Chapter 2
Deccan Traps Flood Basalt Province: An Evaluation of the Thermochemical Plume Model

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Abstract The Deccan volcanic event occurred when India was situated at the present location of Reunion Island in the Indian Ocean. The cause, duration of eruptive pulses of this major volcanic event and its impact on the global climate are controversial. Plume versus non-plume hypothesis for the origin of Deccan melting anomaly is evaluated here based on a review of geochemical and limited geophysical criteria. We know that the most primitive Deccan magmas were picritic in composition that equilibrated in the mantle at about 1,550°C (±25) and 2.5 (±0.3) GPa. These magmas were generated from a large plume. We find that much of the differentiated and contaminated appearing basalts could not have been produced from such picritic magmas, and suggest that such tholeiites are a product of melts derived from the plume, the subcontinental lithospheric peridotites, and from ancient orogenic-type eclogitic blocks embedded within the continental lithosphere.

2.1 Introduction

The Deccan Traps volcanic province is a prominent feature on India's geological map (Fig. 2.1). Bose (1972, 1995) was a pioneer in recognizing the importance of these flood basalts as a volcanic event of global significance and related their origin to global tectonics. This flood basalt province continues to attract global attention today because of its enormous volume and eruption duration that overlapped the Cretaceous–Tertiary boundary (e.g., Mahoney 1988; Duncan and Pyle 1988; Courtillot et al. 1988). Deccan erupted while India was located in the Indian Ocean

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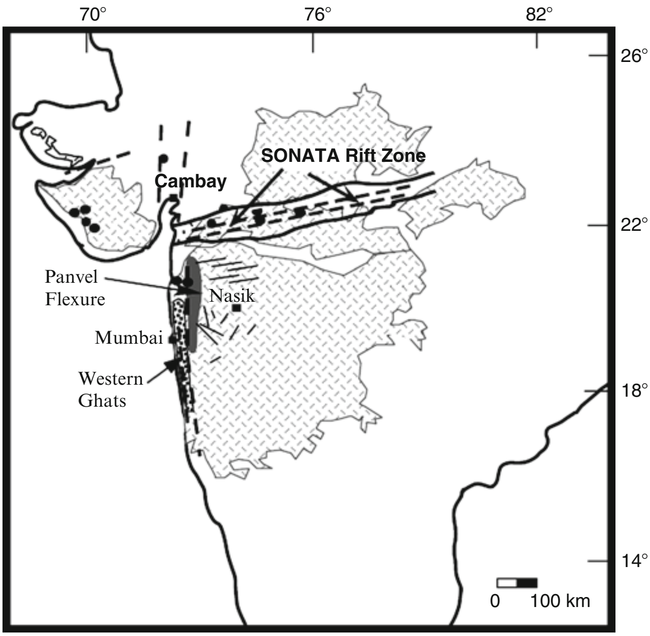

Fig. 2.1 Map of India showing the Deccan Traps and some major intrusive systems related to the Deccan

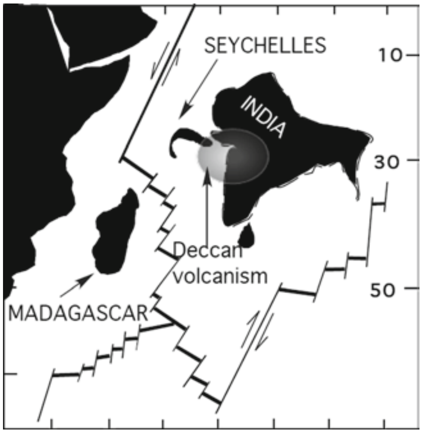

Fig. 2.2 Location of India where Deccan volcanism actually occurred

over where Reunion is presently situated (Fig. 2.2; Mahoney 1988). In spite of the past 2 decades of intensive studies of the Traps, our knowledge of its possible impact on global/local climate, oceans, and biota seems limited (Keller et al. 2008; Self et al. 2006, 2008). The 1783–1784 Laki eruption (Iceland) is the closest, albeit being much smaller (Laki – 14 km^3; Deccan – 1.5 million km^3), analog to the Deccan eruption in terms of rate of lava production, basaltic chemistry of lava, and fissure style of eruption (Self et al. 2008). The Laki eruption wiped out over 50% of Iceland's livestock population and led to a famine that killed 25% of the human population. If we extend the Laki eruption to the scale of the Deccan, then its effect could have been colossal at least over India (Self et al. 2008). A few recent studies have suggested that in the Western Ghats, where the lava package is the thickest, there had been short pulses of massive eruptions lasting a few thousand years (Sen et al. 2006; Chenet et al. 2007). If true, such "spikes" would have had significant impact on climate and biota.

The origin of the Deccan Volcanic Province has been much debated. The debate concerns whether the magmas formed by melting a giant mantle plume, normal plate tectonic processes, or impact of a large extraterrestrial bolide (e.g., Mahoney 1988, Richards et al. 1989; Chandrasekharam and Parthasarathy 1978; Chatterjee and Rudra 1992; Sen 1995; Sheth 2005a, b). In the 1960s several authors recognized the difficulties in explaining all volcanic phenomena on earth with the shallow mantle-melting model required in the plate tectonics theory and proposed the concept of hot spots (Wilson 1963). Wilson felt that the Hawaiian island chain, which is located in the middle of a large oceanic plate, could not be explained by shallow mantle process as required by plate tectonics. Wilson's model for the Hawaiian volcanic chain called for generation of magmas from a spatially fixed thermal plume rooted in the deep, non-convecting, mantle. Soon after Wilson, Morgan (1972) presented the concept of mantle plumes. Whereas hot spot *sensu stricto* refers to a hot jet or thermal plume, Morgan's plume would include material transfer from the deep to shallow mantle. In the subsequent years, geochemists and geophysicists have used the term "plume" at random to mean different things; but in general, "plumes are upwellings and downwellings that are maintained either by thermal or chemical buoyancy or by both in concert" (Anderson and Natland 2005).

The plume model as put forth in those early years was quickly gaining recognition once K/Ar dating of the Hawaiian volcanoes showed that the islands get older with distance from the active volcanoes of Kilauea and Mauna Loa on the island of Hawaii (Dalrymple 1969). However, there were others who viewed the plume hypothesis with some skepticism; for example, in a witty article Holden and Vogt (1977) noted "The mantle plume is just the youngest member of a big and colorful family of geological fads and fashions…Since plumes are better hidden from observation than plates, it may take years to prove or disprove their existence."

The Deccan Traps eruption is often used as a spectacular example of mantle plume activity (Fig. 2.2; e.g., Richards et al. 1989; Duncan and Richards 1991). The basic idea is that the Deccan magmas formed by melting a giant "plume head" that rose from the core–mantle boundary. This plume head was anchored to the source by a long tail that created the Chagos-Laccadive volcanic chain. A jump of a ridge that is now the Central Indian Ridge about 40 million years ago broke up the chain, and the original plume tail is now creating volcanism on Reunion Island.

There are several authors who have doubted the plume theory as far as the origin of the Deccan Traps is concerned (e.g., Sheth 2005a). Chandrasekharam and

Parthasarathy (1978) noted that the Deccan basalts predominantly erupted through fissures in the crust and proposed a model of shallow mantle melting in which the preexisting rift zones were reactivated and magma simply poured out of fissures (Chandrasekharam and Parthasarathy 1978). This was a time when the concept of plate tectonics was gaining ground; and so the melting mechanism was considered to be analogous to passive rifting of the lithosphere and magma generation at the global mid-oceanic ridge system. Sheth (2005a, b) has proposed much more revised versions of the shallow melting model that appeals to normal plate tectonics and lithospheric melting processes.

Finally, Chatterjee and Rudra (1992) and Chatterjee et al. (2006) suggested that a large bolide crashed offshore near the “Bombay High” area and melted the lithosphere, generating large volumes of magma that erupted as the Deccan lavas. This hypothesis has not been generally accepted mainly because it is not a testable hypothesis and requires further exploration: for example, the physical evidence is weak for the existence of an offshore impact crater with an onshore crater rim at Panvel flexure. Such an impact would have produced the first batch of magma close to the impact site and thus the oldest lavas should have been found close to Bombay. Instead, the oldest Deccan lavas are found in Pakistan, much further north of Bombay (Mahoney et al. 2002). Also, the impact idea does not explain why there is an age progression from the Deccan through Laccadives to Seychelles to Reunion (Duncan and Richards 1991). Nevertheless, one cannot completely rule out this impact hypothesis until the deeper lavas beneath Bombay area (both off and onshore) are sampled *via* drilling.

In this paper we do not further explore an extraterrestrial cause for the Deccan volcanism and focus the rest of our discussion on internal terrestrial mechanism. Here we re-visit an ongoing debate concerning whether a large plume was at all involved in forming Deccan magmas or such magmas formed due to normal plate tectonic processes. This is a “hot” topic in geology today.

A website (www.mantleplumes.org) and two volumes (Foulger et al. 2005) have been dedicated mainly to disprove the existence of mantle plumes although, in all fairness, the editors have included several papers that defend the plume hypothesis. Those who do not currently subscribe to the plume hypothesis have come up with alternative models that generally imply shallow upper mantle melting and cracks in the lithosphere creating all the volcanism that are usually attributed to plumes. As Campbell (2005) recently noted, even the sharpest critics of the mantle plume hypothesis have failed to make a convincing case for a non-plume origin of the Hawaiian volcanic chain. If lithospheric cracks were the reason then the Molokai fracture zone, which is one of the longest fractures that reaches close to Hawaii, should have caused volcanism, which of course has not happened. It is true that many volcanic regimes randomly attributed to plumes may be explained better with alternative models. In terms of “record keeping”, however, the plume hypothesis continues to endure the attacks; and over the past few years the focus has fallen on imaging deep plumes using seismic tomography even though Anderson (2006) has urged caution in using tomography alone to interpret mantle dynamics and proposed additional seismic experiments.

Given the above backdrop, we avoid any genetic implication and use the term "Deccan Melting Anomaly (DMA)" throughout this paper to refer to the Deccan melting source region. Here we review the possible conditions of magma generation and examine the following factors: volume of original (primary) magma produced, the time within which the maximum volume of magma was generated, the source rocks, and the temperature–pressure conditions of magma generation. This evaluation leads us to the conclusion that a complex melting model involving both a relatively Fe-rich plume and lithosphere best explains all features of the Deccan Traps.

2.2 Duration of the Deccan Event and Mean Eruption Rate

An important argument in favor of the plume origin of the Deccan is that too much lava came out in too short a time requiring some special melting mechanism that does not fit the normal plate tectonic schemes (e.g., Sen 1995). The most impressive demonstration of this came through the $^{40}Ar/^{39}Ar$ dating of the 2.7 km thick Western Ghats section by Duncan and Pyle (1988). Since that work, other research groups have dated different parts of the Deccan province but the general picture has remained the same – that is, the bulk of the lavas erupted 65–66 Ma within two magnetic chrons – 29R and 29N; however, one important exception is that Mahoney et al. (2002) obtained a 72 million years. date from some lavas in Pakistan (Fig. 2.3; Mahoney et al. 2002). Another alkalic intrusion of ~69 Ma age was found close to Barmer near the northwestern periphery of the Deccan (Basu et al. 1993). The youngest date of ~61 Ma was obtained by $^{40}Ar/^{39}Ar$ dating of some rhyolitic lava/intrusions in the Bombay area (Lightfoot et al. 1987; Sheth et al. 2001). Figure 2.3 shows a summary of Deccan Trap ages obtained by different methods (slightly modified from Chatterjee and Rudra (1992). It shows that about 90% of the lavas came out within 1 million year during the 29r magnetic chron.

As discussed by Sen (2001), estimates of the original (pre-erosion) volume of the lavas vary significantly. If we accept the volume to be 1.2×10^6 km^3 erupted in 1×10^6 years, then the mean eruption rate could have been 1.2 km^3 per year. Sen et al. (2006) have suggested that the actual duration could have been much shorter – of the order of only 30,000 years, which will mean an average eruption rate of 40 km^3 per year. The Laki eruption of 1783–1784 in Iceland, which produced 14 km^3 of lava, is the only historic eruption that comes close to the Deccan's astounding eruption rate. We should say this with the caveat that much finer age refinement with radioisotope dating of the lavas and a more accurate estimate of the volume of the lavas are needed to have a stronger constraint on the eruption rate of the Deccan. Without such refinement, the mean eruption rate could have varied between 1 and 40 km^3 per year. A paleomagnetic study by Chenet et al. (2007) suggests that there were episodic bursts of lava eruption with intermittent quiescence. The mean eruption rate refers to a cumulative rate that included the quiet periods between eruptions. The picture needs clarity with detailed studies of the individual lava outpourings that produced the

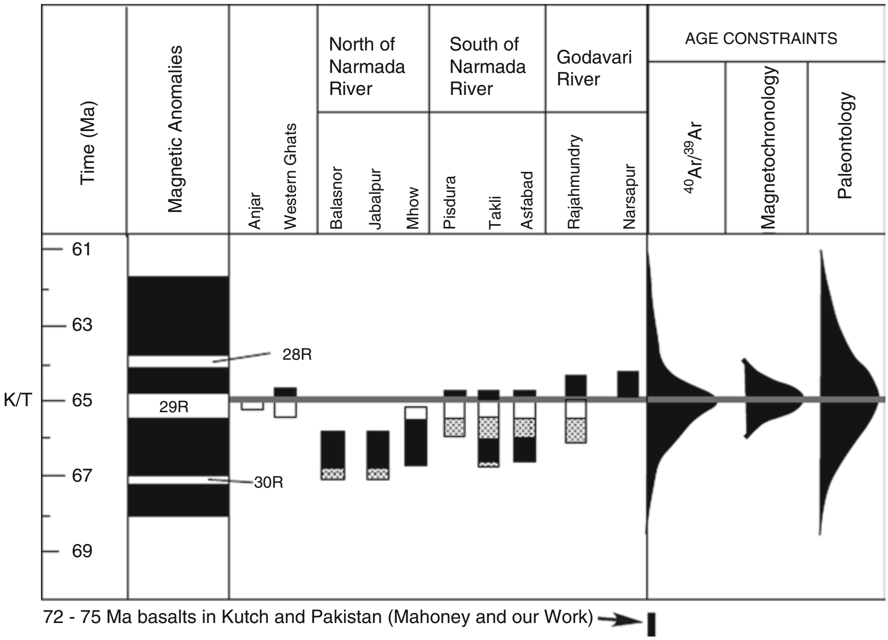

Fig. 2.3 A compilation of ages of the Deccan Traps from various sites and using different age determination techniques. The bulk of the magmatism occurred at 65 ± 1 Ma during the 29R magnetic chron (modified after Chatterjee and Rudra 1992)

geochemically defined formations in the lava province and the intermittent periods when weathering resulted in the formation of "boles" or soil horizons between lava flows.

2.3 Source and Potential Temperature of the Deccan Mantle Anomaly: Message from Geochemistry

2.3.1 General Considerations

The Deccan flood basalt province is predominantly tholeiitic; however, alkalic lavas and intrusions, carbonatite intrusive complexes, and silicic lavas and intrusives also occur. Carbonatites and alkalic lavas, with some of the latter carrying mantle xenoliths, are restricted to the rift zones that occur near the peripheries of the Deccan (Fig. 2.1). Experimental petrology has shown that carbonatites and mafic alkalic melts, such as nephelinites, basanites and alkalic olivine basalts, are generated as near-solidus, low degree melts from carbonated peridotites at pressure of ≥2.8 GPa (e.g., Keshav and Gudfinnsson 2004). Simple volume consideration of the erupted lavas suggests that Deccan tholeiites or their parent magmas were generated in much greater volumes than carbonatites and alkalic magmas.

Presumably, parent magmas of tholeiites were generated at higher potential temperatures and by much greater degrees of melting than the alkalic and carbonatitic magmas (Sen 1995). In the discussion that follows we focus largely on the origin of the tholeiites.

An evaluation of the melting conditions requires an understanding of the composition of the source rock, and conditions of melting, which includes temperature, pressure, and volatiles (CO_2 and H_2O and their fugacities). The first step toward achieving this goal is to "retrieve" the composition of the *primary magma.* Following conventional wisdom we define a primary magma as a natural melt that is in equilibrium with its source rock, which could be an eclogite, garnet pyroxenite, or a peridotite in case of basaltic magmas. Constraining the composition of the primary magma(s) is of first order importance because it sets limits on the thermal conditions reached during magma segregation from the source with which it fully equilibrated at a certain depth or over a depth range. That in turn would allow one to evaluate the excess potential temperature (ΔT_p), defined as potential temperature of the melting anomaly ($T_{p\text{-MA}}$) minus that of Mid-oceanic ridges ($T_{p\text{-MOR}}$). Exactly how much ΔT_p would distinguish a thermal plume (presumably of deep mantle origin) *versus* upper mantle origin of such melting anomalies as the DMA is somewhat debatable but in general, a T_p of >1,450°C would make a strong case for a thermal origin (e.g., Faernetani and Richards 1994; Anderson 2006; Courtier et al. 2007).

Next comes the issue of source rock(s) – peridotite, eclogite, or some other rocks? In the eclogite melting case, the erupted basalts would simply be products of bulk melting (>70%) of a basaltic (eclogite is only a high pressure metamorphosed basalt) source. Also, in this case, the excess temperature required would be very small (<120°C) to generate a large volume of magma (Kogiso et al. 1997; Pertermann and Hirschmann 2003). In the peridotite melting scenario, the primary magmas would necessarily be high temperature picritic magmas that would have lost large amount of olivine by fractional crystallization during their ascent through the crust (e.g., Cox 1980; Sen 1995, 2001). In this scenario, excess temperatures of ≥250°C would be necessary (Sen 1995, 2001). On the other hand, an eclogite/garnet pyroxenite model would not require the significantly excess temperature and could instead favor a shallow mantle origin of the DMA in which the eclogite source could be blobs or blocks derived from old subducted slabs or deep continental crust. Peridotite could be part of the asthenosphere, continental lithosphere, and/or the plume itself.

2.3.2 Isotopic Composition

Most geochemists consider helium isotope ratio ($^3He/^4He$) to be an important indicator of the mantle source (e.g., Class and Goldstein 2005). ^3He is primordial whereas ^4He is produced by radioactive decay of the actinide elements U and Th. Mid-ocean ridge basalts (MORB) are generally accepted to result from shallow melting of the asthenosphere, which is also often referred to as "shallow convecting mantle" (which implies that there is a physically and chemically distinct convecting deeper or Lower Mantle). MORB $^3He/^4He$ ratios range between 7 and 9 R/R_A (measured ratio normalized to that of air). Basalts with elevated R/R_A of >10 are considered to be derived from a deeper mantle region with lower time-integrated $(U + Th)/^3He$, and a thermo-chemical plume is usually taken to be responsible for pulling up such mantle materials to shallow levels where they undergo partial melting. An extreme example of a volcano with very high R/R_A (~32) is Loihi, a submarine seamount off Kilauea (Kurz et al. 1983). Basu et al. (1993) determined the R/R_A values of two Deccan alkaline complexes from northern India to be 10–13, which they used as evidence to support a Lower mantle plume origin of Deccan Traps volcanism.

We now look at the Nd, Hf, Pb, and Sr isotopic composition of Deccan basalts in order to assess the nature of the source rock materials (Fig. 2.4). The various isotopic trends exhibited by various Deccan formations diverge away from a "common signature" area, which was suggested by Peng and Mahoney (1995) to be the actual mantle source composition of the Deccan tholeiites. Notably, the "common signature" overlaps the composition of Reunion lavas. A study by Hanyu et al. (2001) showed Reunion source to have a R/R_A of 13, which is consistent with the similarity between Deccan "common signature" and Reunion lavas in terms of He isotope ratio as well.

Many authors have suggested that the cause of isotopic divergence in the Deccan is contamination of the magmas by mostly Archean/Proterozoic crust (e.g., Peng et al. 1994). The problem is that no quantitative modeling scheme that involves the crust could effectively reproduce the contamination signal involving major and trace elements as well as isotope ratios. Chatterjee and Bhattacharji (2008) recently showed that in some cases the isotopic contamination signals would require incorporation of as much as 64% continental crust into the magma generated from a mantle peridotite. The authors therefore noted (as have others before them) that the

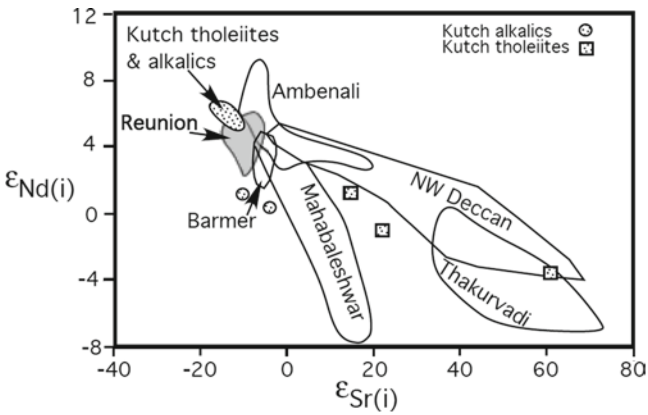

Fig. 2.4 Isotopic variability within some Deccan lava formations (From Sen et al. 2009). The various formations, mantle xenolith-bearing alkalic basalts, and Reunion lavas all seem to converge at a general area

isotopic contamination signal must have been acquired by the magmas prior to entering the shallowest reservoirs where they underwent further mixing and crystallization-differentiation. Sen (1995) deemed these shallow reservoirs to be located no deeper than about 6 km.

In the case of the Deccan, there is a consensus that the isotopic signature of continental crustal contamination is the strongest for the Bushe Formation of the Western Ghats (e.g., Cox and Hawkesworth 1985; Beane and Hooper 1988; Lightfoot and Hawkesworth 1988; Mahoney et al. 2002; Peng et al. 1994; Melluso et al. 2006; Gangopadhyay et al. 2005). For the rest of the formations, the isotopic diversity is perhaps mostly a result of melting the old continental lithosphere and crustal fragments (charnockites, granulites, ecogites) buried within the lithosphere.

The case against bulk crustal contamination at shallow to mid-crustal levels is rooted in the following observations:

1. Geochemists often think of the contamination process in terms of mathematical mixing between a magma and continental crust and do not take into consideration the large amount of heat (enthalpy of fusion) that would be required to accomplish the melting. Glazner (2007) has quantitatively shown that the enthalpy of fusion required to melt such a large chunk of the crust is prohibitively large. Such a large extent of contamination would likely freeze the magma entirely.
2. One may expect to see more silicic and intermediate composition lavas. The fact is that the commonly erupted lavas are tholeiites with 5–7% MgO. Yes, there are some minor rhyolites but andesitic lavas have not been reported anywhere. If we assume that the proportion of erupted lavas are volumetrically representative of the melts generated, then the absence of andesitic melts and presence of tiny volumes of rhyolitic lavas suggest that very little crust was melted, and/or fractional crystallization was not extreme enough to generate the intermediate/silicic melts.
3. Excluding Bushe and other formations that show geochemical evidence of crustal contamination, Deccan tholeiites as a whole follow ordinary liquid line of descent at 2 GPa (Sen 1995). The chemical imprint of fractional crystallization on both major and compatible trace elements significantly supersedes the crustal contamination signal (Figs. 2.6, and 2.7, further discussed in a later section). Bulk assimilation also results in fractional crystallization, for which there is no evidence in the Deccan: for example, there is no correlation between, such fractionation signals as Mg/Fe ratio or TiO_2 content and isotopic signal of contamination.
4. Two recent studies (Sen et al. 2006; Chenet et al. 2007) have suggested that at least some Deccan tholeiites may have erupted at rapid pace, which implies a very short residence time for the magmas in the crust. This would be a problem for models requiring the magmas affected by the continental crust, which would presumably require longer time. This argument is not particularly strong at this point because this line of inquiry is very new and more detailed studies need to be done.

The bottom line is that the spectacular diversity that is exhibited by the isotope ratios is not as dramatic in major element or compatible trace element compositions.

As some authors have said before us, the isotope signal may be partly derived from the melting of complex crustal types already buried in the continental lithosphere and partly from selective contamination by the crust.

2.3.3 Trace Element Chemistry

Several authors have modeled rare earth elements in alkalic basalts and tholeiites and suggested that the alkalic magmas were generated from garnet peridotite and the tholeiites, which are predominant in the Deccan province, were mostly produced at a shallower depth within the spinel peridotite field (e.g., Basu et al. 1993; Melluso et al. 2006). Figure 2.5 illustrates this important constraint. It shows a plot of $[Sm]_n$ vs. $[Sm/Yb]_n$ of Deccan tholeiites from across the Deccan (source of data: GEOROC database) and few picrites from northwestern Deccan that were studied by Melluso et al. (2006). We also show the composition of melts formed by equilibrium melting of a spinel versus garnet peridotite that have the same chondritic REE composition

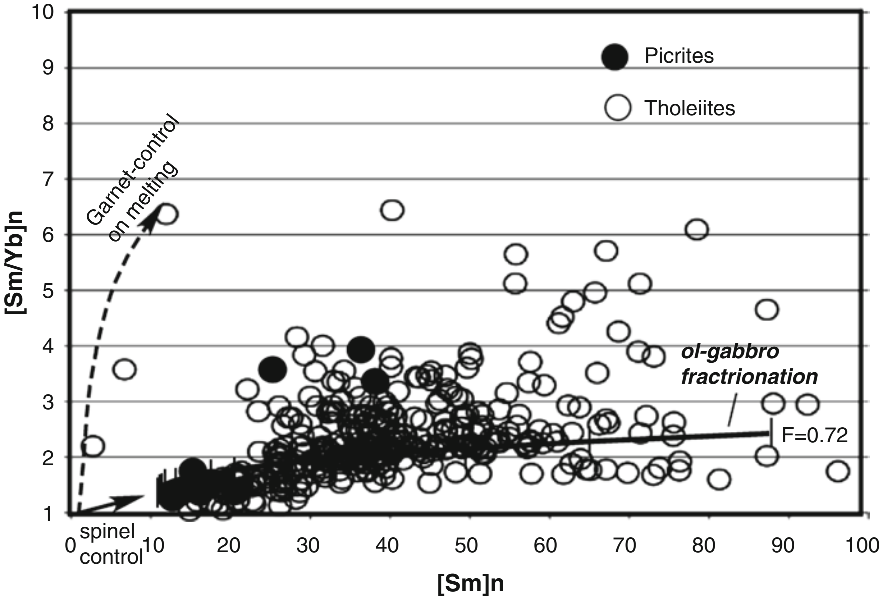

Fig. 2.5 Chondrite-normalized Sm/Yb versus Sm variation in Deccan tholeiites (*circles*, GEOROC database). A few picrites from northwestern Deccan are also shown here (Melluso et al. 2006). Two calculated melting paths in garnet versus spinel peridotite fields from a chondritic source are shown for comparison. The nonmodal equilibrium melting equation was used (additional information is given in Appendix). A hypothetical olivine-gabbro fractionation trend (*bold line with arrow*) is also shown (see Appendix for calculation information). The F reflects melt fraction remaining. Most Deccan tholeiites and the low Sm/Yb picrites appear to form by low pressure melting in the spinel peridotite field (1–2.7 GPa). The range shown by the common Deccan tholeiites can be generated by ~30% olivine-gabbro fractionation

(model calculation data are given in the Appendix). As has long been known, residual garnet selectively retains Yb over Sm and is effective in increasing the Sm/Yb ratio of partial melts. Figure 2.5 shows that Deccan tholeiites, in spite of variable degree of crustal contamination (discussed before), have consistently low Sm/Yb ratio that is best explained by about 30% olivine-gabbro fractionation (see Appendix for calculation) from primary magmas generated from spinel peridotite. We also plotted the high-Ti and low-Ti picrites from Gujarat. The three high-Ti picrites are of alkalic affinity and have higher Sm/Yb ratio, which indicates that they may have had parent magmas that were generated in the garnet peridotite field (Melluso et al. 2006; Sheth and Melluso 2008).

If the source is peridotitic then the minimum pressure at which the residue can have garnet is 2.8 GPa (approximately at 90 km depth); however, if the source is eclogite or garnet pyroxenite then the minimum pressure would be 1.6 GPa (~50 km). As far as REE modeling goes, the eclogite source composition would be expected to vary a great deal in composition because they are basically metamorphosed basalts. The use of this diagram alone, without consideration of other compositional aspects, cannot distinguish between a relatively uniform peridotitic source *versus* a highly variable eclogitic source unless of course garnet stays in the eclogite residue during melting. However, the fact that Deccan tholeiites overwhelmingly exhibit LREE-enriched (chondrite-normalized) character suggest that there was none or extremely minor recycled (previously subducted oceanic crust) eclogite component in its source. The source had to have a predominant LREE-enriched component that could have been old enriched continental lithosphere, old deep crustal metamorphic rocks (e.g., eclogite), or an enriched plume.

2.3.4 Major Element Composition

Major elements are critical in obtaining depth and temperature information on primary magmas of a volcanic province, both of which are of relevance in our discussion in the present paper. Picrites have traditionally played an important and sometimes controversial role in all discussions of flood basalt genesis (e.g., Cox 1980; Sen 1988). Here we pay close attention to Deccan Trap picrites from the point of magma generation conditions, which may provide a strong constraint on thermal conditions of the DMA.

Sen (1988) compared the major element composition of Deccan tholeiites with partial melting experiments conducted by Takahashi and Kushiro (1983) and found that tholeiitic picrites with ~10 wt% MgO are almost identical to the experimental melts generated at the solidus from a peridotite at 1 GPa. At 1 GPa, spinel/plagioclase peridotite transition occurs and garnet is not a stable mineral. This is consistent with the trace element discussion of requiring melting in the spinel peridotite field, as discussed by others (e.g., Melluso et al. 2006) and in the previous section.

Sen (1995) calculated potential primary magma compositions for the Ambenali Formation (Table 2.1). Both Sen (1995) and White and McKenzie (1995) applied more complex modeling methods and interpreted the major element variation to

Table 2.1 Calculated Deccan primary magmas and potential temperatures

		Picrite	Adjusted	Sen (1995)	
		Pavagarh	primary	Amb	Amb
Wt%		K'2000	liquid (PMK)	Melt2	Melt1
SiO_2		48.70	*46.40*	48	50.57
TiO_2		1.76	*1.68*	1.3	0.87
Al_2O_3		10.09	*9.61*	13	12.61
FeO*		10.29	*9.91*	11	10.88
MnO		0.18	*0.17*	0.1	0.1
MgO		14.78	*18.96*	15	13.96
CaO		11.76	*11.20*	10.25	9.13
Na_2O		1.49	*1.42*	1.7	1.96
K_2O		0.68	*0.65*	0.12	0.14
Total		99.73	*100.00*	100.47	100.22
Tp-H&G'09	°C	1,453	*1,550*	1,459	1,431
Tp-Put'08–15	°C	1,488	*1,595*	1,519	1,576
Tp-Alb'92	°C	1,435	*1,549*	1,445	1,402
Tp-Lee'09	°C	1,470	*1,490*	1,503	1,474
Mean Tp	°C	1,462	*1,546*	1,482	1,471
Pressure_Lee	GPa	1.90	*2.30*	2.4	1.80

have resulted from accumulation of partial melts of peridotite from about 3 GPa, close to the garnet/spinel transition, to 2 GPa, well within the spinel peridotite field. Based on two different thermometers, Sen (1995) calculated potential temperatures ranging from 1,370°C to 1,460°C. In contrast, White and McKenzie (1995) and Melluso et al. (1995) proposed potential temperatures of 1,470 and 1,430–1,468°C, respectively. Many more detailed studies of Deccan Traps and laboratory melting experiments have taken place since that time and therefore we revisit some aspects of the major elements and evaluate whether the same maximum temperature of 1,470°C for the DMA still holds up.

Figure 2.6 shows a field of Deccan tholeiites, some selected Deccan picrite compositions, global eclogite compositional fields, and parameterized near-solidus compositions from a peridotite over a pressure range of 1–3.5 GPa. Although there are many more picrite analyses to be found in the Deccan literature, a large number of them have been shown to not be melts but melts with excess accumulations of olivine crystals (e.g., Beane and Hooper 1988). We chose only those compositions that have been deemed to be closer in composition to potential melts based on their petrography (aphyric to near-aphyric) and whether or not such compositions exhibit an olivine/melt FeO/MgO partition coefficient close to ~0.3 (e.g., Krishnamurthy et al. 2000; Melluso et al. 2006).

Figure 2.6a, b show that melts produced from a peridotite exhibit a large variation in MgO based on pressure (and also on degree of melting, F, not shown here) but limited variation in Al_2O_3 and SiO_2. Deccan picrites plot either on or close to the mantle melting path shown in Fig. 2.6a; however, the bulk of them consistently plot lower in Fig. 2.6b. In the MgO–Al_2O_3 plot they coincide with melts generated between 1 and 2.5 GPa. These picrites would then seem to be primary or

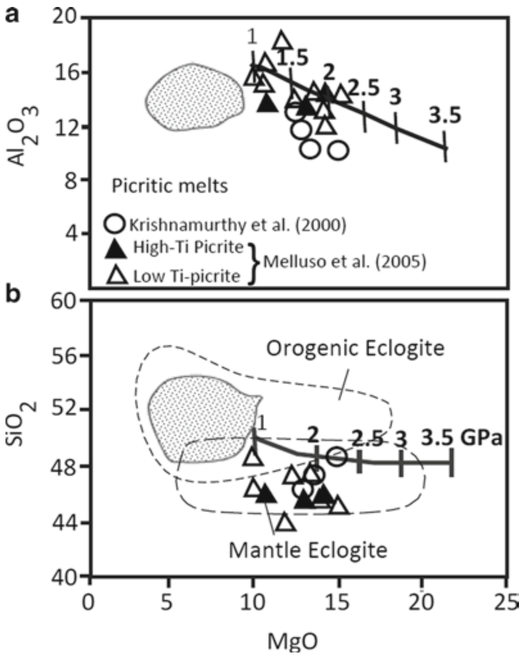

Fig. 2.6 (**a**) Oxide-oxide variation in the Deccan tholeiites (stippled field) and Gujarat picrites. Also shown for comparison is a trend of paramterized near-solidus melt compositions formed from a peridotite source over a pressure range of 1–3.5 GPa. (**b**) The fields of "orogenic eclogites" versus "subducted mantle eclogites" are based on Jacob (2004)

near-primary magmas that could have been generated from a peridotitic source in the DMA between 1 and 2.5 GPa. However, whether there is a possibility of such picrites being generated from mantle (subducted ocean crust) eclogites is discussed next.

Jacob (2004) carried out a global compilation of data on cratonic (presumably deep crustal origin) eclogites and mantle eclogites from kimberlitic intrusions. These fields are shown in Fig. 2.6b. Deccan picrites plot squarely within the mantle eclogite field and therefore, one could perhaps argue for a bulk eclogite melting origin of the picritic magmas. Because subducted oceanic crust (mantle eclogite) is LREE-depleted, one should expect magmas formed by bulk melting of such eclogites to be LREE-depleted; however, the Deccan picrites chosen for this study are all LREE-enriched and do not favor an origin by bulk melting of such eclogite. In fact, Melluso et al. (2006) demonstrated these picrite to have been generated from a garnet lherzolite source. Sheth and Melluso (2008) and others have shown that these picrites are too high in LREE and Ti and could not have generated the more voluminous Deccan tholeiites of the Western Ghats via crystal fractionation.

The tholeiites pose a more complicated problem by virtue of their more chemically evolved character and strong and diverse isotopic contamination. Sen (1995) modeled fractionation paths and showed that all oxide variations, with the exception of SiO_2, can be modeled reasonably well as products of 2 GPa olivine-gabbroic fractionation of primitive magmas. The SiO_2 scatter in the tholeiites is partly due to additional contribution from crustal melts. As Fig. 2.6b shows, common Deccan tholeiites plot well within the field of orogenic eclogites (Jacob 2004). If there were ancient orogenic type eclogites buried within the deep crust/lithosphere of the Indian plate, they could have melted to large degrees and contributed to the average Deccan composition. The idea that ancient eclogite blocks may be embedded in the subcontinental lithosphere is not new as such and has been suggested by Shirey et al. (2001) for the Kaapvaal craton on the basis of 3 Ga Re–Os ages of eclogite xenoliths in kimberlites. The Sr, Pb, and Nd-isotope requirement of strong crustal contamination of much of the Deccan traps may simply reflect such melt contributions. Thus, there is indeed a strong possibility of a mixed origin of the Deccan tholeiites – fractionation of mantle-derived picritic magmas, contribution of melts from deep crustal eclogites, and perhaps smaller amounts of melts contributed by shallow and mid-crustal contaminant crust.

In passing, there is no doubt that peridotite source rocks were involved in generating all of the alkalic magmas because of their olivine ($Fo_{89–91}$) phenocrysts and the upper mantle peridotite xenoliths that occur in them (e.g., Sen et al. 2009). At least some of the Deccan picrites (explained next) and perhaps other tholeiitic formations, like the vast Ambenali Formation, that show little or no isotopic evidence of ancient crustal melt contributions were derived largely from a peridotite source. In the best possible case, the derivation of some of the common tholeiite melts (e.g., Ambenali Formation) from such picrites would require 25–30% olivine fractionation (Sen 1995). Note that Sheth (2005b) carried out a similar calculation and showed that as much as 35% olivine fractionation would be required.

2.4 Deccan Picrites and Potential Temperature of the DMA: Plume Source Confirmed

Deccan picritic flows erupted early in the lava sequence, particularly in the rift zones (e.g., Krishnamurthy et al. 2000 and refs. therein), where the chance of magma stagnation, contamination, and fractionation would have been much less. They are of interest to us in this particular paper because they also give the highest calculated potential temperatures. Among the various Deccan picrites that are plotted in Fig. 2.6, sample PB-39 from Pawagarh or Pavagadh (Krishnamurthy et al. 2000; composition listed in Table 2.1) is of critical importance in the following discussion because this sample has the most forsteritic olivine ($Fo_{91.5}$). We calculate an olivine-whole rock K_d (FeO/MgO) of 0.22 for this sample, which is not an equilibrium value (0.3 ± .02). In order to calculate the composition of the actual equilibrium melt we added olivine while maintaining a K_d of 0.3 until the computed composition could be in equilibrium with the $Fo_{91.5}$ olivine (procedure as in Sen 1995). Composition of this adjusted primary melt composition (PMK) is also given in Table 2.1. The Pavagadh Traps have been extensively studied by many previous workers (e.g., Hari et al. 1991; Melluso et al. 2006; Sheth and Melluso 2008). As indicated above, the Pavagadh picrites could not be parental to the more voluminous Deccan tholeiites (e.g., Melluso et al. 2006; Sheth and Melluso 2008).

There have been a number of new published thermometers that have come out within the last few years (Putirka 2008; Herzberg and Gazel 2009; Lee et al. 2009). Table 2.1 shows mantle potential temperatures calculated for our Deccan primary melt (PMK, in *italics*) using the newer thermometers and Putirka's method of calculating mantle potential temperature. We also show calculations using Albarède's (1992) thermometer to provide a "baseline" comparison with one of the more established, albeit older, thermometer. Among the calculated potential temperatures, we believe that ~1,550°C (±30) is perhaps the most reasonable. The uncertainty shown above is based on discussions presented by the authors of the various thermometers. The new Deccan primary liquid gives a potential temperature of 70–100°C higher than previously reported temperatures calculated by White and McKenzie (1995), Sen (1995), and Melluso et al. (1995); however, it is almost 100°C lower than the maximum potential temperature ~1640°C calculated by Herzberg and Gazel (2009). It is not clear what Deccan composition was used by Herzberg and Gazel (2009) in their calculation; however, based on our careful examination of the Deccan picrites we consider it likely that they selected a picrite like W-1 listed in Krishnamurthy et al. (2000), which has very high whole-rock MgO (23.78 wt%) and a Fo_{90} olivine phenocryst. The calculated olivine/liquid K_d for this rock is 0.47, which is very different from the commonly accepted K_d value of 0.3 (±0.02). Therefore, this sample has too much excess olivine and is not close to being a liquid composition.

In sum, our newly calculated primary picritic liquid PMK with its ~19% MgO is a reasonable and perhaps the hottest primary magma in the Deccan Traps. A powerful constraint that gives a sense of robustness to this composition is its olivine phenocryst ($Fo_{91.5}$), which in turn constraints the MgO/FeO^{2+} ratio of the primary magma. To be sure, this is by no means the only primary magma as a case has been made for multiple primary magmas in the Deccan in earlier publications (Sen 1995, 2001; Sheth and Melluso 2008; and refs. therein). Nonetheless, the calculated mantle potential temperature of 1,550°C for PMK is important as it provides a strong constraint on the maximum T_p of the DMA.

In a comparative seismic and petrological thermometric study of global volcanic systems, Courtier et al. (2007) determined the potential temperature for mid-oceanic ridges to be 1,350°C (±50). On the other hand, hotspot-influenced ridges and hot spots (their definition) gave T_p of 1,447°C (±16) and 1,484°C (±30). *The newly calculated Deccan Tp of 1,550 puts it at the high end of the hot spots, and therefore makes the best case for the thermal characteristic of the DMA.*

2.5 Fe-Rich Nature of the Deccan Plume?

It is important to recognize here, based on many prior studies of the Deccan, that there are at least two types of strongly mafic primary magmas that are different in Fe, K, and some other elements, which is evident from a comparison between Amb Melt-2 and -1 *versus* the newly calculated primary magma, PMK (Table 2.1). Although not shown here, liquid-line-of descent calculations cannot generate Ambenali-like lavas, which are more common in the Deccan, from the PMK

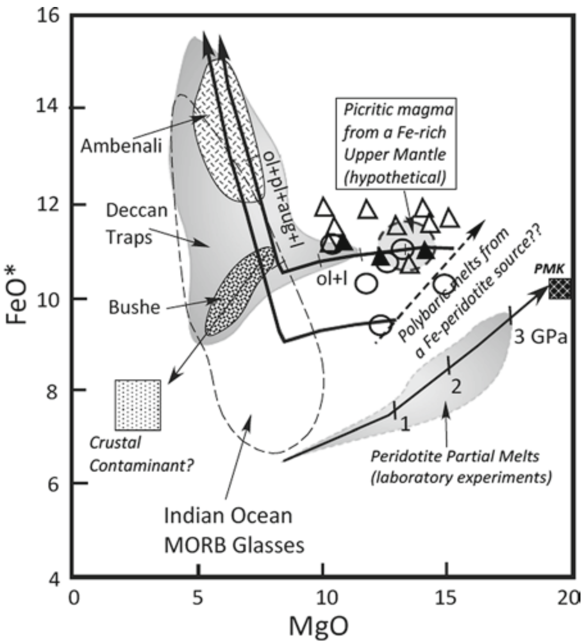

Fig. 2.7 MgO–FeO* relationships in the Deccan (source of data: as in Fig. 2.6) compared with parameterized experimental peridotite partial melt trend over a pressure range of 0–3 GPa. Some equilibrated picrites (see text for discussion) are shown. These require derivation from a Fe-rich source. Two calculated low-pressure (0.2 GPa) fractionation trends are also shown that clearly indicate that Bushe cannot be a result of fractionation of any magma formed by peridotite partial melting. Bushe and other "contaminated" formations are suggested to be products of mixing between peridotite partial melts and eclogitic crustal blocks in the lithosphere (see text for discussion). Indian MORB glass field is shown only as a reference because such glasses have formed by low-pressure fractionation and mixing from relatively Fe-poor asthenospheric partial melts. The calculated primary picrite magma composition for the Pavagadh picrite (PMK) is shown. As discussed in the text, such primary magmas may have produced smaller volumes of magmas at the pre-existing rift zones but did not generate the bulk of the Deccan tholeiites (modified after Sen 2001)

source. Sen (2001) has argued for a Fe-rich peridotitic source for the such lavas based on the MgO–FeO* relationship. We return to this issue here (Fig. 2.7; modified after Sen 2001). In Fig. 2.7 we have plotted Deccan tholeiites (data source: GEOROC Database), selected Deccan picrites (data sources: Krishnamurthy et al. 2000; Melluso et al. 2006), PMK, and MORB glasses from the Indian Ocean (data source: http://www.petdb.org/petdbWeb/index.jsp). Also shown are the fields of the uncontaminated/least contaminated Ambenali Formation basalts and the most contaminated Bushe Formation basalts. We compare them with experimentally derived peridotite melting trend and calculated 0.2 GPa fractionation trends from two hypothetical primary magmas with MgO ~15wt%. This diagram shows the source difference between the PMK Ambenali-like lavas quite well. The "extra Fe" could indicate a Fe-rich peridotitic source as opposed to a more magnesian peridotite that would generate Indian Ocean MORB type melt. Note that in the case of Hawaiian magma source Humayun et al. (2004) also proposed a Fe-rich source peridotite that may have picked up the excess Fe from the Outer Core. In passing, we should mention that Tuff et al. (2005) have suggested that garnet pyroxenite in an otherwise peridotitic plume can also give rise to relatively Fe-rich melts.

We submit that the newly calculated primary magma (PMK) may represent only a small volume of somewhat alkalic or transitional magma that may not have given rise to the more voluminous, Fe-rich, Ambenali-like magmas (compare the computed primary magma composition with Amb Melt 2 and Amb Melt 1 compositions from Sen 1995; and also, Melluso et al. 2006; Sheth and Melluso 2008). Interestingly, our calculated primary magma falls on the experimentally determined magnesian ("normal") peridotite solidus at ~3.5 GPa.

On the basis of the discussion above we conclude that Deccan primary magma generation could have involved multiple sources, but there is no doubt that the primary magmas that yielded the Pavagadh picrites were among the hottest. The highest potential temperature recorded by the new calculated primary magma PMK is about 1,550°C, which can be taken as the maximum temperature within the DMA. We have suggested that the great variation in SiO_2 and Al_2O_3 shown by the more voluminous and evolved Deccan tholeiites was a result of melting of ancient "orogenic" eclogitic pockets buried at various levels within the Deccan lithosphere.

It is interesting to note that Sheth (2005b) presented a model that had some elements very much in common with what we have presented above: his model calls for eclogites of prior subduction origin buried within the lithosphere, and then he attributed the origin of Deccan magmas to large scale melting of these eclogite blocks *via* a lithosphere delamination scheme. While we agree that deeply buried eclogites may have played a role in the production of the more voluminous tholeiites, however, such eclogites could not have had a subduction origin but instead are metamorphosed lower crustal rocks. The biggest difference between Sheth's model and ours is in the process of magma generation – Sheth proposed simple continental extension without the aid of a plume whereas our model requires a large plume as the driving thermal and magma production force.

2.6 Verification of the Picrite Parent Hypothesis: Insights from Geophysics

It is important to consider the constraints imposed on all petrological models from a geophysics perspective. The common Deccan tholeiite basalts with less than 8% MgO have undergone extensive mixing and ol + pl + cpx fractionation within the shallow (6 km) crust, suggesting the presence of extensive network of intrusive complexes at about that depth (Gangopadhyay et al. 2005). However, prior to such fractionation in shallow dikes and sills, the parent magmas could have dropped off as much as 25–35% olivine crystals somewhere deeper in the crust or mantle (Sen 1995; Sheth 2005b). The fraction of olivine could certainly be much less if some of the parental magmas were largely composed of eclogite-derived melts and small amounts of peridotite-derived melts.

Cox (1980) was an early proponent of deriving all flood basalts from picritic primary magma. He argued that ascending picritic melts would stagnate at the Moho because they would be too dense relative to the continental crust. Here these magmas would crystallize significant amount of dunite cumulates and regain the buoyancy that would allow them to rise higher up through feeder fractures.

Based on geochemistry and Cox's conjecture, we have now narrowed the problem to finding thick and laterally extensive dunite cumulate bodies at the Moho and shallower intrusives in the upper crust at ~6 km. The shallow intrusive complexes related to the Deccan have been found along the west coast and more extensively in the Narmada-Son rift (e.g., Sheth et al. 2009). Therefore, their existence is not questionable. One must resort to geophysics to address the bigger question, that is, whether extensive dunite bodies exist at the Moho.

Pandey (2008) made an interesting study of shear wave velocities along a NW–SE transect that cuts across the Deccan – it starts from slightly to the northeast of Mumbai and ends close to the coast, cutting across the thickest part of the Deccan. Figure 2.8 shows smoothed version of one of his two depth – V_s profiles along with the global mean for shields and platforms (Christensen and Mooney 1995, cited by Pandey 2008). The most appealing feature of the depth – V_s profile is that the velocity is significantly greater than the global mean at 0–20 km (shallow to intermediate crust), similar to the global mean in the intermediate-to-deeper

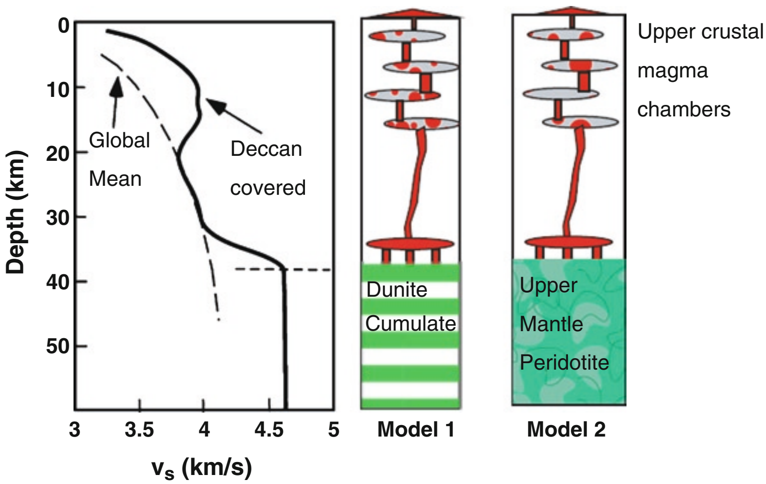

Fig. 2.8 The *left panel* shows a S-wave velocity profile beneath the main Deccan province (Modified from Pandey 2008). The "global mean" represents global mean V_s beneath normal shields and platforms (as quoted by Pandey from Christensen and Mooney 2005). Model 1 is our preferred interpretation of the crustal structure from the velocity profile. Model 2 is our interpretation of Pandey's (2008) inference (see text for further discussion)

crust (20–33 km), and then jumps up to a more mantle-like value, and accordingly, Pandey places the Moho at about 38 km.

We present two interpretative models of Pandey's (2008) velocity profile in Fig. 2.8. Pandey (2008) attributed the large velocity increase in the shallow crust to Deccan Trap intrusive complexes; and he suggested that the material below ~38 km is mantle peridotite. However, we suggest an equally plausible alternative hypothesis: the high velocity materials below ~38 km are dunite cumulates that were the early fractionates from picritic parental magmas of the Deccan lavas. The difference between the two models is that while the "dunite cumulate model" agrees with Cox's (1980) hypothesis, Pandey's model does not allow for large amounts of olivine fractionation and therefore is contrary to it. Moreover, Pandey's model requires the production of great volumes of non-picritic parent magmas. While discussing the elemental geochemistry, we argued for a mixed eclogite–peridotite source for the dominant tholeiites and garnet peridotite source for the picrites. Given the dominance of the tholeiites, and rather restricted occurrence of picrites in rift zones, Pandey's model, i.e., the high velocity material below about 40 km is peridotite, is quite plausible although other materials such as eclogite can also contribute to such high velocity. Unfortunately, seismic velocities are just not good enough to distinguish between these various possibilities.

2.7 A Model

We have considered the magma production volume, rapid eruption, difficulty in explaining the extent of contamination, wide major and trace element diversity of Deccan tholeiites, eclogite melting and the requirement of picritic parent magma (therefore an implied peridotitic source) in some areas. These considerations are best explained with a model that requires the generation of both picritic magma from a peridotite source and the dominant tholeiitic magmas from a mixed source – a mixture of eclogitic blocks and surrounding lithospheric peridotite (dominant). Picritic magmas were produced from the peridotite source at ~1,550°C and >75 km. It is difficult to constrain the generation conditions of the magma from eclogite blocks, but given the extent of thermal anomaly, they would have melted entirely as they were heated (Yaxley 2000). The estimated potential temperature of 1,550°C would have made the DMA significantly hotter than the shallow convecting mantle. This excess temperature, enormous volume of the erupted lavas, short eruption span (the bulk of them erupting in less than 1 million year), age track of Deccan–Laccadives–Maldives-Reunion, and broad isotopic similarity of the "common signature" lavas to those from the Reunion Hot Spot, all favor a plume origin of the Deccan Traps.

We have suggested a dual source, i.e., eclogite or charnockite and a Fe-rich peridotite, as have others (Cordery et al. 1997; Tuff et al. 2005; Sheth 2005b). There is an important difference: the eclogite in our model is a part of the continental lithosphere (also in Sheth 2005b) and not recycled subducted oceanic lithosphere brought up by the plume as suggested by the other authors for other geologic areas (e.g., Campbell 2005). In this sense this model is similar to that presented by Camp and Hanan (2008) for the Columbia River flood basalts of northwestern USA.

We use a four-component isobaric phase diagram (Fig. 2.9; source: Milholland and Presnall 1998) to explain how our dual source melting model "works" even though at least one important component, FeO, is missing from this diagram. We focus on the "eclogite surface" (green) and three invariant points – point "PerM" where a spinel–garnet peridotite would melt, point "ChM" where a charnockitic assemblage quartz + opx + cpx + gt) would melt, and point "M" (refer to Fig. 2.9 and Table 7 in Milholland and Presnall 1998), where a kyanite–quartz eclogite assemblage would melt. The temperature difference between the PerM and point M point is about 170°C whereas that between PerM and ChM is 100°C. Thus, by virtue of having significantly lower melting temperatures, charnockitic and eclogitic blocks (metamorphosed lower crustal blocks), embedded deep in the lithosphere due to ancient orogenic events, will melt to a large degree even though the surrounding peridotitic component of the lithosphere or the plume itself may not melt until the temperature is raised by at least 100°C to reach peridotite solidus (PerM). The hottest zone in the plume would produce relatively picritic magmas, whereas contributions would be produced from melting of old crustal blocks embedded in the lithosphere and some likely by fractionation of picritic magmas.

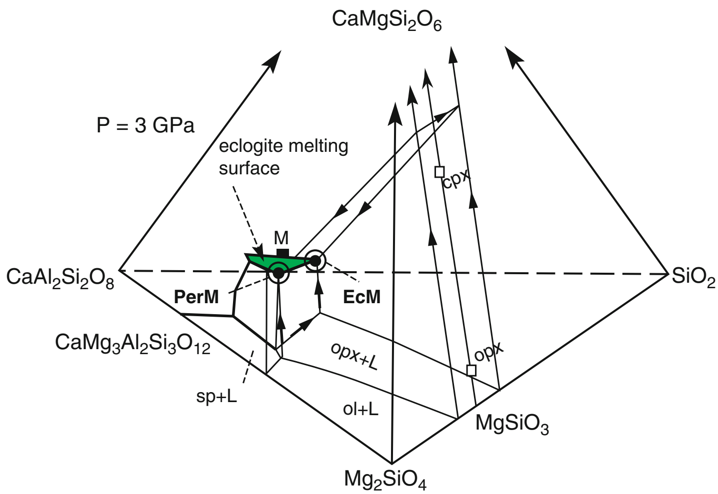

Fig. 2.9 Slightly simplified liquidus diagram CaO–MgO–Al_2O_3–SiO_2 at 3 GPa from Milholland and Presnall (1998). The *colored surface* represents the surface where melts would form from eclogite-like assemblages. "PerM" is the invariant point ol + opx + cpx + gt + sp + liq. "ChM" is the isobaric invariant point opx + cpx + qz + gt + liq. "M" represents kya + qz + cpx + gt + liq. (see text for further discussion)

Sheth (2005b) also suggested the presence of large eclogite bodies in the subcontinental lithosphere; however, instead of a plume, he suggested that these bodies were remnants of ancient subduction; and the Deccan Trap magmas formed when such bodies delaminated from the lithosphere and were heated as the asthenosphere was raised to fill the "void". For reasons stated earlier, we feel that a plume is necessary. Sheth (2007) pointed out that the Deccan lithosphere was not significantly uplifted as would be required by the thermal models. In our model, melting of large eclogite blocks in the continental craton resulting in the lower lithosphere erosion would offset the buoyancy exerted by the plume.

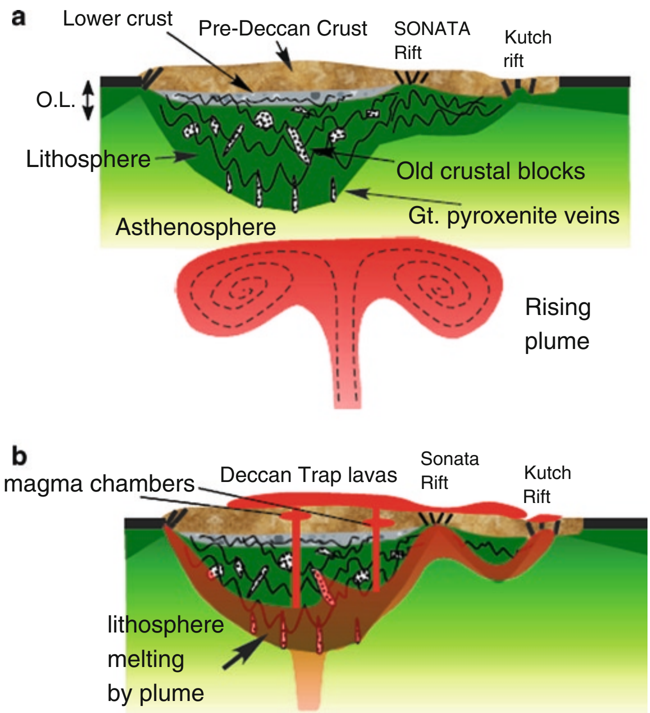

Fig. 2.10 A schematic model for the origin of Deccan Traps volcanism by melting of lithosphere and plume. (**a**) Pre-Deccan lithosphere shown with a thick crust (*brown*) and a thick lithospheric keel. A marginal rift zone, such as the Kutch rift zone, and the interior rift zone (Narmada-Son or SONATA rift zone) are also shown. The lithosphere is assumed to be largely peridotitic or harzburgitic with blocks, lenses, and veins of garnet clinopyroxenite or eclogite. The plume has not impacted the lithosphere in this stage. (**b**) The plume impacts the lithosphere and largely melts the embedded eclogite bodies and some of the surrounding lithosphere. These melts are thought to be the dominant tholeiites. The picrites found in the rift zones near the peripheries of the Deccan Traps are derived from primary magmas such as the PMK and they tap the actual plume materials

In this connection, the investigation by Kumar et al. (2007) shows that the Indian lithosphere to be only ~100 km thick whereas the once contiguous Gondwanaland lithospheres beneath the other southern continents were 180–300 km thick. These authors suggested that the plume that severed the Gondwana continents was responsible for melting the lower lithosphere beneath India although they remarked that the role of the Deccan plume causing such lithospheric erosion could not be ascertained. In our view, the plume that produced Deccan picrites also melted the eclogite bodies embedded in the lower lithosphere and thereby eroded the lower lithosphere.

Figure 2.10 is a model that effectively summarizes our thoughts about Deccan Trap volcanism. Like many authors before us, we suggest that a large plume, rising perhaps from the core/mantle boundary, was the primary cause of this flood basalt event. Following Kumar et al. (2007), it is possible that the pre-Deccan continental lithosphere had an uneven thickness: it was generally 200 km thick beneath cratonic areas and relatively thin (100 km or less) beneath pre-existing rift zones, such as the Kutch and the Son-Narmada (SONATA) rift zones (Fig. 2.10a; e.g., Sen et al. 2009). As the Deccan plume came up it melted and eroded much of the lower lithosphere that had "inclusions" of dispersed blocks of old orogenic eclogite bodies producing contaminated and differentiated appearing tholeiites. Where parts of the plume could rise to shallower levels beneath pre-thinned lithosphere (such as beneath ancient rifts), it produced picritic magmas at ~1,550°C and 2.3 GPa. These picrites produced dunite cumulates near the Moho and gabbroic fractionates in the shallow crust. Our model has components that are similar to hypotheses put forth by "plumists" and "non-plumists" as well and emphasizes a complex magma production history from the plume as well as the ancient continental lithosphere.

Acknowledgments We are pleased to dedicate this review paper to the late Prof. Mihir K. Bose, a leader in Indian petrology and a Deccan Traps enthusiast. We were fortunate to make Professor Bose aware of this volume being prepared in his honor before he passed away. It is unfortunate that neither of us has collaborated with Prof. Bose; however, his papers certainly intrigued us and kept us thinking of the larger issues. We are very grateful to Dr. Hetu Sheth for a thorough review and constructive suggestions that led to some important changes in the original manuscript. We thank Kevin Chau for his help with running Lee et al.'s (2009) program to calculate P, T. We are also thankful to Prof. S. Viswanathan for his critical comments and editing the manuscript.

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