Generation of Deccan Trap magmas

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Deccan Trap magmas may have erupted through multiple centers, the most prominent of which may have been a shield volcano-like structure in the Western Ghats area. The lavas are predominantly tholeiitic; alkalic mafic lavas and carbonatites are rare. Radioisotope dating, magnetic chronology, and age constraints from paleontology indicate that although the eruption started some 68 Ma, the bulk of lavas erupted at around 65–66 Ma. Paleomagnetic constraints indicate an uncertainty of $\pm 500,000$ years for peak volcanic activity at 65 m.y. in the type section of the Western Ghats. Maximum magma residence times were calculated in this study based on growth rates of "giant plagioclase" crystals in lavas that marked the end phase of volcanic activity of different magma chambers. These calculations suggest that the > 1.7 km thick Western Ghats section might have erupted within a much shorter time interval of ~55,000 years, implying phenomenal eruption rates that are orders of magnitude larger than any present-day eruption rate from any tectonic environment. Other significant observations/conclusions are as follows: (1) Deccan lavas can be grouped into stratigraphic subdivisions based on their geochemistry; (2) While some formations are relatively uncontaminated others are strongly contaminated by the continental crust; (3) Deccan magmas were produced by 15–30% melting of a Fe-rich lherzolitic source at $\sim$ 3–2 GPa; (4) Parent magmas of the relatively uncontaminated Ambenali formation had a primitive composition with 16% MgO, 47% SiO_2; (5) Deccan magmas were generated much deeper and by significantly more melting than other continental flood basalt provinces; (6) The erupted Deccan tholeiitic lavas underwent fractionation and magma mixing at $\sim$ 0.2 GPa. The composition and origin of the crust and crust/mantle boundary beneath the Deccan are discussed with respect to the influence of Deccan magmatic episode.

1. Introduction

"The close of the Mesozoic era was marked by the outpouring of enormous lava flows which spread over vast areas of Western, Central, and Southern India. They issued through long narrow fissures or cracks in the earth's crust, from a large magma basin and are therefore called *fissure eruptions* ..... The flows are called *traps* because of the step-like or terraced appearance of their outcrops, the term being of Scandinavian origin."
-M. S. Krishnan ("Geology of India and Burma" 1982)

Today, the Deccan Traps volcanic province (Figure 1) has emerged as one of the most interesting subjects of research for two principal reasons—its enormous size and eruption at the K/T boundary. The predominantly tholeiitic lavas of the Deccan appear to have erupted some 65($\pm$4) m.y. ago when the Indian continent was rapidly migrating northward (e.g., Chatterjee and Rudra 1992; figure 2). There are several other voluminous basalt provinces on Earth like the Deccan, such as theParaña basalts of South America, Siberian Traps (Russia), Karoo (Africa), Columbia River Basalts (North America), Caribbean Sea-floor basalts, and the Ontong Java plateau (western Pacific Ocean).

Keywords. Deccan Trap; giant Plagioclase basalt; age; contamination; fractional crystallization; magma generation.

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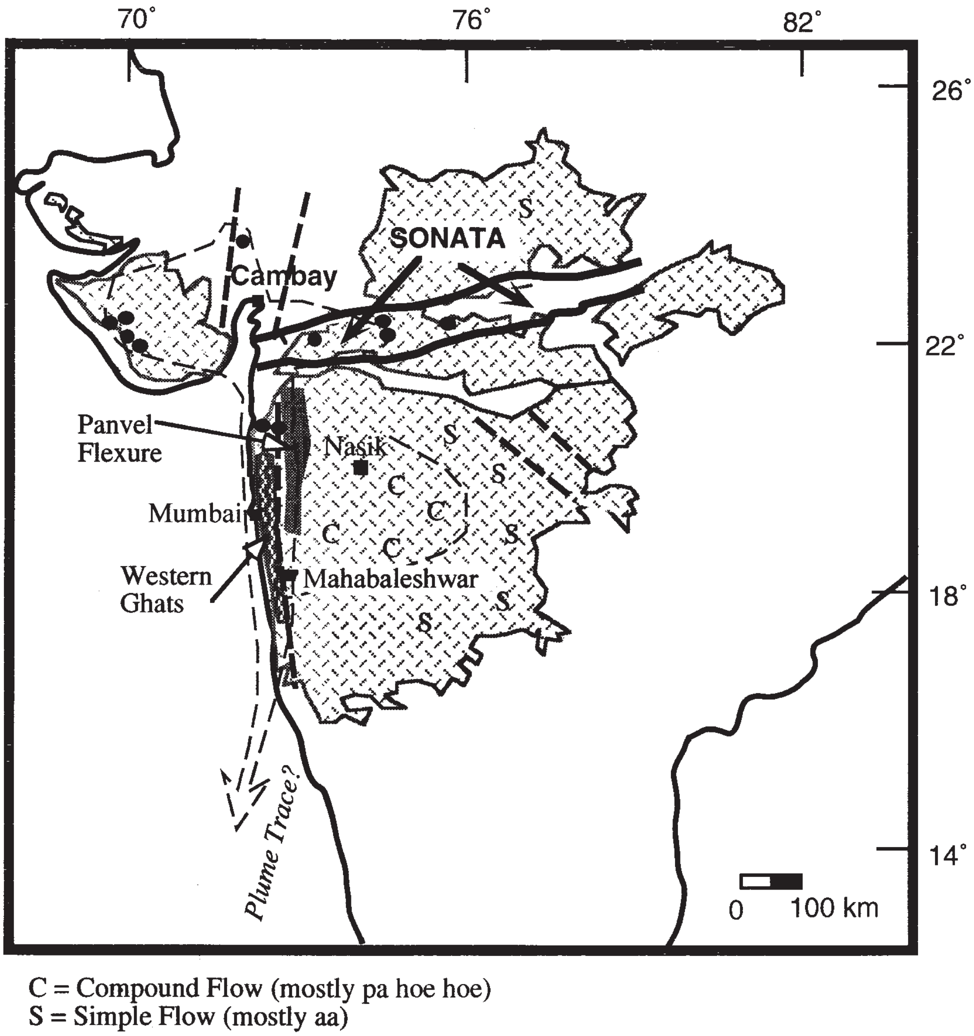

Figure 1. Map showing distribution of Deccan Trap lavas and important rift systems. The dots represent alkalic/carbonatite occurrences. The distribution map of simple and compound flows is from Walker (1999). The plume trace (dashed with arrow) is thought to hug the western coast of India however, its form near the Cambay triple junction is unclear.

Such predominantly basaltic provinces have also been called "flood basalts", "plateau basalts", and "large igneous provinces". In spite of the Deccan's obvious appeal, systematic studies of this province did not begin until the 1980s. Two exceptions to this statement are the works of West (1958) and Sukheswala and Poldervaart (1958). The reader is encouraged to peruse Mahoney's (1988) outstanding review of Deccan research up to about 1986 for important background information during that period.

The period from 1980 to early 1990s saw a sudden burst of research activity on the Deccan, starting with the publication of a few critical papers. Although stated as a "personal perspective", the recently published review article by Hooper (1999) is a must read for all Deccan geochemists because it relates current issues to pre-1980 research. Hooper addresses a range of topics, from stratigraphic correlation, migration of the source of the magmas, to feeder systems and the relationship between tectonic extension, uplift and subsidence, magma eruption, and morphologic development of the Western Ghats. Another interesting read is Cox's (1999) paper in which he focused on the role played by Deccan research in the "picrite" vs. "tholeiite" primary magma controversy.

In this author's view, the stage for systematic studies (1980s onward) of the Deccan was set by a detailed petrographic study by Deshmukh *et al* (1977) of two Western Ghats sections, particularly the famous Mahabaleshwar section (1.2 km thick), where the authors identified 42 lava flows. This was followed by a geochemical study by Najafi *et al* (1981) of the lava flows of the Mahad-Mahabaleshwar section. An Nd, Sr isotopic study by Mahoney *et al* (1982) of the Mahabaleshwar section quickly followed and demonstrated that flood basalts are not characterized by monotonous chemistry. They showed that strongly contaminated lavas and virtually uncontaminated lavas occur in the same section of the Western Ghats. Mahoney *et al* (1982) also showed that the most contaminated (e.g., high $^{87}Sr/^{86}Sr$ ratio)

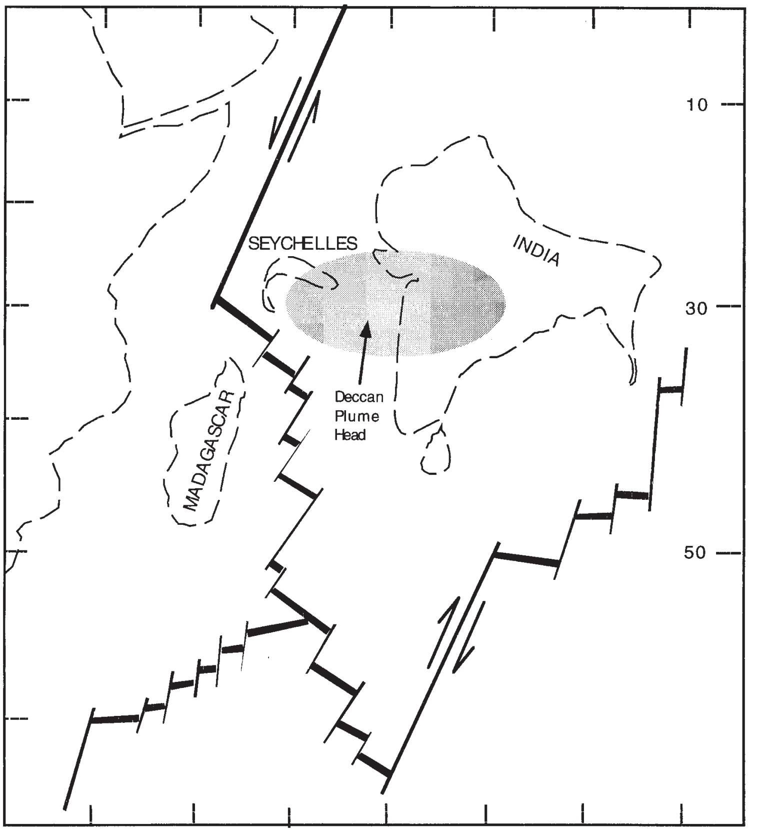

Figure 2. Paleo-location of India with reference to the plume head (after Duncan and Richards 1991).

lava samples were also the least differentiated (e.g., higher Mg#) — a feature that would seem to go against common intuition! Their finding was timely because at the same time Watson (1982) published a paper detailing how basalt magmas passing through the continental crust might selectively pick up some elements from the surrounding crust while disposing of others. Based on this study, Mahoney *et al.*'s finding would appear to be a good example of the process of *selective contamination.* Sen (1986) presented a mineralogical synthesis of the Mahoney *et al* samples in a follow-up publication and concluded that open-system fractionation and magma mixing processes in shallow, crustal magma chambers were a controlling factor in determining the major and trace element chemistry of Deccan lavas.

Cox and Hawkesworth (1985) and Beane *et al* (1986) made a significant leap in Deccan lava geochemistry. They presented "geochemical stratigraphy" of the lavas of the Western Ghats, elucidating details of elemental and isotopic variations. Beane *et al* provided additional information on the petrography of the samples. Formal lithostratigraphic nomenclature was used to classify the Western Ghats lavas into three subgroups, and several formations were assigned to each subgroup (table 1). It became apparent that lava geochemistry can be used as a tool to carry out spatial correlation between distant areas of the Deccan. This in turn may help resolve such important issues as the relative volumes of the various lava formations in the Deccan, lateral extent of individual flows, extent of involvement of the continental crust, location of major eruption centers, etc. As far as the Deccan is concerned, this new approach changed the way this lava province was viewed.

Mahoney *et al* (1985) carried out an isotopic investigation of some alkalic and tholeiitic basaltic lavas in the northern Deccan area along the Narmada River. These lavas are essentially contemporaneous because they alternate in the same field section. Mahoney *et al* determined that the alkalic and tholeiitic lavas have similar isotopic composition and are roughly equal in volume in that particular Narmada section. Although it has long been known that the Deccan Trap lavas are predominantly tholeiitic, Mahoney *et al* justifiably wondered whether other unexplored areas of the Deccan might be found where alkalic basalts occur in significant volumes.

Alkalic basalts, nephelinites, basanites, picrites, and carbonatites do occur along the peripheral regions of the Deccan (figure 1; e.g., Bose 1980). They all occur along three prominent tectonic areas that have received much attention: the east-west trending "SONATA" region, which is a rift sys-

Table 1. *Deccan Trap lava Formations of the Western Ghats.*

Subgroup	Formation	Thickness (m)	Phenocrysts	MgO Range
Wai	Desur		Ol + Pl	5–6
	Panhala	(>150)	Ol + Pl	6.3–6.8
	Mahabaleshwar	(280)	Ol + Pl	5–6.7
	Ambenali	(500)	Ol + Pl	5–7
	Poladpur	(370)	Ol + Pl	6–9
Lonavala	Bushe	(325)	Ol + Pl + Aug	5–12
	Khandala	(140)	Ol + Pl + Aug	4.2–9.4
Kalsubai	Bhimashankar	(140)	Ol	5–6.5
	Thakurvadi	(400)	Ol + [Pl] + Aug	5–10
	Neral	(100)	Ol + Pl	5–11
	Igatpuri	(150)	Ol + Pl	5–10
	Jawahar	(>200)	Ol + Pl	5–10

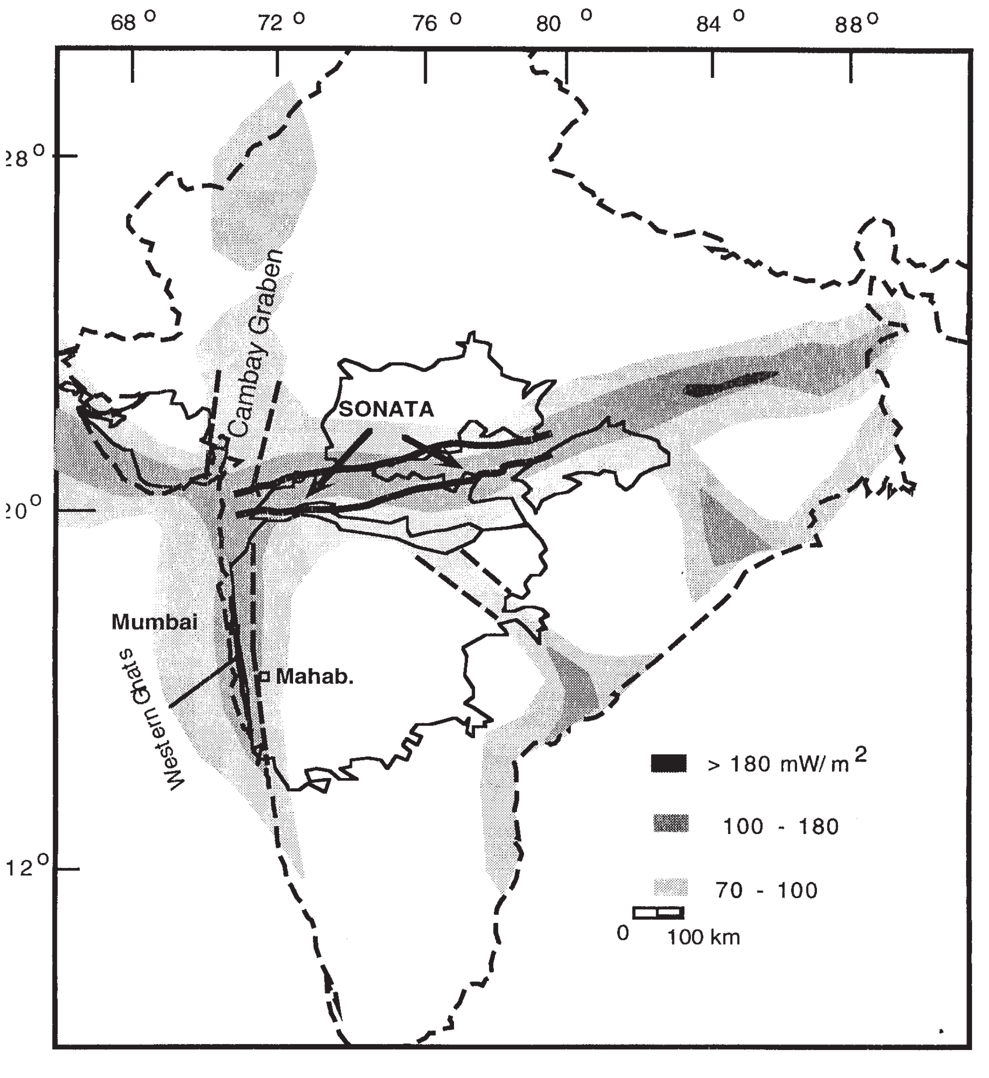

Figure 3. A generalized heat flow map of the Indian peninsula (modified from Ravi Shanker 1988).

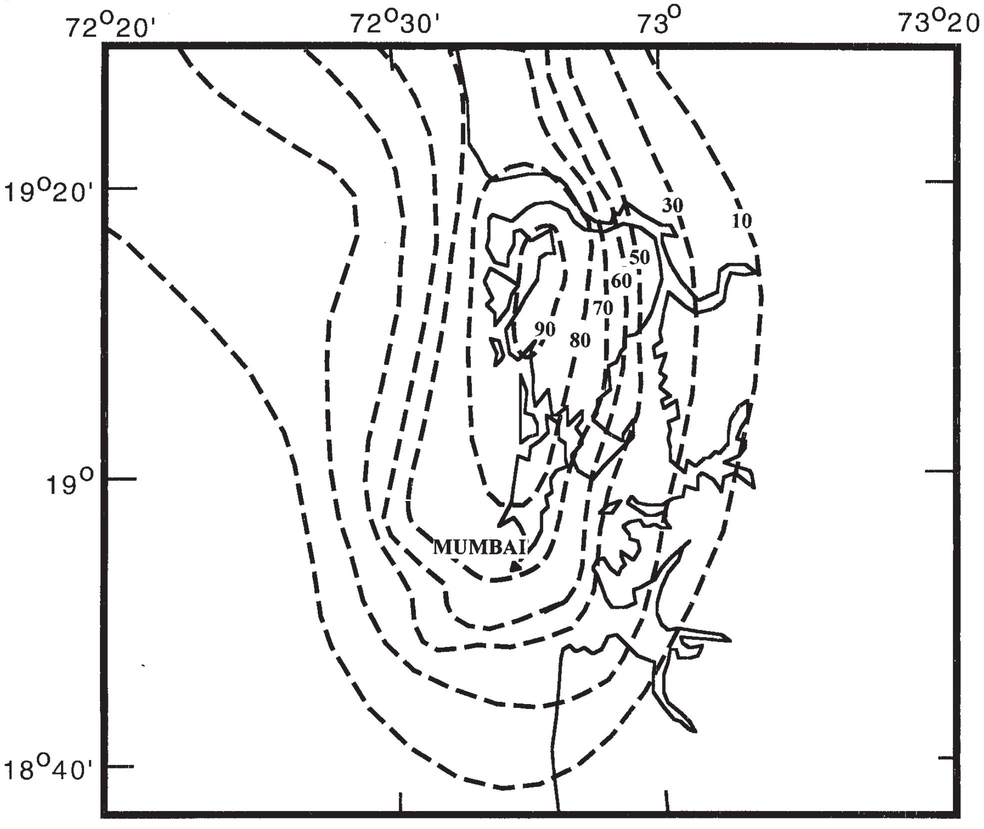

Figure 4. Gravity map around Mumbai (from Takin 1966). The numbers are in milligals.

tem that has undergone many episodes of activation, the Cambay rift system in the northwest, and the Panvel Flexure to the west of the Western Ghats (figure 1). These regions are also characterized by high heat flow and a concentration of dikes (Figure 3). Based on recent ^{40}Ar-^{39}Ar dates it appears that some alkalic lavas (68–69 m.y.) in the northwest Deccan predate the tholeiites (65–66 m.y.) (Basu *et al* 1993). On the other hand, other alkalic lavas along the Narmada rift and in the southern areas are contemporaneous with or are younger than the predominantly tholeiitic lavas (e.g., Basu *et al* 1993; Gwalani *et al* 1993, 1995; Simonetti *et al* 1995; Ray *et al* 2000).

Mildly alkaline as well as tholeiitic dikes trending roughly in a N-S direction occur on the western side (Panvel Flexure) of the Western Ghats. The specific rock types include trachyte, rhyolite, lamprophyre, nepheline syenite, basanite, and ijolite (e.g., Sethna and Mousavi 1994). Some of these dikes carry mantle xenoliths of garnet pyroxenites and spinel lherzolites (Dessai and Vaselli 1999 and personal communication). These 60–61 m.y. old dikes are believed to be related to the E-W extension that produced an off-shore gravity high (Bombay High: figure 4) and N-S grabens (Hooper 1999). Hooper believes that this younger extension and magmatic episode, which postdate the peak tholeiitic eruption, was probably related to the splitting of the Seychelles platform from the Indian plate. Carbonatites, alkaline magmas, and the tholeiites are thus all temporally and spatially part of a big picture that likely involves the Deccan plume, plume-lithosphere interaction, continental rifting, and magma generation. It is now clear that any model of Deccan tholeiite petrogenesis must have a satisfactory explanation for the generation of all of these magmas and not just the tholeiites (e.g., Basu *et al* 1993; Sen 1995).

While great strides were being made on Deccan lava geochemistry, important laboratory "analog" experiments relevant to the behavior of mantle plumes were being conducted in a few laboratories, particularly that of Ross Griffiths in the Australian National University. Questions pertaining to the origin of flood basalts, relationship between hot spot chains (such as the Hawaiian-Emperor chain) and mantle plumes, and the depth of origin and migration of plumes now took center stage. We learned that a plume, generated at the core/mantle boundary, may rise to shallow mantle while developing a large head and a long, narrow tail (figure 5: Richards *et al* 1989; Griffiths and Campbell 1990, 1991a,b; Campbell and Griffiths 1990). Richards *et al* proposed that flood basalts are generated over a relatively short period *via* melting of the plume head, whereas the plume tail may persist for millions of years and produce a hot-spot

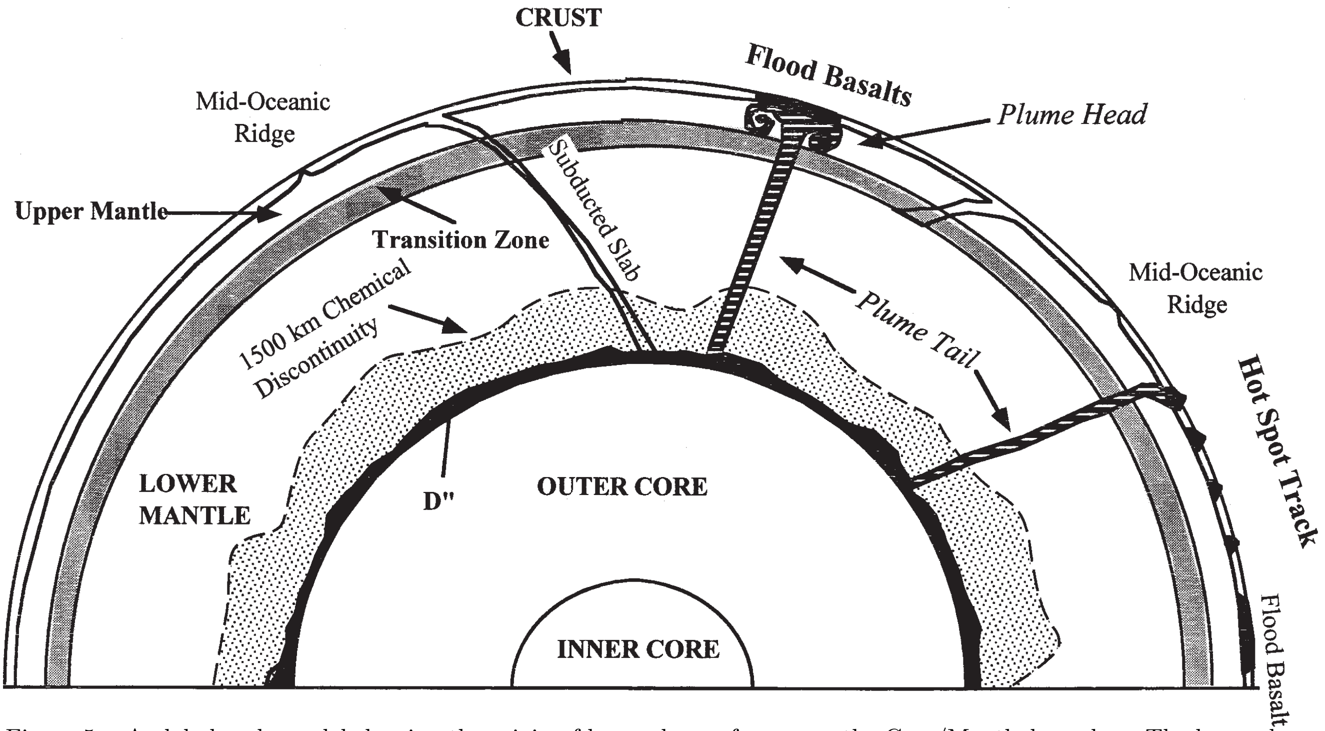

Figure 5. A global scale model showing the origin of large plumes from near the Core/Mantle boundary. The large plume heads melt and produce flood basalts whereas their tails persist for millions of years and generate hot spot tracks (source refs. in: Sen 2001).

track, such as the Hawaiian islands, on migrating lithosphere. In the Deccan case, it was shown through dating of the rocks that a hot spot track extends from the Deccan to the Chagos-Laccadive (or *Lakkhadeep*) and Rèunion islands (Duncan and Richards 1991). Presently, the hot spot that is believed to have once fed Deccan lavas is still producing lavas on the Rèunion island.

There is considerable debate about whether plumes rise from the core-mantle boundary or from the transition zone, or from a recently proposed chemical boundary layer often referred to as the 1500-km discontinuity (Kellogg *et al* 1999). Furthermore, even the plume theory for the origin of the Deccan has been questioned (e.g., Sheth 1999; discussed later). It is beyond the scope of this paper to review such matters in extensive detail.

The objectives of the present article are two: acquaint the reader with some overall background concepts about the Deccan and bring up some new issues about the Traps. The emphasis is on geochemistry and petrology because the bulk of the work has been done in these fields. It is beyond the scope of this review to address the significance of the fossils that have been found in ash (?) beds ("intertrappeans") that occur between lava flows in some areas (e.g., Krishnan 1982). In the end I summarize what we think we "know" about the Deccan.

2. Some general features

2.1 *Spatial variation in thickness and sources of eruption*

The Deccan Trap lava pile is the thickest in the western part of the province, reaching an exposed thickness of about 1.7 km in parts of the Western Ghats. It is the thinnest in the east, reaching no more than about 100 m. As reflected in the above quotation from Krishnan (1982), most authors prior to about 1980 believed that Deccan lavas erupted through fissures or large cracks in the crust. In recent years, some authors have proposed that a major center of eruption was located near Nasik in the Western Ghats because of the following reasons:

- The lava pile is the thickest here.
- A rough mapping of the simple and compound flows shows that the latter are concentrated in the southwestern Deccan, whereas the former are found in the eastern and northern parts (Walker 1999). By comparison with Hawaiian and Columbia River basalt lava flows, it appears that compound structures are formed in lava piles that are very thick, which in turn is related to the proximity of source.
- Although the lava flows are essentially flat-lying, a broad shield-volcano-like structure has been identified in the Western Ghats (figure 6;

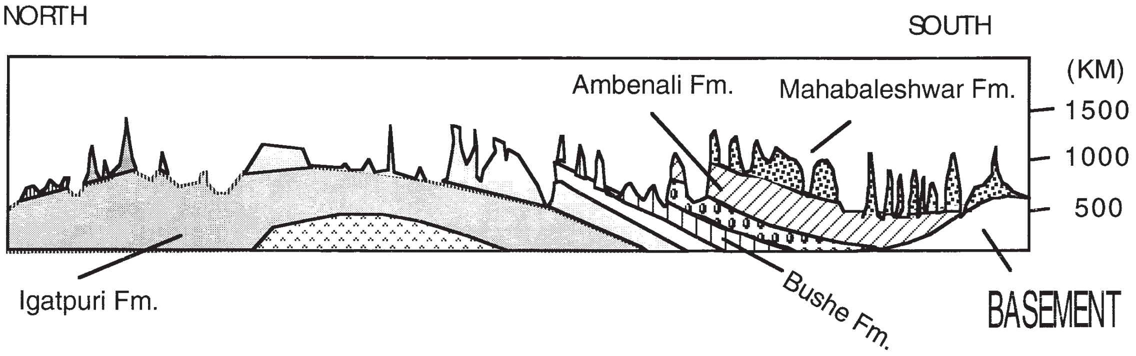

Figure 6. The shield volcano type structure along a north-south section through the Western Ghats ridge (from Belgaum in the south to Kondaibar in the north: after Subbarao *et al* 1994). Some prominent formations are shown.

cf. Beane *et al* 1986; Widdowson and Mitchell 1999). Based on the small dips (1°) of various lava formations, Watts and Cox (1989) inferred that this structure formed due to lithospheric flexure caused by the "load" (crust added by the volcano, which was migrating southward). Widdowson and Mitchell (1999) suggest that the Western Ghats escarpment and the Panvel Flexure resulted from erosion of the load that was uplifted as a result of isostatic rebound.

Aside from this major volcanic edifice, a second locus of extrusion has been described from the Satpura area of Madhya Pradesh, where feeder intrusions can be linked to overlying lavas (cf. Crookshank 1936; Sen and Cohen 1994; Bhattacharji *et al* 1994). This was also substantiated by the seismic finding of a locally thick (900 m) basalt sequence near Jabalpur (Kaila 1988). There are other minor eruptive sites, particularly of alkalic magmas, that occur in the northwestern Deccan. These lavas have very distinct isotopic, major and trace element composition compared to those from southwestern Deccan (Krishnamurthy and Cox 1977; Melluso *et al* 1995; Peng and Mahoney 1995).

2.2 *Spatial extent of lava formations*

Stratigraphic correlation of the lava formations has been done for the southwestern and southeastern Deccan. A map showing the distribution of the formations in these areas has been published (Subbarao and Hooper 1988). Although geochemical data are also available for the northern, northeastern, and northwestern parts of the province, detailed correlation work has not been done. Major similarities and differences between the lavas of the Western Ghats and the eastern areas have been documented (see comments by Hooper 1999 and Mahoney *et al* 2000). Hooper (1999) pointed out the difficulty in using geochemistry as a long-distance correlation tool, noting that lavas of similar chemistry can erupt at two different sites at two different times. With this limitation in mind, one can still explore which chemically defined class or "magma type" is spatially most abundant, regardless of its position in a vertical sequence in any particular site. For example, in the CRB, the most abundant type is the Grande Rhonde formation. In the Deccan case, Poladpur-type lavas seem to be laterally most extensive, reaching some 800 km away from the Western Ghats (Mahoney *et al* 2000). At the other extreme, the Bushe formation appears to be rather "spotty" (Subbarao and Hooper 1988).

Post-Deccan faulting has made flow-by-flow correlation across major fault systems very difficult. For example, a well known and puzzling lack of correlation exists across the SONATA lineament, which has led to a suggestion of possible post-Deccan left-lateral strike-slip faulting of 200–400 km along the SONATA lineament (Mahoney 1988; Hooper 1999). Post-Deccan faulting and earthquakes still continue in the Deccan province, the most recent events being the Killari earthquake of 1993 and the Bhuj earthquake of 2001. These earthquakes occur principally in two belts – the SONATA and along a southwest coastal belt that essentially marks the hot spot trace (Mahadevan and Subbarao 1999).

On the basis of isotopic and trace element similarities and dissimilarities, several authors have noted that geochemical equivalents of the Thakurvadi, Khandala, Poladpur, Ambenali, and Mahabaleshwar formations extend far to the east and northeast (Mitchell and Widdowson 1991; Baksi 1994; Sen and Cohen 1994; Peng *et al* 1998; Khadri *et al* 1999; Mahoney *et al* 2000). Mahoney *et al* (2000) suggested that Poladpur formation–type lavas may be spatially the most extensive of all. Peng *et al* (1998) noted that Poladpur-like lavas of the northeastern Deccan are higher in $^{206}Pb/^{204}Pb$ than the Poladpur formation-type lavas of the Western Ghats, although they are similar in both Nd and Sr isotopic compositions. These authors interpreted this dissimilarity to mean that the northeastern lavas and the southwestern lavas of the same formation used very different feeder systems, as a result of which northeastern lavas underwent less crustal contamination.

2.3 *Volume of the Deccan*

Most articles on the Deccan Traps begin with an attempt to impress the reader how voluminous this lava province really is. However, a great deal of inconsistency between various authors in the reported volume is apparent (table 2). Also, it is not always clear whether the authors were intending to mean the erupted volume (i.e., volume of lava originally erupted) or the presently exposed volume, which would be less than the original erupted volume as some of the lavas would have been lost via erosion. It is likely that some melt was lost *via* crystallization in the crust and/or mantle, and thus the erupted volume (as well as the presently exposed volume) of lava is less than the actual volume of melt generated at the source region. Furthermore, some of the lavas either erupted on the ocean floor adjacent to the Western Ghats or became submarine as a result of post-rift subsidence and perhaps large landslides. Therefore, it is advisable to know the volume of Deccan lavas that are buried under off-shore sediments. In the future MCS (multi-channel seismometers) may be used to detect seaward dipping reflectors, which would be Deccan-related (J. Mahoney, pers. Comm., 2001).

The volume estimated from the exposed area and thickness of the lava province can only be considered as an apparent volume. The estimation of the apparent volume is far from easy, and a good estimate must be based on a clear knowledge of the "basement" topography; i.e., the topography of the surface on which the Deccan lavas erupted. While we have some understanding of the nature of that surface, significant 3-D details are lacking (cf. Ravi Shanker 1988). Our knowledge is primarily based on gravity and seismic measurements along a few transects or on a broad scale of coverage.

The question is what is more important— apparent volume or the actual volume of melt generated in understanding the Deccan volcanic episode? The answer will depend on who is seeking what: if one is interested in post-Deccan uplift of the Indian subcontinent and the erosion of the lava pile then he/she would be interested in both the erupted volume and present volume estimates (and of course, time). On the other hand, if for example the purpose is to understand how the Deccan magmatic episode may have affected the lower crust and upper mantle beneath the Indian subcontinent, then of course, the interest will be in the volume magma generated. It is with the above background that table 2 is presented, in which some volume and/or area estimates by previous authors are listed. The numbers clearly vary considerably. Considering the fact that a significant portion of the lava pile has probably been eroded, an erupted volume of about $3 \times 10^6\,km^3$ is probably a fairly conservative estimate. This estimate is based on an average thickness of 1 km and an originally erupted area of $2 \times 10^6\,km^2$ (Hooper 1999).

2.4 *Age and rate*

Much has been written already about the timing of Deccan lava eruption. Briefly, one would be correct to say that the "bulk" (95%) of the lava erupted some 65–66 (±2) m.y. ago (figure 7; e.g., Courtillot *et al* 1986, Duncan and Pyle 1988; Venkatesan *et al* 1993; Baksi 1994, Allegre *et al* 1999). The lavas span only three magnetic chrons, 30N-29R-29N, with the bulk erupting at 29R (figure 7). Somewhat alkalic and carbonatitic lavas, believed to be related to the dominantly tholeiitic lavas, erupted both before and after the main tholeiitic episode (Basu *et al* 1993). Including these, it would be safe to say that the total eruption of Deccan lavas occurred from 68.5 to 64 Ma.

The volumetric rate at which these lavas erupted is an unresolved question. Part of the problem is that no existing dating method can be employed to obtain dates that can distinguish between ~65 m.y. old lavas whose eruptions were separated by only a few thousand years. Those authors (e.g., McLean 1985) interested in the short-term (on 10–100 year time scales) impact of the Deccan eruption on mass extinction and climatic events have therefore been frustrated by the limitations of dating methods. Application of the magnetic polarity time scale and evaluation of the radioisotope dates vis-à-vis the magnetic time scale led Courtillot *et al* (1986) to the conclusion that the "average extrusion rates could have been in excess of $1\,km^3$ per year". This could very well be the case, which is also implied by the general lack of significant erosional features between lava flows (e.g., West 1981). Courtillot *et al* pointed out that this is a very high rate when compared with Hawaii ($0.1\,km^3$ per year). Even if we accept their analysis of what the various magnetic chrons in the Deccan mean, we still have the uncertainty of the true erupted volume, and hence the actual rate remains uncertain. Also, the rate as stated is a mean rate; and in reality it is likely that even within the geologically

Table 2. *Some published estimates of volume/area of Deccan Traps.*

Author(s)	Year	Volume	Area
P R Hooper	1999		1-2 million km^2 (erupted)
Coffin & Eldholm	1993	9 million km^3	1.8 million km^2 (erupted)
A B Watts & K G Cox	1989		800,000 km^2 (present coverage)
W D West	1983	"probably" $> 250,000\,km^3$ (erupted)	
S S Deshmukh	1982	>10 million km^3 (erupted)	
K V Subbarao & R N Sukheswala	1981		500,000 km^2 (present coverage)
E H Pascoe	1964		>2.6 million km^2 (erupted)

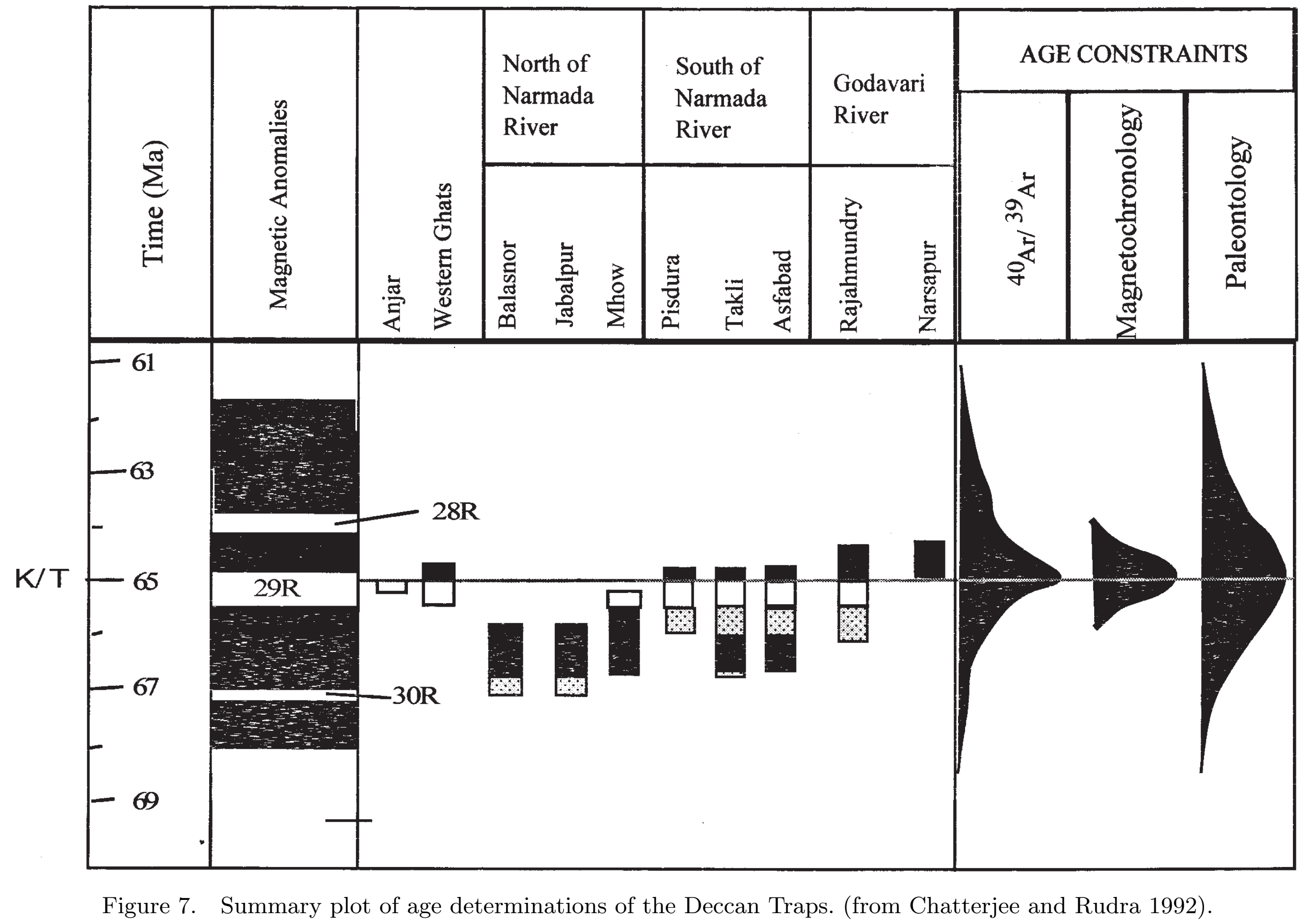

Figure 7. Summary plot of age determinations of the Deccan Traps. (from Chatterjee and Rudra 1992).

short interval within which these lavas erupted, the true rate was highly variable.

3. Petrography

Olivine, augite, and plagioclase phenocrysts are common in the tholeiitic lavas. Titanimagnetite, ilmenite, and sulfides occur as groundmass. Olivine has been found to occur in the groundmass in some rare cases, mostly in intrusives. Olivine is commonly altered to iddingsitic material, and such olivine pseudomorphs can only be recognized when the original euhedral shape is preserved. The average modal content of (total) phenocrysts in the Western Ghats lavas is around 10–12% (Sen 1986, Devey and Cox 1987). The actual phenocryst content varies rather widely, however. Noting that Poladpur, Ambenali, and Mahabaleshwar formation lavas have similar mean total phenocryst contents, Devey and Cox suggested that this meant that the flow rates of these lavas from their source magma chambers were similar. Of course, this is a very simplistic interpretation because total phenocryst content depends upon nucleation and growth rates, bulk composition (i.e., proximity to the saturation curve for a given phase) of the magma, and magma residence time in subcrustal chambers. A thorough CSD (crystal size distribution) study is needed in order to address some of the kinetic issues related to phenocryst growth and abundance.

3.1 *A new estimate of average Deccan eruption rate from red boles and giant phenocryst basalts (GPB)*

In contrast to all prior publications, I adopt a very different "back-of-the-envelope" approach, based on phenocryst growth rates, to address the issue of magma residence times in Deccan magma chambers. Figure 3 shows the "average" phenocrysts present in each formation (Data sources: mainly Deshmukh *et al* 1977; supplementary information from Beane 1988, Sen 1986). Note that within each formation a number of flows occur, some of which may be free of phenocrysts, others carry all three (ol+pl+cpx) phenocrysts, and still others may have a single phenocryst phase. The modes also vary tremendously between and within individual flows, which is well-documented in J Beane's (1988) dissertation. Phenocryst accumulation, particularly of olivine, has demonstrably occurred near the base of some flows (Beane and Hooper 1988). This accumulation is often local in nature, making the lava flows locally picritic. This is particularly true of the flows in the lower formations, as reflected in the large range of MgO values cited in figure 3.

Lava flows, termed "giant phenocryst basalt" (GPB), characterized by plagioclase megacrysts ($\sim$2–10 cm long), occur within each formation (Hooper *et al* 1988; Pankov *et al* 1994) and are of particular relevance in this study. GPBs are generally highly fractionated (low MgO) lavas and yet their plagioclase megacrysts (An_{61-64}) have similar or greater anorthite content than in higher-MgO lavas in which plagioclase does not form a distinct phenocryst (cf. Sen 1986; Beane 1988; Pankov *et al* 1994).

Pankov *et al* (1994) made a detailed study of the plagioclase phenocrysts in three GPBs from the Khandala, Jawhar, and Thakurvadi formations of the Kalsubai subgroup (Western Ghats). Plagioclase crystals in the three samples they examined generally exhibit normal zoning with the core-to-rim ranges as follows: $An_{69(\mathrm{core})-42(\mathrm{rim})}$, $An_{67(\mathrm{core})-60(\mathrm{rim})}$, $An_{63(\mathrm{core})-42(\mathrm{rim})}$. The rim is generally no thicker than ~ 0.5 mm. Pankov et al. (1994, p. 190) pointed out the presence of reverse zoning of $\sim 20\,\mu$m width in the inner parts of some plagioclase crystals; and that there are mineral and melt inclusions that are evenly distributed within individual plagioclase phenocrysts. Extremely Fe-rich olivines (Fo_{32-40}) were found to occur near the rims of these plagioclase crystals. Both augite and pigeonite were found to be included in these plagioclase crystals, with both pyroxenes becoming more Fe-rich from the core to rim of the host plagioclase crystals. Pankov *et al* (1994) also noted the occurrence of an extremely Fe-rich subcalcic ferroaugite type pyroxenes near the edge of the plagioclase phenocrysts. These Fe-rich pyroxenes apparently formed as quench crystals from extremely differentiated, Fe-rich, interstitial liquid.

A straightforward interpretation of the above observations is that the GPBs represent flows in which the phenocrysts accumulated by flotation in highly differentiated (therefore, denser than plagioclase) magmas that concentrated near the roofs of magma chambers. During a period of magma-chamber dormancy such plagioclase crystals grew to large sizes. Finally, a GPB eruption occurred, perhaps due to magma chamber collapse or fresh input of magma. *Thus, each GPB eruption represents the culmination of an eruptive cycle of a magma chamber.*

Figure 8 shows a distribution of phenocrysts in the Western Ghats lava sequence and the horizons at which GPBs occur (Deshmukh *et al* 1977). In addition, Beane (1988) identified at least two more GPBs. It is not possible at this time to determine where the Formation boundaries are located in this figure from Deshmukh *et al*'s description. Although Beane (1988) suggests that GPB flows do not occur in the Wai Subgroup, this claim is disputed by D. Chandrasekharam (2001, pers. Comm.). An inspection of the data presented in Deshmukh *et al* (1977) suggests that at least the uppermost GPB occurs within the Wai subgroup. However, even if we accept Bean's conclusion that GPBs do not occur in the Wai subgroup, then it is possible that the eruptions were so rapid during the Wai stage that no magma batch managed to reside in its chamber long enough to form the giant plagioclase phenocrysts.

Figure 8 also shows the locations of "red bole" or red clay-rich horizons. A review of previous papers suggests that there are two fundamentally different interpretations of such horizons (e.g., Hooper *et al* 1988; Wilkins *et al* 1994; Inamdar and Kumar 1994; Inamdar 1995, Gupte 1995). One interpretation is that they are *in situ* or transported clay-rich (soil) horizons that may have formed by oxidation of the lava flows. Alternatively, they represent altered (lateritized) pyroclastic material (Wilkins *et al* 1994). Figure 8 shows that red bole horizons are commonly associated with GPBs, with the GPBs (and coarse-grained lava flows) often erupting on a red bole horizon. Note that this association was corroborated by recent preliminary field studies conducted by D. Chandrasekharam (2000, pers.comm.) This observation leads me to

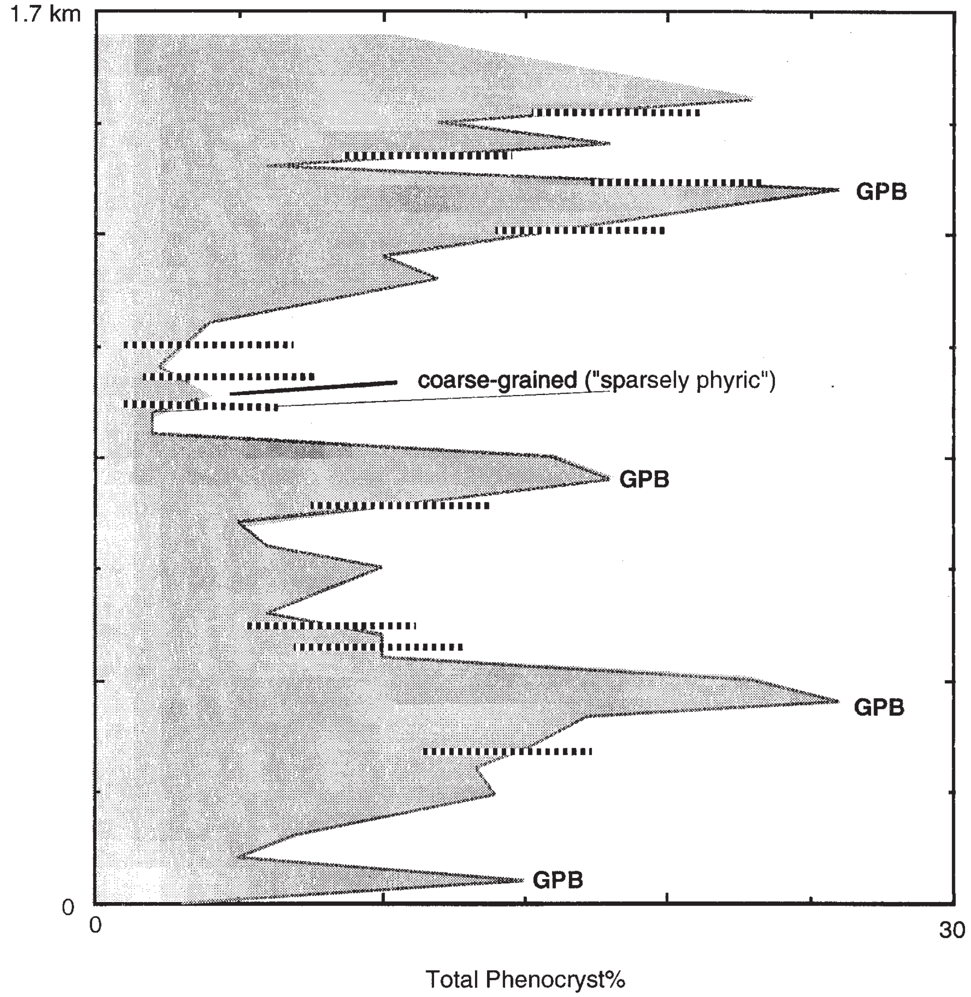

Figure 8. Distribution of Giant Plagioclase Basalt (GPB) lavas and red bole horizons (dotted lines) in the Western Ghats. The shaded area represents variation in total phenocryst%. (Source: mainly Deshmukh *et al* 1977, with some input from Beane 1988).

infer that while the red bole (soil) was forming at the surface, the subsurface magma chamber was undergoing a dormant (non-eruptive) phase during which the magma was differentiating and plagioclase crystals in it were growing to large sizes. As mentioned before, GPB eruption perhaps occurred when a new batch of magma entered the magma chamber from below and squeezed the GPB out of the chamber or the chamber itself collapsed. Alternatively, if we accept a pyroclastic origin for the red boles, it would seem that as the giant phenocryts were forming near the roof of the magma chamber (dormancy implied), heat conducted out of the magma chamber and set up convective circulation of groundwater. Such heated fluid may have later been responsible for pyroclastic eruption. Removal of the roof by the pyroclastic eruption would have created the pathway for a GPB eruption.

Irrespective of which of the two alternative interpretations of the red bole horizons we accept, a time gap is implied which would allow the growth of plagioclase phenocrysts to large sizes. In our attempt to have an approximate estimate of this time we assume that these plagioclase crystals were growing continuously (uninterrupted) in a shallow crustal magma chamber (at ~2 kbar). This is not a bad assumption considering that the giant plagioclase crystals are generally unzoned or weakly zoned (normal zoning) except for their outermost thin rim, which presumably formed in equilibrium with the highly differentiated melts near the roofs of magma chambers. Using some reasonable plagioclase growth-rate data it should be possible to estimate the residence time of such a giant plagioclase crystal in the magma chamber.

Here we use plagioclase growth rate data from a Hawaiian lava lake (Makaopuhi Lava Lake: Cashman and Marsh 1988) and make the assumption that plagioclase crystals in GPBs and Makapuhi grew under similar undercooling rates. Using an approximate growth rate of 9.9×10^{-11} cm/sec (Cashman and Marsh 1988) we calculate that it would take about 3200 years for these giant plagioclase crystals to grow to 10 cm from a small nucleus. Accepting that each GPB resided in the magma chamber for that length of time, the six GPBs in figure 8 would account for a total minimum (explained below) time of 6×3200 or 19,200 years. Based on Beane's data we use a mean thickness of 100 m for each GPB at the Western Ghats and calculate a one-dimensional eruption rate of 0.031 m/year. *Using this rate, an approximate "back of the envelope" calculated minimum time for the eruption of 1.7 km of lavas of the Western Ghats is* $\sim$55,000 *years.*

The time estimated above is likely a minimum number because of the following reasons: (1) There could well be other GPBs that have not been found or are not exposed in the field sections studied. (2) Cohen and Sen (1994) pointed out that Deccan tholeiites underwent fractionation and mixing in relatively shallow (6 km) chambers. The rate of undercooling in such chambers may have been somewhat slower than that of the Hawaiian lava lake because of the difference in depth. (3) There has been only one detailed study of zoning in individual plagioclase crystals in three GPB flows. 20μm reverse zones within the core regions of crystals and melt inclusions in some cases suggest that dissolution and reprecipitation may have occurred during the formation of some of these plagioclase crystals. Such complexity may translate to a somewhat longer time of residence for the plagioclase crystals. (4) During crystal growth, the rate of growth may not remain a linear function of time because several factors may change. These include the availability of nutrients (proximity to saturation boundary) in the proximity of the crystal surfaces, rate of diffusion, rate of latent heat (released by new growth) dissipation into the melt etc. These factors result in a slower growth rate as the crystal approaches saturation. (5) If indeed the Wai subgroup, which accounts for more than half of the total thickness of the Deccan lavas, does not have a GPB in it as suggested by Hooper (pers. Comm., 2000), then one could propose that, relative to the lower subgroup magmas, the Wai subgroup magmas had a shorter residence time in their magma chambers such that giant phenocrysts did not form (as stated above). In this case, the quoted 55,000.00 years for the entire Western Ghats eruption would be too high a number because it is based on GPB flows.

While the above calculation may have some flaw in details, I believe that the approximate number of 55,000 years for the Western Ghats is still useful because it is a drastically smaller number than the 500,000 years estimated by Courtillot *et al* (discussed earlier). It is possible that the apparent discrepancy between the time scales estimated from phenocryst growth rate versus paleomagnetic data is either due to the invalidity of one or more assumptions that were made above, or simply reflects the inability of the paleomagnetic time scale to resolve ages < 0.5 m.y. The time scale obtained from phenocryst growth rate suggests that the duration of the bulk of the Deccan Trap activity could have been significantly shorter than that inferred from paleomagnetic data.

4. Mineralogy

4.1 *Olivine*

Olivine in the Deccan is generally altered to a brown iddingsitic material, and can only be recognized by their original crystal form and occurrence as phenocryst. The most magnesian olivines (Fo_{88-91}) were discovered in the somewhat unusual basalts in the Dhandhuka borehole in the state of Gujarat (West 1958; Krishnamurthy and Cox 1977). In general, however, it appears that the most magnesian olivines of normal Deccan tholeiite has a Fo_{77} composition, although Fo_{84} olivine phenocrysts have been found in Neral and Khandala fomations (cf. Beane 1988; Sen 1980, 1986; Sethna and Sethna 1988). Careful examination of tiny dark brown inclusions in many olivine crystals, particularly in MgO-rich lavas, often revealed that these are chrome-spinels (Sen 1986; Beane 1988; Melluso *et al* 1995). Plagioclase has also been found to occur as poikilitic inclusion in olivine in the slightly more differentiated lavas. Beane (1988) pointed out that the olivines were generally in equilibrium with the host lavas, although there are clearly proven examples where olivine accumulation has occurred on a local scale

Sen (1980, 1983) presented a detailed examination of olivine compositional variations in the famous Chakhla-Delakhari sill in central India. In this sill, compositionally and texturally bimodal olivine occurs throughout the sill. For example, the Upper Chill Zone contains subhedral phenocrysts of olivine (Fo_{69}) and Fe-rich skeletal olivine crystals (Fo_{20}) in the groundmass (Sen 1983).

Recently, Krishnamurthy *et al* (2000) carried out a detailed examination of olivine in picrite basalts and other basalts of the Deccan in an effort to bracket the composition range of possible primary magmas of the Deccan. Based on bimodal distribution of olivine composition and associated bulk rock elemental composition, these authors classified olivine phenocrysts in Deccan basalts and picrites into two types – Type 1 and Type 2. Cores of Type 1 olivine grains are significantly more forsteritic (Fo_{86-92}) than Type-2 olivine phenocrysts ($< Fo_{86}$). Type 1 olivines occur in alkaline-to-transitional lavas in the northwestern state of Saurashtra and western SONATA lineament (locations: Ambadongar and Kawant, Pawagarh, Anila and Paliyad, south Kathiawar, and drill holes at Botad, Dhandhuka, and Wadhwan junction). Type 2 olivine is characteristic of the common Deccan tholeiites of the Western Ghats and from other areas.

It is useful to compare the olivine compositions listed above with that of olivines in ultramafic xenoliths that were discovered by De (1964) and analyzed by Krishnamurthy *et al* (1988). Spinel peridotites, clearly of upper mantle origin, have Fo_{88-92} olivines; and olivines in dunites, which are likely to be of magmatic origin, have Fo_{86-92} compositions. This comparison suggests that primary Deccan magmas probably equilibrated with a mantle that was dominantly peridotitic with "normal" olivine compositions (Fo_{88-92}).

4.2 *Plagioclase*

Plagioclase phenocrysts commonly occur in all Deccan basalts with MgO $< 7\%$ (Beane 1988). Plagioclase phenocryst composition ranges from An_{82-61}, with plagioclase megacrysts in GPB being the most sodic (An_{64-61}; see earlier discussion). Based on Sen's (1986) and Beane's (1988) data, it seems that while GPB plagioclases exhibit little zoning (a thin Ab-rich rim is generally present) and a small range in An-content, plagioclase crystals in individual samples of non-GPB lavas exhibit wide variation in An-contents and complicated zoning features. Sen (1986) noted the occurrence of normal and reverse zoned plagioclase in some lavas of the Western Ghats, which he inferred to represent magma mixing. Also, at the Western Ghats, Beane (1988) noticed that the An-content generally correlates well with the Ca/(Ca+Na+K) ratio of the whole rock, suggesting that, in general, the plagioclase crystals were in equilibrium with the host lava. Krishnamurthy and Cox (1977) found extremely calcic plagioclase (An_{88}) in the drill hole lavas from northwestern Deccan. However, the maximum calcic plagioclase found by Melluso *et al* (1995) to be An_{82} from the lavas in the same general area. Melluso *et al* applied plagioclase thermometry to calculate eruption temperatures of 1125–1200°C.

4.3 *Pyroxenes*

Both augite and pigeonite occur in the average Deccan tholeiite (figure 9). Pigeonite is not always easy to detect, and therefore, may seem to be rare (Sethna and Sethna 1988; Beane 1988). In many cases, single pyroxene grains were found to be zoned, with cores of pigeonite and rims of augite (references in Cohen and Sen 1994). Cohen and Sen thought that in many of the lavas magnesian pigeonite is probably metastable. On the other hand, slightly more Fe-rich pigeonites were thought to have crystallized as a stable phase from the magmas. Sen (1986) calculated 1000–1145°C minimum lava temperatures for the Western Ghats based on pigeonite thermometry. A recent experimental study of Bushe lavas has shown that they may have been saturated with a magnesian pigeonite (Gangopadhyay 2000). Pigeonite-fractionation may also be the reason for the Bushe Formation to have a very different fractionation trend than other Deccan lavas (discussed later).

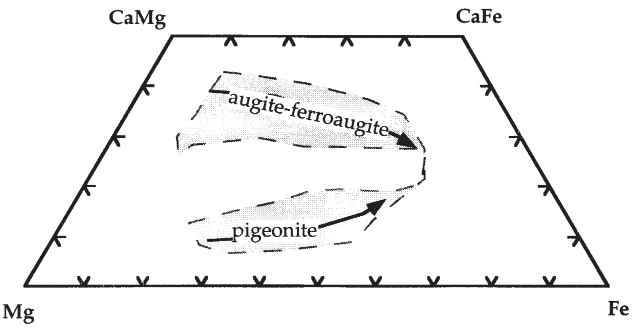

Figure 9. Fields of Deccan pyroxenes. (Data sources: Sen 1980, 1986, 1988; Beane 1988; Sethna and Sethna 1988).

Orthopyroxene is not at all common in the Deccan, although a localized occurrence is clearly related to crustal contamination (Chandrasekharam *et al* 2000). The general absence or extreme rarity of Ca-poor pyroxene in the Deccan lavas and intrusions is intriguing. Campbell (1985) suggested that one important difference between continental tholeiites and oceanic tholeiities is in the major role of a Ca-poor pyroxene phase in the former and absence (particularly of orthopyroxene) in the latter. He attributed this difference to deep crustal contamination of continental tholeiitic magmas, which forces the magmas to reach the orthopyroxene-saturation surface prior to their further ascent through the shallow crust. One could extend Campbell's argument to the Deccan and suggest that, excluding the Bushe (which does have Ca-poor pyroxene on the liquidus), Deccan lavas did not undergo crustal contamination or the level of contamination was not enough to force orthopyroxene-saturation. Isotope data suggest that with the exception of the bulk of Ambenali, most Deccan lavas are contaminated, and in some cases, strongly contaminated. A plausible explanation of this discrepancy probably lies in extensive magma mixing that these magmas have undergone (e.g., Sen 1986). Efficient magma mixing can keep the mixed magma on the pl+aug+ol+liq surface even though its isotopic composition (particularly, Pb, Sr, O) may become dominated by the contaminant.

4.4 *Other minerals*

The Fe-Ti oxide minerals in the groundmass of Deccan Trap tholeiites are titanomagnetite (sometime partially or wholly altered to maghemite) and ilmenite. These coexisting oxides in the Western Ghats basalts and elsewhere in the Deccan suggest that the groundmass quenched over a temperature range of 1075–975°C (cf. Sen 1980; Melluso *et al* 1995). The T-fO_2 path follows (or closely follows) the QFM buffer curve. Sulfide minerals occur as immiscible globules (De 1974). Rare high temperature sulfides include pyrrhotite and pentlandite; but more commonly it is chalcopyrite or pyrite (De 1974).

5. Geochemistry and petrogenesis

The hypothesis that primary Deccan magmas formed by melting of a large plume head is principally based on three principal observations:

- High $^3He/^4He$ ratio of some alkaline intrusive rocks related to the main tholeiitic volcanic episode (Basu *et al* 1993).
- Large volume of eruption over a relatively short time.
- A hot-spot track that extends from the Deccan to the Chagos-Laccadive islands and the islands of Mauritius and Réunion (with the intermediate complication of post-Deccan sea-floor spreading along the Central Indian and Carlsberg Ridge).

Melts produced from the plume head presumably traveled through the continental mantle and crust prior to eruption. The erupted melts thus potentially carry signatures of several sources: continental crust, continental lithospheric mantle, asthenosphere, and the plume. However, identifying the different contributor signals is a difficult task. First, the constraints placed by Nd, Sr, and Pb isotopic data are discussed. Some discussion of trace element data is interspersed throughout. The major element composition of the Deccan tholeiites is then summarized and its petrogenetic significance discussed.

5.1 *Isotopic signatures*

Isotopic compositions are a useful tool to assess the extent of crustal contamination of mantle-derived magmas. Figure 10 shows a plot of Nd-Sr isotopic ratios of some of the western Deccan lava formations (diagram after Peng *et al* 1994). In this figure, the Ambenali formation lavas (ϵ_{Nd} of +4 to +7, $^{87}Sr/^{86}Sr_T$ of 0.7038-0.7044) represent the least contaminated, end-member composition; and the other formations exhibit different extents of contamination by different components. Noting that the lower subgroup data array radiate from a *"common area"* (marked by a star in figure 10), and based on Pb-isotopic and trace element arguments, Peng *et al* inferred that the "common signature lavas" (i.e., those plotting on or near the star) themselves are plume-derived magmas that were contaminated in the lower crust with high-degree melts (∼40% partial melts) of Archean amphibolite (Peng *et al* 1994). These authors considered an alternative suggestion of a continental lithospheric mantle origin of the common signature lavas, but favored crustal contamination because of the high $\delta^{18}O$ of phenocrysts in the common signature lavas.

According to Peng *et al* (1994), the three radiating trends exhibited by the lower formation lavas could have resulted from subsequent contamination (i.e., a second stage) involving different crustal components (marked schematically as E1, E2, and E3 in figure 10), possibly Archean amphibolites and granulites, that the lavas came in contact with as they rose through the crust along different pathways.

The Bushe Formation, with its unusually high $^{87}Sr/^{86}Sr$ ratios and low $^{143}Nd/^{144}Nd$, shows the strongest signature of crustal contamination. This is also borne out by its O-isotopic composition, Pb-isotopic composition and relatively high SiO_2 content (Cox and Hawkesworth 1985; Lightfoot *et al* 1990; Peng *et al* 1994). However, its relatively high MgO (as compared to other Deccan formations, e.g., Ambenali) is an interesting puzzle.

The trend shown by the Mahabaleshwar Formation is also interesting. It turns out that Mahabaleshwar lavas reach much lower $^{206}Pb/^{204}Pb$ values (16.66-17.99) than the Ambenali (17.64-18.24) or Bushe (18.26-22.45: Peng *et al* 1994). The various hypotheses presented to date to explain this trend are as follows (as reviewed by Peng and Mahoney 1995):

- variable contamination of Ambenali or Reunion type magma by Archean granulites;
- contamination by continental lithospheric mantle;
- Mahabaleshwar lavas are entirely from an Ocean Island Basalt (OIB)-type mantle.

Peng *et al* rejected the third hypothesis on several grounds, including the lack of any ocean islands with Pb isotope values as low as those recorded by Mahabaleshwar lavas, and on the basis of Pb- and O-isotopic data, which clearly show some crustal influence in these lavas.

5.2 *Major element geochemical considerations*

Although Deccan Trap lavas underwent variable degrees of crustal contamination, most of their major element abundances exhibit systematic pat-

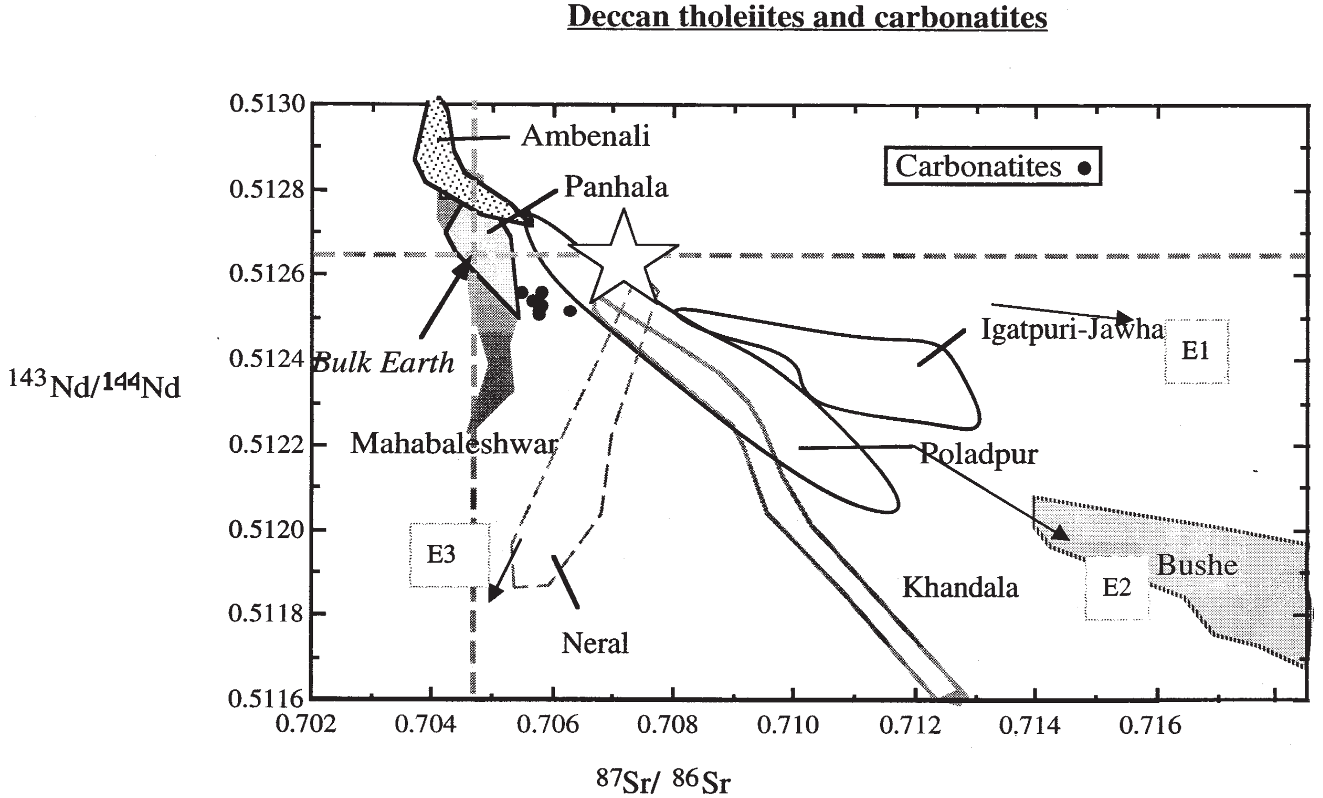

Figure 10. Nd-Sr isotopic composition of various tholeiitic lava formations of the Western Ghats compared with that of some Deccan carbonatites. E1, E2, and E3 represent three components that may have affected the Deccan tholeiities. (After Peng *et al* 1998).

terns that appear to be largely controlled by crystal-liquid fractionation, magma mixing, and partial melting processes (cf. Sen 1995). It further appears that a major control on major element abundances of Deccan basalts in general was fractionation and mixing in shallow (∼2 kbar) crustal magma chambers, because they cluster around the 2 kbar pseudocotectic ol+pl+cpx+melt (figure 11; Cohen and Sen 1988). Therefore, any attempt to model melting conditions and other, deeper magma ascent processes must first filter out the low-pressure signature.

A somewhat standard approach to "filter out" the low pressure effect is to compare different liquid lines of descent (or differentiation trends) at a comparable level of differentiation. Klein and Langmuir (1987) developed this approach for comparing mid-oceanic ridge basalt trends from different parts of the world at a MgO value of 8%. This value is significant because primitive MORB glasses or lava have 8% MgO and carry only a few per cent olivine phenocrysts. Whether the same approach works for isotopically contaminated basalts of the Deccan is an issue that has been visited by several researchers (e.g., Peng *et al* 1994; Sen 1995; Turner and Hawkesworth 1995). The general conclusion is that major element composition of these basalts is largely controlled by fractional crystallization and

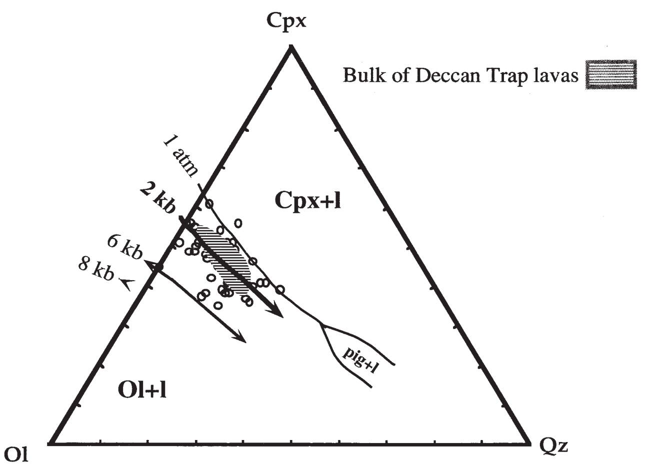

Figure 11. Liquidus projection of Deccan tholeiites (dots and shaded area) compared with ol+pl+aug+l curves at various pressures (After Cohen and Sen 1994).

mixing and very little by contamination (e.g., Cox and Mitchell 1988; Sen 1995). Peng *et al* (1994) and Turner and Hawkesworth (1995) calculated mean oxide abundances of several western Deccan formations with respect to 8% MgO. They did the same for Paraná, Siberian Traps, Karoo, and Columbia River Basalts. Based on the available data, some new plots of chemical variations have been made

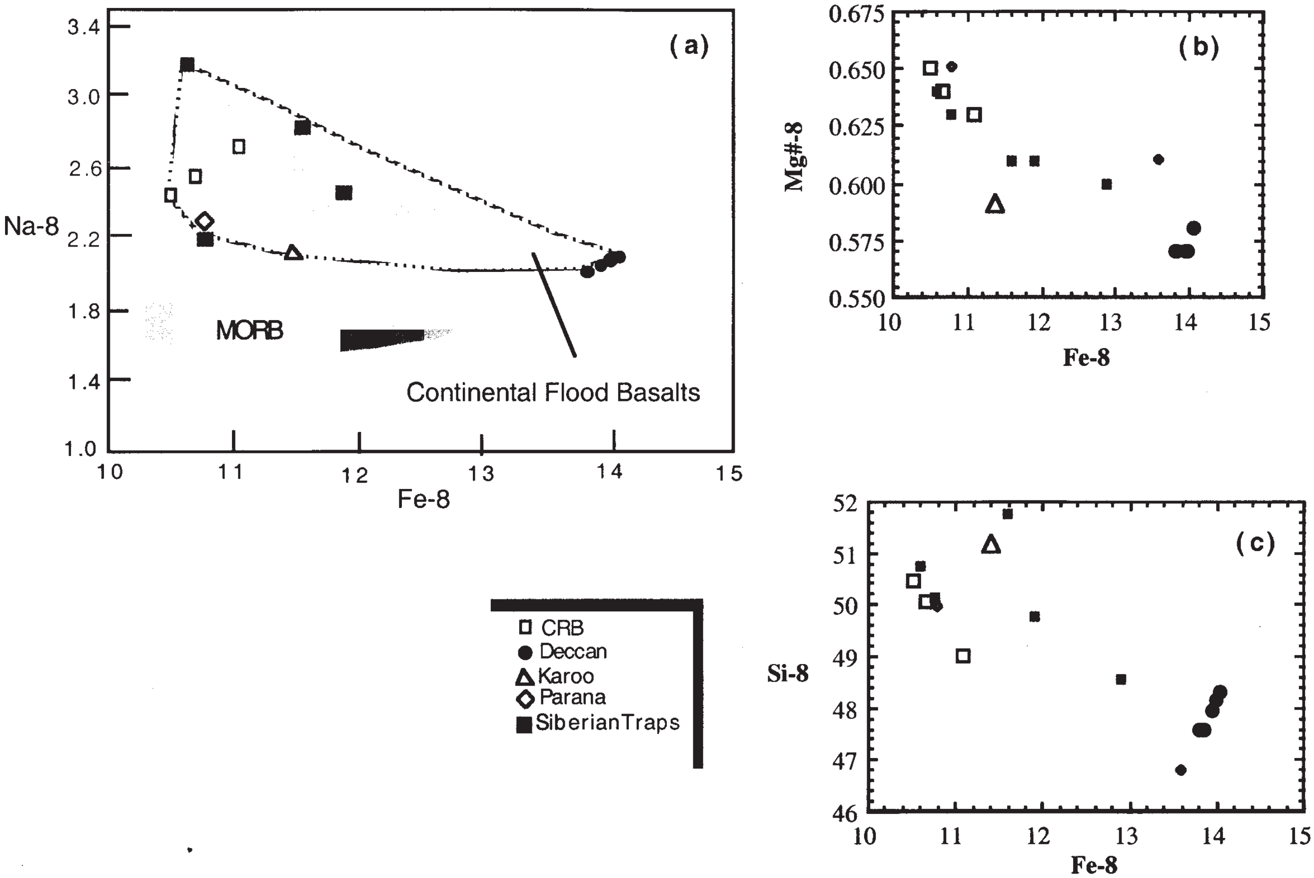

Figure 12. Deccan Trap tholeiites are compared with other flood basalt provinces and MORB on various oxide-oxide plots in which the oxides are normalized to 8% MgO. **(a)** Na-8 vs. Fe-8 plot. Each point refers to Na_2O and FeO^* values corresponding to 8% MgO (see Klein and Langmuir 1987 for the appropriate philosophy and equations). **(b)** Si-8 vs. Fe-8 correlation diagram. **(c)** Fe-8 vs. Mg# (i.e., Mg/(Mg+Fe)) correlation diagram. The significance of these plots is discussed in the text.

that expose some interesting aspects of the Deccan basalts (figure 12):

- In terms of Na_8 - Fe_8 (i.e., Na_2O and FeO^* at 8% MgO) Deccan lavas form a tight cluster and define an extreme end member among all continental flood basalt provinces (figure 12a). While other flood basalt provinces broadly overlap the MORB field, the Deccan stands out as distinct from any MORB. Klein and Langmuir (1987) concluded that higher Fe_8 reflects greater mean depth of melting (i.e., mean of the entire depth range of melt generation), whereas higher Na_8 is an indicator of higher mean percentage of melting of the source (see also, Lassiter and DePaolo 1997). Assuming that the same interpretation holds true (i.e., the source composition remains constant in terms of major elements) for flood basalt provinces, one could argue, based on figure 12(a), that all of Deccan basalts were generated at a mean depth that was greater than other flood basalts and MORB. Si_8 (i.e., SiO_2 at 8% MgO) variation, which correlates with mean depth of melting, is the greatest in the Deccan (figure 12b). This substantiates the idea that Deccan magmas were generated at a greater mean depth than other flood basalts.
- The $Mg\#_8$ vs. Fe_8 (figure 12c) plot shows that the Deccan has the lowest Mg#. However, this is entirely due to high FeO^* (and not lower MgO, because MgO values are similar or higher than the others) in the average Deccan basalt relative to averages for the other flood basalt provinces. The implication is that the low Mg# in the Deccan is a characteristic inherited during the melting process and was only subsequently enhanced by crystallization-differentiation processes.
- The Nb/La ratio of the Deccan varies a great deal relative to the other flood basalt provinces, while its Fe_8 is essentially constant (figure 13a). I calculated the mean Nb/La and ϵ_{Nd} of some key Deccan formations and plotted them in figure 13(b). Réunion lavas are also plotted for comparison. Interestingly, the Réunion trend is isotopically virtually invariant and, excluding one anomalous sample, is distinctly higher in Nb/La than the bulk earth value and the Deccan. As pointed out by many previous authors

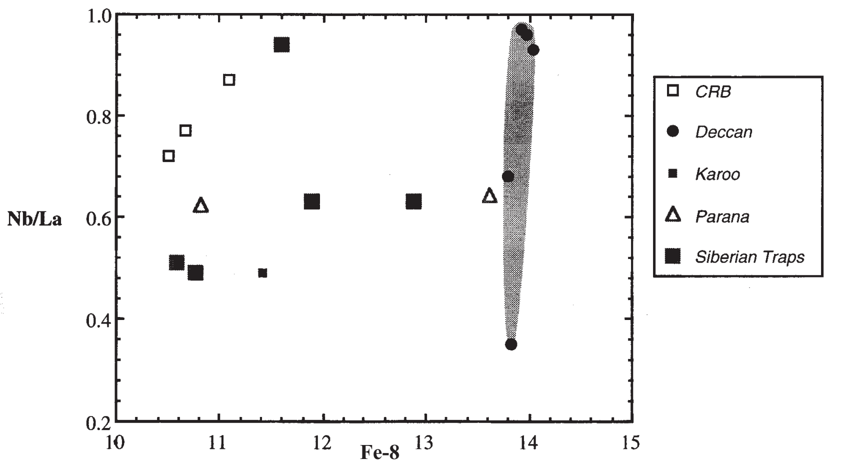

Figure 13(a). Comparison of Nb/La vs. Fe-8 values of the Deccan and other continental LIPs.

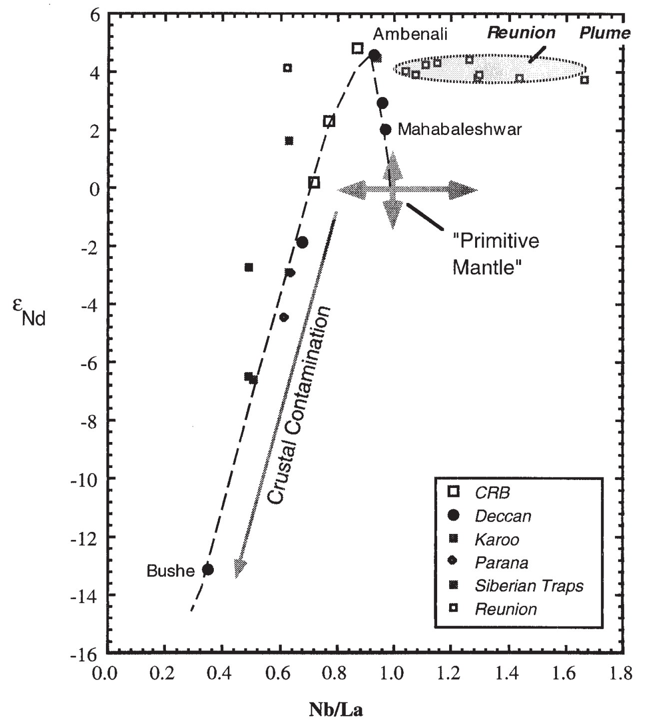

Figure 13(b). Mean values of several Deccan formations, particularly, Ambenali, Mahabaleshwar, and Bushe are compared with that of other continental LIPs, "Bulk Earth" (C1-chondritic) and Reunion basalts (Réunion data: Fisk *et al* 1988).

(e.g., Peng *et al* 1994), Ambenali is the closest to the Réunion lavas. In this figure, two separate trends for the Deccan radiate away from the Ambenali—one of which is evidently a trend of crustal contamination (marked by the location of Bushe datum). The other trend, with Mahabaleshwar at its extreme, appears to point toward the primitive mantle (chondritic). One would be tempted to suggest that the Deccan plume tapped a truly primitive mantle layer. However, as discussed earlier, this is ruled out by the isotopic data. The Mahabaleshwar trend was produced by crustal contamination of Réunion-type magma.

6. Phase equilibria and magma generation

Simple liquid-line-of-descent (LLD) calculations at 2–10 kbar pressure were performed using a number of parent magmas with a program written by C. Langmuir (Pers. Comm. 1993). One particular parent composition, Amb-2 (47% SiO_2, 1.2% TiO_2, 13% Al_2O_3, 11%FeO*, 16% MgO, 9.6% CaO, and 1.8% Na_2O), produces a LLD at 2 kbar pressure that approximately fits most oxide variations in the Ambenali Formation lavas (figure 14a,b,c). The only significant exception is Na_2O, which forms a scatter for Ambenali lavas (figure 14d). Bushe Formation trends on these diagrams cannot be fitted by Amb-2 type parent magma. The Bushe trend is likely a result of fractionation of a contaminated magma. In fact, the occurrence of pigeonite on the liquidus of Bushe lavas and ol+pl on Ambenali lavas is also suggestive of contamination-influenced differences (Gangopadhyay 2000).

MgO-FeO plot (figure 15) shows that the Amb-2 starting material (i.e., parent magma) generates a LLD that only touches the Ambenali field; on the other hand, the DeccParent-1 LLD gives a better fit to the Ambenali data. Thus, starting magmas with composition varying between Amb-2 and DeccParent-1 provide satisfactory fit to the bulk of Deccan tholeiite fields. Amb-2 is considerably more Fe-rich than all experimentally produced batch partial melts: for example, 32% melting of the pyrolite source at ∼1.5 GPa (15 kbar) produces a melt that has about 1 wt% less FeO* than the Amb-2 parent melt at a similar MgO value. Noting

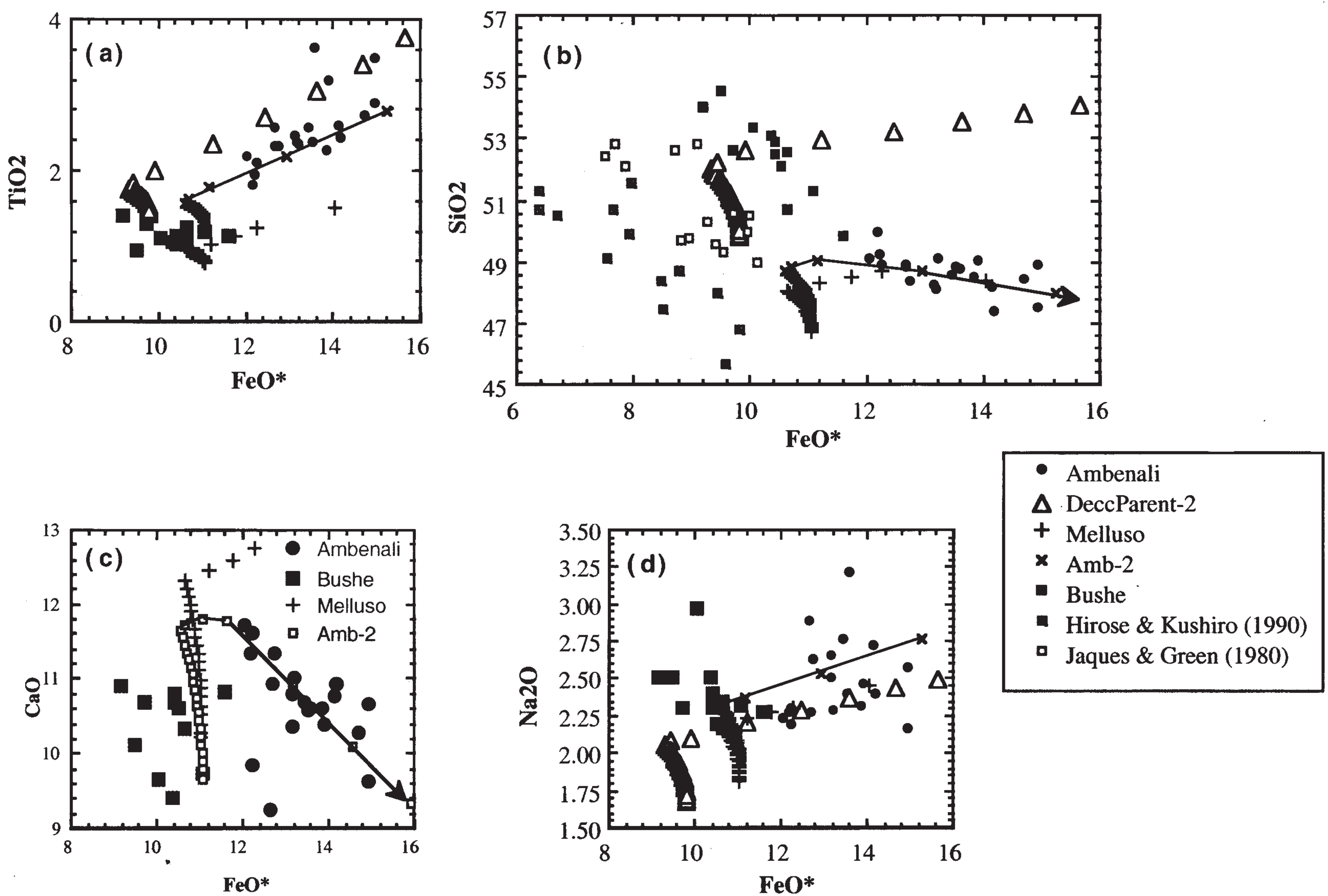

Figure 14. Ambenali and Bushe formation lavas are compared with calculated 2 kbar liquid lines of descents from three different parent magmas – one proposed by Melluso *et al* 1995; Amb-2 (proposed here, see text), and DeccParent – proposed before by Sen (1995) as an endmember parent magma. Each step in each of the LLDs represents 2% fractional crystallization. Note that the parent magmas were calculated following Sen (1995) by adding olivine to the least fractionated lava within the Ambenali Formation (keeping ol/l Kd for FeO=MgO exchange fixed at 0.3). Amb-2 LLD fits the Ambenali data quite well on most oxide-oxide plots except for Na_2O, which shows scatter.

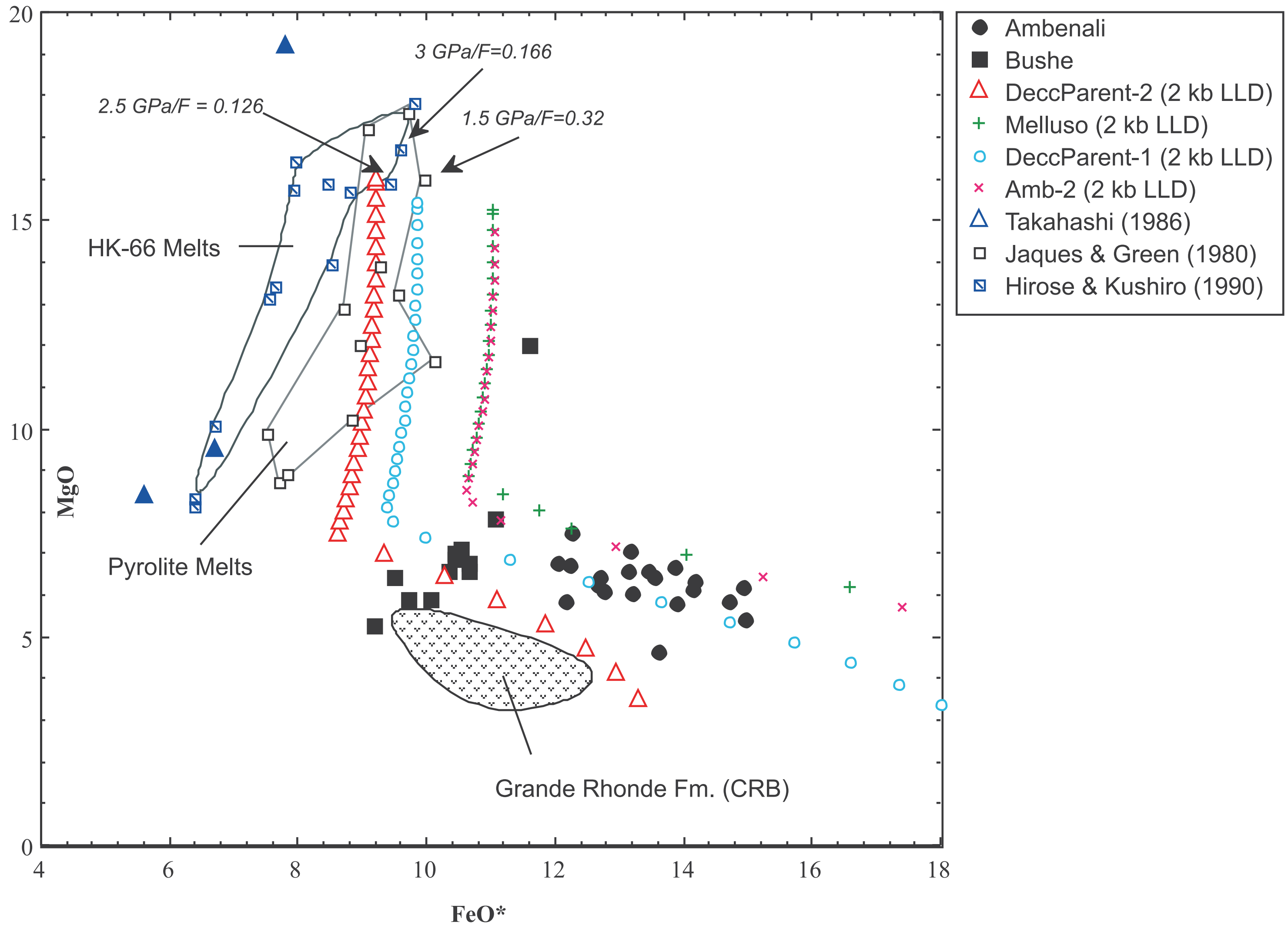

Figure 15. Ambenali and Bushe formation lavas are compared with experimentally produced partial melts from a relatively Mg-rich pyrolite (Jaques and Green 1980) and a Fe-rich peridotite (HK-66: Hirose and Kushiro 1993). The pressures for some run products are given in GPa and melt% as F; e.g., 1.5 GPa/F=0.32 means 1.5 GPa of pressure and 32% partial melting. Three calculated 2 kbar (0.2 GPa) liquid lines of descent for the three starting melt compositions are shown for comparison. Amb-2 is too Fe-rich relative to the experimental melts; however, DeccParent-1 can be generated from a pyrolitic source.

that DeccParent-1 is our best possible candidate for the Ambenali primary magma, and by extension, parent magma of all "common Deccan tholeiites", it is clear that generation of DeccParent-1 type magma would require a more Fe-rich source rock. Prior modeling efforts by White and McKenzie (1995) and Sen (1995), using very different approaches, suggested a mantle potential temperature of 1400°C for the Deccan plume and 15–25% mean melting of the plume. Both authors concluded that melting started around 100 km (3 GPa) and ended at about 60 km (2 GPa) below the surface.

7. Geophysical and petrologic constraints on Deccan magmatism

A recent re-evaluation of the gravity and seismic data over the Deccan plateau by Pant *et al* (1999) is of considerable relevance in view of the above summary of petrological assessment of the melting process. Pant *et al* contrasted studies by previous workers with theirs and came to the following conclusions:

- A density "interface" (i.e., minor discontinuity) occurs at 117 km, which they interpret to be the base of the Indian lithosphere.
- On average, the Moho occurs at 40 km.
- The crust across the SONATA is perhaps trilayered with a (i) lower crust (Vp = 7.2–7.4 km/sec) occurring at 25–40 km, (ii) upper crust (Vp = 6 km/sec) of variable thickness between 2 and 12 km; and (iii) middle crust (Vp = 6.9–7.1 km/sec (Kaila 1988).

Pant *et al* felt that the upper crust as defined above is "granitic" crust, and the lower crust is perhaps composed of "underplated" materials without offering any additional explanation.

Sen (1995) calculated that Deccan magmas had lost on average a minimum of 26% olivine cumulates as they ascended to the mid-crustal "chambers". It is possible that the "lower crust" is composed largely of these dunitic cumulates. The problem is that the observed velocities are perhaps a little too low (should be closer to 8). It is possible that the presence of intercumulus materials in the cumulate-rich lower crust is responsible for driving the Vp to lower observed values or some preexisting lower Vp crust remains. The "middle crust" is consistent with intrusive complexes where gabbroic fractionation may have occurred prior to the eruption of lavas.

If the petrological inference that plume melting occurred in the 100–60 km depth range is correct, then comparison with geophysical interpretations leads to the following conclusions:

- The continental lithosphere could have been heavily involved at some point in the melting process; or, alternatively, such lithosphere could have been convectively eroded by magmas and digested back into asthenosphere (a suggestion made by J. Mahoney 2001, pers. comm.)
- The 40–117 km thick mantle region, which Pant *et al* call the lithosphere, could very well be partially melted plume residue material that was plated on to the base of the crust. By implication, the 40–117 km thick mantle region beneath the sub-Deccan crust is very young (∼68–65 m.y.) is probably mostly plume-derived.

8. Summary of conclusions

- The bulk of the Deccan Trap lavas erupted at the K/T boundary. Paleomagnetic data suggest ∼90% of the eruption took place in less than 500,000 years. Calculations of the time scale of plagioclase phenocryst growth in giant plagioclase basalts suggest the possibility of a much shorter interval (perhaps as short as 55,000 years) for the eruption of the entire package of Western Ghats basalts (the type section).
- The main center of eruption appears to be an area near Nasik. There were other centers as well, most notably, one in the Satpura region of Central India, one in the northwest in the Cambay area, and a few more along the SONATA lineament.
- The bulk of the lavas are tholeiitic with $< 7\%$ MgO and carry phenocrysts of olivine and plagioclase. Many also contain augite phenocrysts. Pigeonite phenocrysts are rare but its relative abundance in the groundmass is a topic of debate. Aside from the tholeiites, carbonatites and other mafic alkaline lavas also occur in minor amounts. Mantle xenoliths, mostly spinel lherzolites and pyroxenites, have been found in some intrusions and lavas on the west coast.
- The Deccan Traps of the type area have been divided into eleven formations based on geochemistry, among which the most definitive are the Ambenali, Poladpur, and Bushe formations. Bushe lavas show the strongest signatures of contamination by the continental crust. The Ambenali is the thickest formation and is the least contaminated. The Poladpur may be laterally the most extensive among all formations.
- Comparison between the Deccan and other continental flood basalt provinces in terms of Na_8, Fe_8 and Si_8 (where the subscript 8 stands for data at 8% MgO) indicates that the Deccan magmas were produced by the greatest degree of melting and at a depth range greater than

the other flood basalts. These melts underwent olivine-fractionation near the Moho and then further gabbroic fractionation within the shallow-intermediate crust (6 km below the surface; ∼2 kbar pressure). Quantitative modeling suggests that the melting range may have been 100–60 km below the surface. This depth range would suggest that the continental lithosphere was involved in the melting and contamination process; and the present mantle portion of the Indian lithosphere may have a large component of plume residues "plated" onto the base.

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