Stratigraphy, structure and volcanology of the SE Deccan continental flood basalt province: implications for eruptive extent and volumes

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Abstract: The Deccan Volcanic Province is one of the world’s largest continental flood basalt provinces, and derives additional importance because its eruptions (64–67 Ma) straddle the Cretaceous–Tertiary boundary. To better assess the environmental impact of Deccan volcanism, and its possible effect upon Cretaceous–Tertiary boundary biota, it is necessary to document the stratigraphy, chronology and volume of the eruptions. New chemostratigraphical data permit mapping of the SE Deccan. These data strengthen the likelihood that the Rajahmundry Traps of eastern India were originally fed by long-distance flows, and an extension of the Main Deccan Volcanic Province. An east–west cross-section reveals a depression or ‘moat’ around the SE periphery of the Deccan Volcanic Province. This provided a site in which shallow lakes initially formed, and along which later lava eruptions became channelled and confined. Published palaeomagnetic data indicate that the lavas of the SE Deccan were erupted during Chron 29R, coeval with the Cretaceous–Tertiary boundary, and the chemostratigraphic data place the associated lake sediments (i.e. Lameta Group) beneath and within lavas of the Wai Subgroup. Finally, these new map data are combined with previous work to provide a quantitative estimate for the original Deccan Volcanic Province eruptive volume of c. 1.3 × 10⁶ km³.

The Deccan Volcanic Province currently occupies c. 500,000 km² of NW peninsular India (Fig. 1). This continental flood basalt (CFB) province erupted as a consequence of the arrival of the proto-Reunion mantle plume beneath the northwestern margin of the Indian continent (e.g. Cox 1989; Ernst & Buchan 2001; Courtillot et al. 2003). The earliest basalt eruptions of the Main Deccan Volcanic Province (Fig. 1) occurred in its northwestern part (i.e. Nasik–Narmada region; Fig. 1) (e.g. Subbarao et al. 1994; Hooper 1999; Widdowson et al. 2000). Later lava successions built on the southern flank of the evolving volcanic edifice as India moved northward over the plume head (Beane et al. 1986; Devey & Lightfoot 1986; Mitchell & Widdowson 1991, fig. 3), and the last Deccan flood basalt eruptions were in the southern Deccan Volcanic Province near Belgaum (Fig. 1). In post-Cretaceous–Tertiary boundary times the plume, now much reduced in its activity, emerged from beneath the attenuated and rifted western continental margin and manifested itself as a chain of progressively younger minor volcanic edifices forming the Maldive–Laccadive Ridge, and the currently active volcano of Piton de la Fournaise (Réunion Island) located south of the Carlsberg Ridge (Duncan 1990). ⁴⁰Ar/³⁹Ar and palaeomagnetic dating indicate that Deccan volcanism (c. 64–67 Ma) spanned the Cretaceous–Tertiary boundary (e.g. Courtillot et al. 1986, 1988; Duncan & Pyle 1988; Venkatesan et al. 1993; Widdowson et al. 2000), and the possible impact of the eruptions upon Late Cretaceous biota has been a source of considerable debate (e.g. Courtillot 1999; Wignall 2001). Accordingly, investigations concerning the extent and volume of the Deccan Volcanic Province, the nature of flow fields (e.g. Khadri et al. 1988; Gallet et al. 1989; Bondre et al. 2004; Jay 2005; Chenet 2006), and their degassing characteristics (Self et al. 2005, 2006), are essential to understand any possible environmental impact these eruptions may have had (Samant & Mohabey 2005).

The Main Deccan Volcanic Province consists of the main outcrop region (c. 73°–78°N and c. 16°–22°E), but the significant subregions (i.e. outlier successions) of Saurashtra, the Malwa Plateau and the Mandla lobe lie to the NW, north, and NE, respectively (Fig. 1). The chemostratigraphy of the Main Deccan Volcanic Province (Fig. 2) was developed by a number of workers during the 1980s on the basis of field mapping and geochemical characteristics of successions exposed along the Western Ghats (Beane et al. 1983, 1986; Cox & Hawkesworth 1984, 1985; Devey & Lightfoot 1986).

This study explores the SE corner of the Deccan Volcanic Province (Figs 1 and 3). It extends from the peripheral basement area northwards and westwards across the basalt terrain towards Killari (18°00′20″N, 76°34′53″E), encompassing the area from Gurmatkal (16°51′40″N, 77°23′23″E) in the south to Gulbarga (17°19′58″N, 76°49′50″E) in the west and Bidar (17°54′27″N, 77°31′38″E) in the north. It is bordered by the areas mapped by Mitchell & Widdowson (1991), Subbarao et al. (1994) and Bilgrami (1999) (Fig. 1). To the south and west, Mitchell & Widdowson (1991) identified predominantly Ambenali and Poladpur-type flows, and to the north, Bilgrami (1999) identified basal flow units with a geochemical signature corresponding to the Bhimashankar, Khandala and Bushe formations, as well as the more widespread outcrop of Poladpur and Ambenali chemo-types of the Wai Subgroup (Fig. 1).

The new geochemical data and map provide details of the stratigraphy and structure of the SE Deccan Volcanic Province. This information provides evidence concerning the original extent of Deccan lavas in the southeastern area, and permits a maximum and minimum estimate for the original eruptive volume of the Deccan Volcanic Province. Importantly, these new data also identify Mahabaleshwar Fm lavas at the SE Deccan margin, thus strengthening the argument that the Rajahmundry Traps in eastern India were originally part of the main Deccan eruptions, and formed when lava became channelled along palaeovalleys (e.g. Baksi 2001; Knight et al. 2003; Self et al. in press). This work also confirms that the construction of the Deccan CFB province has had a significant flexural effect upon the Indian lithosphere (Watts & Cox 1989), as the stratigraphic
structure of the eastern periphery reveals a dip reversal, and associated development of a flexural moat around the south and east of the Main Deccan Volcanic Province. This flexure generated a syneruptive topographic low, which initially became the site of extensive shallow lakes that are now preserved as the thin sedimentary successions (infra- and intra-trappean deposits) of the Lameta Group (e.g. Prasad & Khajuria 1995; Mohabey & Samant 2005).

### Deccan structure and stratigraphy

The main part of the Deccan Volcanic Province (Fig. 1) is essentially lensoid in character thinning eastward and southward, with the greatest thicknesses of 2–3 km occurring 50 km inland of the west coast along the Western Ghats escarpment (i.e. between 18° and 20°N). This erosional escarpment provides spectacular exposure of the lava succession, and the associated road cuttings have provided ‘type’ sections for many geochemical, stratigraphical and volcanological studies (e.g. Walker 1972; Beane et al. 1983, 1986; Cox & Hawkesworth 1984, 1985; Devey & Lightfoot 1986; Mitchell & Widdowson 1991; Khadkikar et al. 1999; Bondre et al. 2004). Inland, east of the escarpment, the Deccan succession forms a plateau region (c. 500–600 m elevation), punctuated by isolated mesas. The latter are erosional outliers of the higher stratigraphical units, and both eastward and southward become lower and fewer. Extensive road-based reconnaissance sampling is required in this plateau region to generate outcrop-based geological maps.

The chemostratigraphy divides the lava succession into three subgroups and 11 formations (Fig. 2), of which the Wai Subgroup is the most widely exposed. Within the Wai Subgroup, formation boundaries are based on changes of 87Sr/86Sr ratios, Sr and Ba concentrations, and Ba/Y and Zr/Nb ratios (e.g. Devey & Lightfoot 1986). The 87Sr/86Sr data provide clear breaks at formation boundaries across a single sheet flow boundary, whereas the element and element ratio values change over a number of sheet flow lobes and therefore often show ‘transitional boundaries’. Nevertheless, the diagnostic elemental criteria (Table 1) are useful, as they provide an easily acquired, accurate classification of single eruptive units within the chemostratigraphy (Mitchell & Widdowson 1991). Identification of chemostratigraphic units has previously been

![Fig. 1. Outline of the Main Deccan Volcanic Province, showing the areas covered by previous maps and Figure 3. Area A, Mitchell & Widdowson (1991); area B, Subbarao et al. (1994); area C, Bilgrami (1999). X'–X and Y'–Y are the lines of the cross-sections shown in Figure 5. Inset shows Deccan subregions: Saurashtra (Kutch), the Malwa Plateau and the Mandla Lobe.](image-url)

![Fig. 2. Composite stratigraphic column showing the geochemical formations of the Main Deccan Volcanic Province, demonstrating their maximum cumulative thickness. There are 11 widely recognized formations; the Desur Fm is restricted to a few flows in the southern Deccan only (i.e. Belgaum area), and considered to be essentially a return to Mahabaleshwar-type eruptions (e.g. Lightfoot & Hawkesworth 1988; Lightfoot et al. 1990). The total basalt thickness is c. 3 km (at Kalsubai Peak), but is not fully exposed in any one section. Also shown are the palaeomagnetic chrons (dates of reversals from Cande & Kent 1995).](image-url)
used to construct geological maps (Fig. 1) of the Deccan Volcanic Province (Beane et al. 1986; Subbarao & Hooper 1989; Mitchell & Widdowson 1991; Subbarao et al. 1994; Bilgrami 1999; Khadi et al. 1999). The development of the chemostратigraphy also provided a means to investigate the broad structure of the Deccan Volcanic Province; it has elucidated the overall southward-dipping nature of the volcanic pile, manifested by the younging of the lavas from north to south, and the reversal of dip and subsequent overstepping of younger units that is observed towards the south and SE of the province (Devey & Lightfoot 1986; Mitchell & Widdowson 1991; Subbarao et al. 1994). The palaeomagnetic stratigraphy (Fig. 2) broadly divides the Deccan Volcanic Province into lavas that lie within the 30N–29R–29N sequence. The 30N–29R boundary is found only in the northern (Narmada) region (e.g. Dhandapani & Subbarao 1992), whereas the 29R–29N palaeomagnetic reversal horizon occurs widely and is located near the base of the Mahabaleshwar Fm in the western Ghats sections (e.g. Jay 2005). The palaeomagnetic stratigraphy provides a useful, broad correlation tool and, significantly, corroborates the structures identified by the chemostратigraphical data (Vandamme & Courtillot 1992).

The SE Deccan field area

The towns of Bidar, Zahirabad and Hommabad (Fig. 3) lie on an upland area that rises c. 130–140 m above the granite plains that form the terrain north of Hyderabad. In the most peripheral regions the lavas are limited to 2–3 inflated pahoehoe sheet lobes each of 5–10 m thickness, the eroded remnants of which form flat-topped mesas and ridges 20–40 m high. At this southeastern-most limit of the Deccan Volcanic Province the basalts commonly lie directly upon the Archaean–Protorezoic granitic basement, though patchy, fossiliferous, Late Cretaceous lacustrine sediments occasionally intervene between basalts, and between basalt and basement (i.e. infra- and infra-trappean deposits; e.g. Prasad & Khajuria 1995; Mohabey & Samant 2005; Samant & Mohabey 2005). Also around the periphery of the Deccan Volcanic Province, ‘black cotton soils’ (a dark-coloured regolith derived directly from the breakdown of basalt; e.g. Wadia 1985) commonly occur up to 20–30 km beyond the current basalt outcrop; the limit of these roughly demarcates the original extent of the Deccan Volcanic Province lava fields. Beyond the basalt outcrop, the granitic terrain is characterized by low, undulose topography, punctuated by monadnocks and small lakes.

Within the Main Deccan Volcanic Province outcrop the basalt succession has been dissected by major eastward-flowing rivers that drain towards the Bay of Bengal; these include the Godavari–Manjra and Krishna–Bhimav river systems (Fig. 1). In some instances, these rivers have eroded through the basalt succession to expose granitic basement and sedimentary rocks beneath the basalts, as in the Bhima valley south of Gulbarga (Mitchell & Widdowson 1991).

The basalt thickens to at least 150 m thick around Gulbarga and Chincholi (Fig. 3) but, because of poor vertical exposure, it is not possible to assess the total number of flows preserved here. However, given that average flow thickness in the Western Ghats sections is 20 m (Jay 2005), the thickness preserved at Gulbarga probably consists of a minimum of eight flows. In the north of the study area, the elevated plateau around Bidar and Hommabad are capped by c. 20 m thickness of Late Cretaceous laterite (Schmidt et al. 1983). Widdowson (1997) and Kisakurek et al. (2004) have demonstrated that the laterite represents a deep weathering residuum of the post-eruptive lava field surface, and that its preservation in this area indicates that vertical erosion has largely been confined to adjacent river valleys cut to a depth of 20–50 m.

Sampling and analytical methods

Away from the periphery of the Deccan Volcanic Province, exposure is infrequent and predominantly restricted to road cuttings and quarries. Accordingly, the sampling method adopted is similar to that of Mitchell & Widdowson (1991). Attention was given to retrieving the least altered materials at key locations interspersed along c. 1000 km of road traverses (e.g. road cuttings, quarries, stream river beds and mesa flanks). The location and elevation of each sample was recorded using a hand-held global positioning system (GPS) and barometric altimeter, and then cross-checked with topographic map data. Descriptions of any flow characteristics and/or their volcanological context were also recorded for each sample.

Stringent petrographic inspection yielded 36 samples suitable for chemical analysis, and these were prepared using a jaw-crusher and an agate mill. Major and trace element analyses were carried out using an ARL 8425+ dual-goniometer wavelength-dispersive XRF spectrometer at the Open University employing routine XRF procedures and analytical packages (Potts 1987). The data and detailed analytical technique are available online at http://www.geolsoc.org.uk/SUP18282. In addition to internationally recognized standards (see Supplementary Publication), previously characterized Ambenali, Mahabaleshwar and Panhala basalt chemotypes were also included to provide replicate analyses. This latter precaution provides a cross-check with previously classified Deccan basalt sample suites, thus ensuring that trace element abundance and ratios identified for the SE Deccan samples were consistent with those of the original stratigraphical chemotypes, and thus directly comparable with the Deccan Volcanic Province analytical database (Widdowson et al. 2000). Error in reproducibility, based upon these replicate analyses, was less than 5% for all of the key chemostратigraphical ratios, and for most elements (further details of these cross-check procedures have been given by Widdowson (1990)). Trace element geochemistry was also determined for a sample suite from the depth-indexed core retrieved from the Killari borehole (Gupta et al. 2003) where 338 m of basalt lies on an 8 m thick infra-trappean (possibly Lameta-type) sedimentary succession; this then

### Table 1. Criteria used to determine the geochemical formations during this current study, from Devey & Lightfoot (1986)

| Formation | Sr (ppm) | Ba (ppm) | Ba/Y | 87Sr/86Sr | Zr/Nb |
|-----------|---------|---------|------|----------|-------|
| Panhala   | < 200   | < 90    | –    | –        | >13   |
| Mahabaleshwar | >250   | >100   | >4   | >0.705   | < 10.5 |
| Ambenali  | 200–250 | < 100  | < 3.5| <0.705   | 10.5–15|
| Poladpur  | –       | >100   | >3.5 | 0.705–0.713| 15–20 |
| Bushe     | –       | >100   | >0.713| >20      |       |
lies unconformably upon the Upper Proterozoic granitic or gneissose basement. The geographical position of these borehole data (Fig. 3) makes possible a direct stratigraphical correlation between the SE Deccan region and the Western Ghats sections.

Chemostratigraphical interpretation and geological map

Previous studies indicate that, between 18° and 20°N, the formations of the Wai Subgroup overstep the earlier Bhimashankar–Bushe Fms in a southerly direction (Mahoney 1988). Further, Mitchell & Widdowson (1991) demonstrated that the Poladpur Fm is itself overstepped near Gulbarga at c. 17°N, and that Ambenali and then Mahabaleshwar units come to lie directly upon the basement in the southwestern Deccan. Thus, it was expected that the succession of the current study area (i.e. between 17° and 18°N) would consist predominantly of basalts of the Wai Subgroup and, accordingly, the appropriate chemostratigraphic determinants (Table 1) were employed.

Figure 4 shows that all of the sample data fall within the element and element ratio ranges of the Poladpur, Ambenali and Mahabaleshwar Fms (Table 1). The majority of the data display Ambenali Fm chemical characteristics, or alternatively appear to be transitional between the Ambenali and the Poladpur type flows. Significantly, Figure 4b (Sr v. Ba) demonstrates a transitional Ambenali–Mahabaleshwar character for many of the samples, which suggests that the succession encompasses the boundary between the Ambenali and Mahabaleshwar Fms or the upper Mahabaleshwar Fm. A small number of samples from the basaltic mesa summits in the Gurmatkal area are of the Mahabaleshwar Fm, an interpretation corroborated by additional $^{87}\text{Sr}/^{86}\text{Sr}$ data.

Fig. 3. Geological map of the southeastern part of the Deccan Volcanic Province.
The majority of the basalt surface outcrop consists of the Ambenali Fm, capped in places by laterite (e.g. the Bidar area). This is consistent with the findings of Mitchell & Widdowson (1991) and Bilgrami (1999). Significantly, Mahabaleshwar Fm basalts (Samples Gm 4, 11, 18) are identified capping a basalt outlier of Gurmatkal (Fig. 3). Mahabaleshwar Fm lavas may also occur below the laterite cap on the spur to the east of Gurmatkal (17°10′N, 78°00′E) as this area is at a similar altitude to the outlier, but logistical difficulties prevented sampling here.

**Bidar (17°54′27″N, 77°31′38″E)**

The Bidar area lies at c. 700 m above sea level (a.s.l.), and consists of a WNW–ESE-trending plateau that rises 150 m from the surrounding basalt plateau (Fig. 3). All the samples in the Bidar area are of the Ambenali chemotype, and the units at the highest elevation have been extensively lateritized (Kisakurek et al. 2004). By contrast to the map of Bilgrami (1999), no Poladpur Fm was identified in the Manjra river valley to the east of Bidar. Instead, sampling carried out close to the river (BB18), revealed an unequivocal Ambenali Fm chemotype. Thus, outcrop of Poladpur Fm must occur only to the north, at elevations below 450 m; this further supports the suggestion that the Poladpur Fm is overstepped at c. 18°N in the eastern periphery of the Deccan (Mitchell & Widdowson 1991; Bilgrami 1999, fig. 5).

**Killari (18°00′20″N, 76°34′53″E)**

Killari borehole at Killari village (Fig. 3), c. 580 m a.s.l., provides information concerning the formations present to the NW of the study area. Here, Ambenali Fm crops out at the surface, and all basalt outcrops in the area, and within the borehole, are reversely magnetized (i.e. Chron 29R; G.V.S. Poornachandra Rao & J. Mallikharjuna Rao, pers. comm.) The uppermost 173 m of Killari borehole basalts have an unequivocal Ambenali Fm signature (to KB175); 65 m below, the units are Ambenali-type with either an elevated Ba content (KB184–197) or elevated Zr/Nb ratio (KB214). The next 40 m is unsampled, and the lowermost 60 m displays a typical Poladpur Fm signature (KB89–118, 235). The Ambenali–Poladpur boundary must lie within the unsampled zone, and is here placed midway between KB214 and KB235 at 260 m depth (i.e. c. 320 m a.s.l.).

**Nizimabad outlier (18°15′00″N, 78°15′00″E)**

Poladpur Fm basalt occurs at the southeasternmost tip of the Nizimabad outlier (Dd01). Bilgrami (1999) also identified Bushe Fm basalt on the northwestern side of this outlier. Accordingly, we propose that a thin sheet of Poladpur Fm basalt intervenes here between the overlying Ambenali and basal Bushe Fm units. As this Poladpur flow extends down from the north it is not shown in the cross-section (Fig. 5a) east of the Manjra river valley.

### Discussion

#### Assessing the stratigraphy and volcanology of the SE Deccan Volcanic Province

Fewer formations occur in the study area (i.e. Poladpur, Ambenali and Mahabaleshwar) than in either the thick Western Ghats succession at Mahabaleshwar (i.e. Bushe–Panhala Fms) in the
west of the Deccan Volcanic Province or the region immediately to the north (i.e. Khandala–AmBenali Fms). At the southeastern periphery of the Deccan Volcanic Province, east of Zahirabad, the thickness of the basalt pile has decreased from an estimated 2000 m or more, in the Western Ghats, to a small scarp c. 30 m high. However, west of the periphery (near Bidar), where the basalt succession is capped by laterite, the original erupted thickness may be estimated because the presence of the laterite indicates that minimal vertical erosion has occurred since lava emplacement (see Widdowson (1997), and discussion therein). As Bidar lies at c. 665 m a.s.l. and the adjacent basement occurs at c. 560 m, the original thickness of the basalt succession in this peripheral region of the Deccan Volcanic Province is unlikely to have been >100 m (i.e. a minimum of 5–6 flow units). Eastward, beyond the current edge of the basalt (i.e. over the 20–30 km characterized by the black cotton soils), this 100 m thickness of flows would have thinned further, and a single sheet flow would have eventually demarcated the edge of the Deccan Volcanic Province. It is, therefore, likely that at many peripheral locations an entire formation would have been only one flow thick, and that this would have represented the entire Deccan basalt succession of that area.

There are several plausible reasons why relatively few formations are present in the southeastern Deccan Volcanic Province, and why the lava succession there is so thin. First, if the eruptive centres were originally located along the west coast in the thickest part of the succession (i.e. the Western Ghats; Hooper 1990; Khadri et al. 1999), then only the most voluminous eruptions would have produced flow fields sufficiently extensive to traverse the 400–500 km to this peripheral area. Because formations of the Wai Subgroup appear to have been amongst the most voluminous of the Deccan eruptions (Fig. 2), these would have had the greatest capability of reaching furthest east. Second, feeder dyke geochemistry suggests that the older, more areally restricted, stratigraphic units of the Kalsubai and Lonavala Subgroups were erupted from more northerly vent systems than those of the Wai Subgroup, and are thus more restricted in their areal extent (Jerram & Widdowson 2005). Accordingly, only rare examples of these chemotypes (e.g. Khandala and Bushe) appear to have reached the southeastern periphery of the Deccan, possibly via propagation along palaeovalleys cut into the pre-Deccan basement (Bilgrami 1999) and, in most instances, Poladpur and AmBenali units lie directly upon the basement.

Structure across the SE Deccan Volcanic Province

The overall structure of the Deccan Volcanic Province in the area of the Western Ghats is a southerly plunging anticline–monocline, with a progressive southward younging of the lava stratigraphy (Fig. 5b; e.g. Devey & Lightfoot 1986; Beane et al. 1986; Subbarao et al. 1994; Raja Rao et al. 1999). At the southermost periphery of the Deccan Volcanic Province the younger formations (Poladpur to Mahabaleshwar) progressively overstep the older formations, and there is a reversal of dip at the southermost peripheral regions such that the units dip northwards (Devey & Lightfoot 1986; Fig 5b). Mitchell & Widdowson (1991) presented an east–west cross-section at 17°15′N with an essentially flat-lying stratigraphy inland of the Western Ghats. However, by combining our current work with the Killari borehole data, we can significantly improve upon this interpretation. The cross-section at 18°N traces the Ambenali–Poladpur boundary from the Mahabaleshwar Plateau inland of the Killari borehole to the Nizimabad outlier (Fig. 4a). East of Mahabaleshwar, a low-angle, eastward dip defines the eastern limb of the broad Ghats anticline; this continues to the Killari area. However, further eastward, the elevation of the Poladpur and AmBenali Fm boundary increases from c. 320 m in the Killari borehole to c. 500–550 m in the region north of Bidar and to c. 600 m at the southeastern edge of the Nizimabad outlier, demonstrating that a significant reversal to a westerly dip occurs across the east and SE periphery of the Deccan.

Assessing the links between the SE Deccan Volcanic Province and the Rajahmundry Traps

Geochemical comparisons (Fig. 4) confirm that basalts with the same chemostatigraphic signatures as those of the Western Ghats extend to the far SE corner of the Deccan Volcanic Province. The identification of Mahabaleshwar Fm basalt, in the Gurmatkal outlier, is one of the most important discoveries of this work. Moreover, the presence of Ambenali and Mahabaleshwar chemotypes in the SE Deccan Volcanic Province signifi-
cantly strengthens the argument that the Rajahmundry Traps of eastern India (c. 500 km from this current study area) were the end-point of topographically confined eruptive units that propagated along palaeovalleys (Baksi et al. 1994; Knight et al. 2003; Self et al. in press).

The Rajahmundry Traps consist of a few, relatively small (c. 35 km$^2$) basaltic lava flows located in the Krishna–Godavari Basin (Fig. 1). These extend c. 70 km in the offshore subsurface, providing a total areal extent of c. 15 000 km$^2$, and a thickness of up to 150 m (Raju et al. 1996). Geochemical data from the Rajahmundry Traps published by Baksi et al. (2001), Cripps (2002) and Knight et al. (2003) identify both Ambenali and Mahabaleshwar Fm chemotypes $^{40}$Ar/$^{39}$Ar dating places the Rajahmundry Traps coeval with the main pulse of the Deccan Volcanic Province, at 64.7 ± 0.5 Ma (Knight et al. 2003). Palaeomagnetism further substantiates the date of emplacement of these lavas, as the upper flows are normal whereas the lower flows reversely polarized. This has been identified as the 29R–29N reversal that elsewhere in the Deccan Volcanic Province occurs in the base of Mahabaleshwar Fm (Vandamme & Courtillot 1992). Isotopic data further strengthen the argument for Rajahmundry lavas originating from Deccan Volcanic Province vents because the $^{87}$Sr/$^{86}$Sr ratios reported by Baksi (2001) are comparable with those reported for the Ambenali and Mahabaleshwar Fms from the Main Deccan Volcanic Province. The alternative interpretation, that two geographically disparate lava successions would inherit the same trace element and isotopic characteristics although they have been eroded from different vent sources, seems geologically unlikely.

As described above, the extensive and voluminous Poladpur Fm also crops out in the SE Deccan, yet it does not appear in the base of the succession at Rajahmundry. There are two possible explanations. First, any earlier erupted Poladpur units could have been eroded away at Rajahmundry, prior to the arrival of Ambenali and Mahabaleshwar-type lava flows. However, as there is little evidence of syneruptive erosion elsewhere in the Deccan Volcanic Province this seems unlikely; moreover, the Ambenali and Mahabaleshwar-type units preserved at Rajahmundry also show no evidence of erosion. Second, although Poladpur flows form a thick and extensive formational unit elsewhere in the Deccan Volcanic Province, it is possible that these flows never invaded the peripheral palaeovalley systems of the SE Deccan to the same extent as did the later Ambenali and Mahabaleshwar Fm lavas. This latter interpretation is consistent with the overstep of Poladpur units detected by Mitchell & Widdowson (1991), and with this chemotype having been fed from earlier, more northerly, fissure and vent systems compared with the later eruptive centres that fed the Ambenali and Mahabaleshwar flows (Beane et al. 1986; Mitchell & Widdowson 1991; Jerram & Widdowson 2005). Post-Mahabaleshwar Fm flows are absent in the Rajahmundry Traps; this is consistent with a rapid waning of Deccan flood basalt volcanism after these eruptions.

The occurrence of Ambenali and Mahabaleshwar Fm flows at Gurmatkal indicates that the most likely (i.e. shortest) route for these lavas to arrive at and feed the Rajahmundry Traps would have been along a palaeovalley system that fed into the ancestral Krishna valley (Baksi et al. 1994). Further north, the Godavari river also occupies an ancient palaeovalley along the Godavari rift system (Fig. 6), which could similarly have provided a route between the Main Deccan Volcanic Province and the Rajahmundry area. However, this valley exits the Main Deccan Volcanic Province from a region where Poladpur Fm units occur, but where no Mahabaleshwar Fm units have been recorded. Accordingly, if this route from the expanding Deccan Volcanic Province lava fields had fed the Rajahmundry units, it is likely that Poladpur–Ambenali Fm rather than Ambenali–Mahabaleshwar Fm units would now be preserved in the east coast outcrops.

The origin of Maastrichtian-age lacustrine sedimentary deposits

Watts & Cox (1989) argued that the reversal of dip observed in the north–south cross-section at the southern periphery of the Deccan Volcanic Province was the result of lithospheric flexuring caused by the development of the Deccan volcanic edifice. The identification of a similar reversal of dip in our east–west cross-section confirms that this flexure continues around the southern and eastern periphery of the Deccan Volcanic Province. Such a flexure would have resulted in a ‘flexural moat’ developing around the edge of the lava fields as the Deccan edifice developed and thickened (Subbarao et al. 1994), and thus provides an explanation for the occurrence of large shallow lake deposits (Lameta Group sediments) that developed contemporaneously around the margins of the Deccan (Fig. 7).

These lake deposits are formed of sedimentary material transported by the east-directed drainage system that traversed both the evolving lava fields and the exposed regions of the adjacent pre-Deccan basement. One such lake, and its associated marshlands, developed over an area south of Nagpur (Fig. 7), and formed part of the shallow, c. 700 km$^2$, Nand–Dongargaon basin (Mohabey & Samant 2005). The deposits now form intra- and infra-trappean sedimentary successions of up to 20 m thickness (Prasad & Khajuria 1995; Tandon 2002). Significantly, these deposits also contain palaeontological evidence that shows that the lakes were volcanically coeval depocentres during the Late Cretaceous (Samant & Mohabey 2005), and our geochemical data reveal that many of these peripheral lakes were eventually overrun by Ambenali-type flows.

Development of the Mahabaleshwar and Ambenali Fm lava fields

Accepting that lavas from the Deccan Volcanic Province reached the east coast of India and formed the Rajahmundry Traps, this would then represent a propagation distance of c. 500 km farther than the majority of the SE Deccan lavas. Therefore, the presence of these few long-travelled flows, together with the occurrence of Poladpur, Ambenali and Mahabaleshwar Fm units farther north in the Deccan Volcanic Province requires further explanation.

One consequence of the development of a putative flexural moat around the evolving Deccan Volcanic Province would have been a confinement of later eruptive units such as those of the Poladpur, Ambenali and Mahabaleshwar Fms. As well as providing a low-lying region for the development of lakes, this moat would also have channelled and ponded those lavas that were sufficiently voluminous to reach this peripheral, down-flexured region. Only those few lavas that either breached (i.e. overtopped) the moat or propagated along palaeovalley systems could have travelled beyond the limit of the flexure (e.g. to Rajahmundry). By contrast, it is probable that most of the lava units of the Wai Subgroup became confined to the area around the periphery of the earlier volcanic edifice that had formed during the eruption of the Kalsubai and Lonavala Subgroups (Fig. 7). Significantly, the Poladpur, Ambenali and Mahabaleshwar units found cropping out in the north and NE Deccan Volcanic Province (i.e. Nagpur, Buldana, Chikaldara, Jabalpur and Toranmal areas; Peng & Mahoney 1995; Peng et al. 1998; Mahoney et
al. 2000; Shrivastava & Pattanayak 2002) could therefore have reached these regions by following this down-flexed region, and propagating northwards around the moat (Fig. 7).

Estimating the original area and volume of the Deccan Volcanic Province

The areal extent and volume of the Deccan eruptions have long been a matter of discussion and conjecture. Providing realistic volume estimates for CFB provinces is difficult, yet quantitative determinations are becoming increasingly important when attempting to assess degassing histories and the potential environmental impact of the eruptions (e.g. Jolley & Widdowson 2005; Self et al. 2006). Although estimates exist for many CFB examples, poor exposure, erosion, fragmentation and foundering as a result of rifting often result in wide ranges in their reported volumes. Consensus suggests that the eruptive volume of CFB provinces varies from $c.0.2 \times 10^6 \text{ km}^3$ for the Columbia River flood basalts to $>3 \times 10^6 \text{ km}^3$ for the Siberian Traps. Volumes as great as $(2–4) \times 10^6 \text{ km}^3$ have also been reported for the Deccan (Courtillot & Renne 2003), but more commonly are in the range of $c.(0.5–2) \times 10^6 \text{ km}^3$ (e.g. Krishnan 1960; Pascoe 1964; Officer et al. 1987; Richards et al. 1989). However, because no calculations are offered with these values, they can only be thought of as qualitative estimates. If we are to better understand the effect of Deccan eruptions upon Late Cretaceous environments, or else as a trigger for climatic and biotic change at the Cretaceous–Tertiary boundary (Courtillot 1999; Wignall 2001), it becomes important to provide realistic, volcanologically constrained estimates of the original Deccan Volcanic Province volume.

Here we provide a calculation to estimate the volume of the Deccan Volcanic Province by using the maximum extent of the lavas as determined from such studies as those by Subbarao et al. (1988), Mitchell & Widdowson (1991), Bilgrami (1999) and this work, and the established thicknesses preserved along the Western Ghats (Widdowson & Cox 1996; Widdowson et al. 1997). To make this estimate, and for simplicity, we assume the structure of a single cone (i.e. shield volcano), as opposed to the more complex, and possibly more accurate, model, proposed by Beane et al. (1986), Devey & Lightfoot (1986) and Mitchell & Widdowson (1991), which consisted of a series of cones formed by a progressive southerly migration of active vent systems. We assume that the main eruptive centre of this cone is Nasik and the radius is 600 km.

Our map indicates that the combined thickness of the eruptive units at the eastern Deccan periphery is $c.30 \text{ m}$, and there consists of only three or four flow units. Thinner, eroded and
weathered basalt outliers occur 10–20 km beyond the current easterly periphery of the preserved Deccan lava fields, and eventually pass into black cotton soils for a further 20–30 km beyond. We take these thicknesses to be representative of the whole of the Deccan Volcanic Province periphery and therefore take the original limit of the Deccan Volcanic Province to be c. 50 km from the current outcrop edge. Having assumed an originally roughly circular outcrop for the Deccan lava fields, we take the distance from the putative early eruptive centre at Nasik to the original periphery of the Deccan volcanic edifice to be 600 km; this provides an estimate of radius for the original volcanic edifice (Fig. 6). From this a value of c. 1.3 × 10⁶ km² can be determined, representing the original maximum area of the Deccan Volcanic Province prior to continental rifting and erosion.

Having now defined the extent and area of the original lava fields, to calculate an original Deccan Volcanic Province volume we must now determine the original thickness at the centre of the Deccan volcanic edifice (i.e. Nasik area). By contouring the post-eruptive Deccan surface, and its extrapolation northward to the deeply eroded Nasik region, Widdowson & Cox (1996) and Widdowson (1997) determined that the maximum thickness of basalt that had been eroded from the top the Deccan volcanic edifice, near the eruptive centre, was c. 1.5 km (Fig. 6). The current maximum elevation in the Nasik area is 1680 m at Kalsubai Peak (19°35'N, 73°44'E). This has a small amount of Bushe Fm units preserved at its summit (Fig. 2), suggesting that some of the Lonavala and all of the Wai Subgroup stratigraphy may have been removed. The original maximum thickness of basalt in the Nasik area may therefore have been c. 3 km. We do not know to what depth the current Deccan lava extends beneath the current surface outcrop because there are no basement–basalt contacts exposed in the Western Ghats sections near Nasik. However, Kaila (1988) estimated a total basalt thickness of at least 1.3–1.5 km in the Kalsubai Peak–Igatpuri area, which suggests that the majority of the succession is exposed above datum.

Given these areal and maximum thickness estimates, we can now determine the original total eruptive volume. If, as seems likely from flexural and isostatic arguments (Watts & Cox 1989), part of the Deccan succession does extend beneath datum, then this subsurface volume should also be considered. Accordingly, we have assumed a maximum subsurface thickness of 0.5 km (e.g. Mahoney 1988) beneath the succession of the Nasik region, giving a total thickness of 3.5 km. Our volume estimate assumes a simple geometric form for the main Deccan edifice of a lensoid structure calculated as two cones, with one inverted beneath the other (Fig. 6). The volume of such a lensoid structure provides an original Deccan eruptive volume of c. 1.3 × 10⁶ km³.

We believe our calculation provides a maximum value for the original erupted volume of the Deccan Volcanic Province. This is because: (1) flood basalt provinces are highly asymmetrical relative to their rift axis (Kazmin 1991) and, therefore, the volume of lava we assume to have been present offshore (i.e. on the Arabian Sea continental margin) may be an overestimation;
(2) Patro et al. (2005) revealed that significant topography existed on the granitic basement before the lavas were erupted, so the volume of the lava in our inverted cone would be less than we have calculated; (3) the sub-regions of Saurashtra, the Malwa Plateau and the Mandla Lobe (Fig. 1) may have originally been erupted as discrete volcanic successions (e.g. Melluso et al. 1995, 2006; Peng et al. 1998; Shrivastava & Pattanayak 2002), and so were never actually part of a continuous Deccan Volcanic Province outcrop (i.e. encompassed within the 600 km radius shown; Fig. 6). Alternatively, using a similar approach, the volume of the Main Deccan Volcanic Province inland of the present coastline may be considered in isolation, thus providing a minimum value limit. Ignoring any rifted and/or foundered offshore segment, this approximates to roughly one-third of the lensoid structure (Fig. 6), giving a total volume of at least 0.4–0.5 \times 10^6 \text{ km}^3 for the Main Deccan Volcanic Province alone. If the model of Cox (1993) is correct, this estimated eruptive volume will represent only a fraction of the total magmatic volume generated during the Deccan episode, because, according to petrogenetic arguments, at least 30–40% will have remained as cumulates trapped within base of the Indian lithosphere (i.e. as ‘continental magmatic underplating’). Accordingly, this simple calculation re-confirms the Deccan as one of the world’s largest CFB provinces.

Conclusions

This work completes the basalt chemostratigraphy in the SE part of the Deccan. It provides further understanding of the construction of the Deccan Volcanic Province edifice, its effect upon the Indian lithosphere, and how this controlled the distribution pattern of younger lava flows and generated lacustrine environments and depositional basins around the Deccan Volcanic Province. The main findings may be summarized as follows.

(1) Geochemical data provide the first evidence of the Mahabaleshwar Fm in the SE Deccan Volcanic Province. Extensive Ambenali and Poladpur Fm lavas are also confirmed. The occurrence of Mahabaleshwar and Ambenali Fm chemotype lavas (and absence of Poladpur Fm) in the Rajahmundry Traps strongly suggests that these east coast lavas originated as long lava flows that extended from the Main Deccan Volcanic Province along the palaeo-Krishna river valley via the SE Deccan. If this is correct, at c. 1000 km long they represent the longest lava flows ever recorded.

(2) At the current periphery of the Deccan Volcanic Province the lava is only c. 30 m thick and comprises only 2–3 lava sheets. From this periphery, it thickens by 100 m over a distance of c. 50 km. Some of these inland lavas are capped by laterite, indicating that this preserved thickness is similar to the original erupted thickness (some vertical shortening will inevitably have taken place during lateritization of the uppermost flows).

(3) The reversal of dip observed elsewhere in the southern Deccan Volcanic Province also occurs in the study area, further confirming the idea that lithosphere loading by the growing volcanic edifice caused a ‘moat’ to develop around the periphery of the Deccan Volcanic Province. We suggest that the voluminous Ambenali and Mahabaleshwar Fm lavas were ‘channelled’ by this moat, which allowed them to reach to the NE of the Main Deccan Volcanic Province and as far as the Mandla Lobe (Jabalpur). This provides a possible explanation for the more complex stratigraphical relationships observed in these northerly regions.

(4) The moat formed by the loading of the lithosphere provided a site at which large, shallow lakes could form around the periphery of the evolving Deccan Volcanic Province. The resulting deposits are now preserved as the patchy but extensive Late Cretaceous–Early Palaeocene Lameta lake sediments. Accordingly, the presented basalt chemostratigraphy now provides the information required to place these lake sediments within a stratigraphical and chronological context.

(5) Combining the new volcanological data on the peripheral thinning of the Deccan succession with those of previous studies detailing the maximum thicknesses of the Deccan basalts provides the basis for estimates of the original volume of the Deccan eruptions. Simple geometric models indicate that the maximum total erupted volume was no more than c. 1.3 \times 10^6 \text{ km}^3.

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