hundreds of km with low gradients and flat tablelands (often capped by Tertiary laterites or with lateritic soil) and intervening hills with a steplike topographic profile add to this perception. The DVP (covering the wide Deccan, Malwa and Mandla plateaux) as a part of the southern Peninsular block has been largely considered a stable continent interior as a result. The subsidence of the shelf of the Arabian Sea (Bombay offshore complex: Fig. 8.8) and in the Bay of Bengal and Tertiary tectonics along Cambay rift and Kutch region enabled deposition of younger sediments above the Cretaceous volcanics (Kent 1991; Mehr 1995; Saunders et al. 2007; Biswas 2008; Ghatak and Basu 2011; Bastia et al. 2010). The post-trappean activity along the SONATA (that hosts the anomalous west-flowing Narmada and Tapi rivers) and

KLZ is manifested in the form of thick fault-controlled Quaternary alluvial deposits that occur along the middle reaches of rivers that subsequently flow over bedrock channels (Tiwari 1999; Tiwari, et al. 2001a, b; Kale et al. 2017).

Whether the Deccan Plateau (as a part of the Peninsular block) represents a rift-margin, or is its uplift related to the volcanism and doming of the crust due to mantle upwelling, or is the uplift related to the Himalayan orogeny of Tertiary–Quaternary times has been debated upon for long (e.g. Auden 1954; Kailasam 1979; Ahmad and Ahmad 1980; Watts and Cox 1989; Widdowson and Cox 1996; Sheth 2007). Its post-volcanic history is best studied through geomorphic analysis. The contributions to the geomorphological evolution of the Western Ghats Escarpment, Konkan Coastal Belt and the Deccan Plateau compiled by Gunnell and Radhakrishna (2001) provide a glimpse of the large volume of work that has gone into it.

The Davisian model of landscape evolution provided the framework for these geomorphic studies that documented ‘planation’ surfaces across the Indian Peninsula (Dikshit 1970; Vaidyanadhan 1977, 1987), with a rider that in the DVP, planation surfaces can be confused with the gentler slopes that evolve on successive flow-tops as a result of the steplike weathering pattern of the Traps (Subramanyan 1981). Figure 8.20 depicts a generalised overview of the erosional topographic development in the Deccan Traps. These studies tend to attribute the asymmetric drainage and peneplanation across Peninsular India to climate and eustatic sea level changes and epirogenic uplift (see Vaidyanadhan and Ramakrishan 2008: p. 934–951).

The occurrence of Tertiary laterites at various levels across the province (e.g. Widdowson and Cox 1996), the geometry and nature of the river profiles (e.g. Kale 2003) and the morphometric indices (e.g. Harbor and Gunnell 2007; Kale and Shejwalkar 2008) provided evidence to the fact that antecedent drainage systems have been modified during Quaternary times under the influence of climate change and bedrock structures in successive denudational cycles.

Evidence of neotectonic activity from different parts of the DVP (see Chamyal et al. 2002; Dole et al. 2000, 2002) and recognition of blocks whose boundaries are marked by geophysical anomalies that have suffered uneven uplift in Quaternary times (Kale et al. 2017) foster doubts regarding the traditionally assumed tectonic stability of the Deccan Plateau. They show that the present landscape of the DVP has been sculpted by an antecedent drainage that was modified during Quaternary times by not only climatic and eustatic changes but also have been subjected to deviations due to uplift and tectonic movements between crustal blocks at different times. Whether the driving forces for the recent tectonic events are (a) far-field stresses transmitted from the Himalayan orogeny; or (b) derivative forces due to continued expansion of the Indian Ocean floor; or (c) isostatic rebalancing of the Indian plate consequential to the erosional cycle; or (d) a tectonothermal stress regime resulting from a combination of all of them remains a matter of conjecture. A detailed morphometric analysis using modern tools in conjunction with geophysical mapping of the trappean thickness and the hydrological parameters of the fluvial systems may provide some answers in the future.

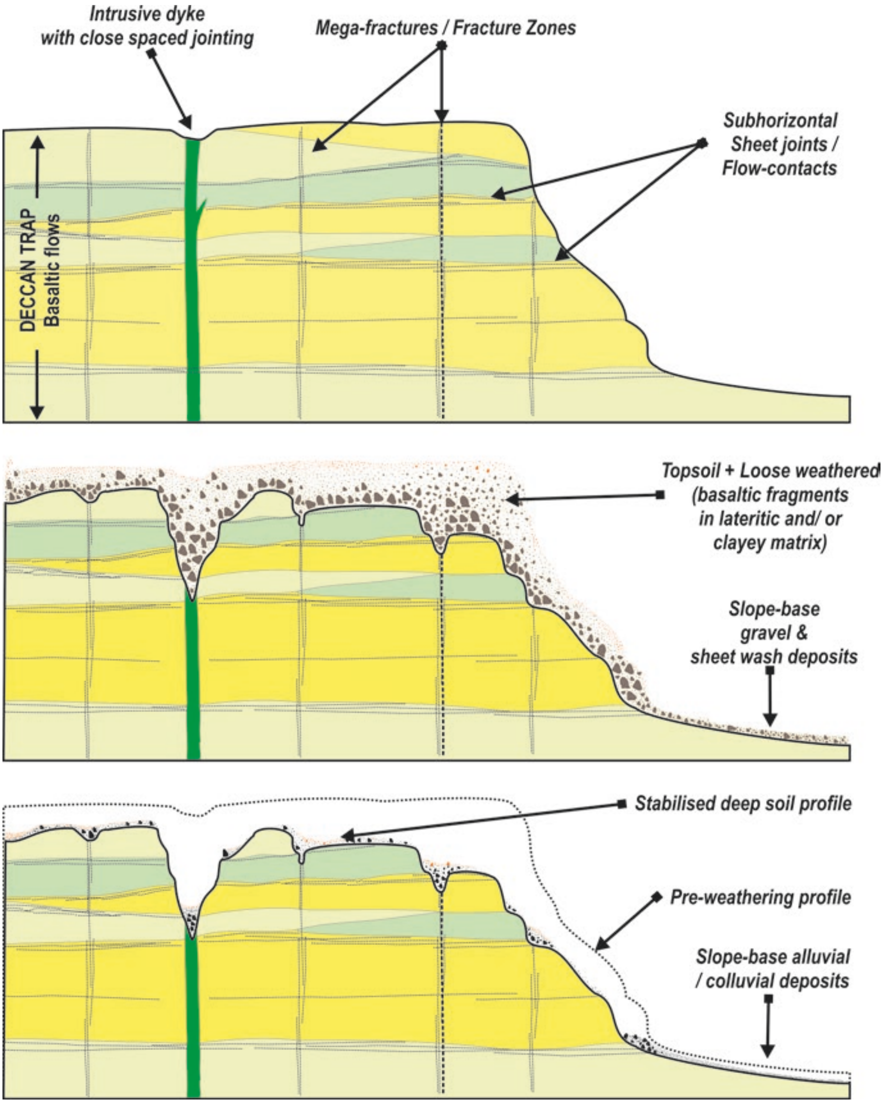


**Fig. 8.20** Generalised cartoon depicting the erosional sequence and slope evolution in the DVP (based on Subramanyan 1981; Peshwa and Kale 1987). The narrow (often linear) valleys in the plateau sectors are generally fracture-(/dyke-)controlled and being more easily erodible lead to entrenched channels. They eventually may widen out giving rise to profiles similar to the plateau edges

## 8.5 Summary and Conclusions

The preceding compilation of the status of knowledge suggests that a very exhaustive documentation of the Cretaceous volcanism in Peninsular India is available. The present knowledge suffers from a major lack of unbiased granularity and equant distribution of data across the two volcanic provinces. For example, the data on the RBS Province is primarily based on its exposures that do not account for even 10% of its postulated extent. Data from the Cretaceous igneous rocks derived from the drilling through the petroliferous sediments is essential to complement this knowledge but broadly absent. Similarly, most of the models and postulations on the DVP are based on data collected from a narrow 100–120 km wide strip of its exposures along the Western Ghats, while its wider expanses stretching across more than 500 km in the east and north have not yet been subjected to the same details.

The petrological characters, chemical signatures and their variations have been exhaustively documented in both the volcanic provinces. So, have been the fossil records from the associated sedimentary horizons. There appears to be little doubt that these volcanic episodes are linked to the passage of the Indian plate over hotspots and the resulting upwelling of upper-mantle/lower crustal melts through a continental crust. The volcanic emplacement mechanisms, plumbing systems and distribution of the lavas across the subprovinces, leading to their stacking patterns and stratigraphy, are yet poorly understood. The linkage of the magmatism with the non-basaltic intrusives such as the carbonatites and lamprophyres in terms of petrogenetic relations is an open question. The correlations and ages of various paleomagnetic reversals recorded in the differing subprovinces remain contentious.

Within the framework of these limitations, a broad chronology of events related to the Cretaceous magmatism in the Indian Peninsular emerges as follows:

- *Holocene:* Differential uplift within some blocks attended by seismicity along block boundaries.
- *Late Pliocene–Pleistocene:* Scarp retreat and excavation of deep gorges and waterfalls along the WGE and SONATA. Block adjustments and local tectonic reactivations leading to antecedent drainage development, river capture and knick point development particularly along the structurally active zones transecting the DVP.
- *Mid-Pliocene:* Detrital (low-level) laterites along KCB.
- *Miocene–Early Pliocene:* Period of relative stability and amenable climate leading to wide planation surfaces, extensive (high-level) laterite formation across western India.
- *Late Oligocene:* Post-eruptive faulting (often by reactivation of ancient basement shears/zones of weakness) and differential uplift attended by development of the western coastal shelf and the passive continental margin of India, following the onset of rapid sea-floor spreading.
- *Eocene–Early Oligocene:* Sedimentation in rifted zones along the Cambay rift and in Kutch.
- *Late Paleocene (−? Earliest Eocene):* Tilting of the peninsular block towards East and establishment of the easterly drainage across the Peninsula. Volcanism in southernmost tip of Indian Peninsular shield along the Lakshadweep and offshore parts of Arabian Sea.

- *Early Paleocene (Late Danian):* Late volcanic phase of DVP (Bombay Group) with differentiates and intrusives (~62 Ma). Separation of India from Seychelles and evolution of Laxmi ridge.
- *Early Paleocene (Early Danian):* Eruptive pulse in Mandla subprovince and Second eruptive pulse in Western DVP (~65–64 Ma).
- *Terminal Cretaceous (Late Maastrichtian):* First eruptive pulse of DVP (active in Malwa, Central and Western DVP) between 67.5 Ma and 66 Ma over eroded basement.
- *Late Cretaceous (Early Maastrichtian–Late Campanian):* Infratrappean (Bagh Group, Lameta Formation and equivalents) sediments. Shallow rifting, local marine incursions and precursory igneous activity (intrusives and lava flows) in Gondwana basins and along (paleo-)Narmada valley around 68 Ma.
- *Late Cretaceous (Turonian –? Campanian):* Onset of the passage of the Indian continental block over the Reunion hotspot. Separation of India from Madagascar.
- *Early Cretaceous (Albian–Aptian):* Flood basalts in the RBS Province and along the eastern coastal basins in the Bay of Bengal.

The models enumerated above are essentially working hypotheses that need validation from future multidisciplinary studies that aim at filling up gaps in our knowledge. This has relevance not only from the earth-science perspective, but more so given the fact that these two provinces together occupy almost a fourth of Peninsular India and have a direct impact on human endeavours in that region.

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