

Were the Deccan Flood Basalts Derived in Part from Ancient Oceanic Crust Within the Indian Continental Lithosphere?

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Abstract

Deep mantle plumes supposedly incorporate deeply subducted eclogitized oceanic crust, and continental flood basalts (CFBs) are now thought by some to be derived from such eclogite-bearing peridotite plumes. Eclogite-peridotite mixtures have much lower solidi (and produce much greater melt fractions for a given temperature) than peridotite. Fe-rich (eclogite- or pyroxenite-bearing) sources have been inferred for many CFBs. However, plumes with considerable amounts of eclogite should have difficulty in upwelling owing to the high density of eclogite. Besides, CFBs are always located along pre-existing lithospheric structures (suture zones, edges of thick cratons) and commonly associated with lithospheric rifting and continental breakup. India's major late Mesozoic CFB, the Deccan Traps, erupted through rift zones and a new continental margin that had developed along ancient suture zones traversing the subcontinent. Many Deccan basalts are too Fe-rich to have been in equilibrium with a peridotite mantle source, and have commonly been considered to be significantly fractionated derivatives of picritic liquids. However, it is possible to view them as relatively less evolved liquids derived from a source with extra fertility (i.e., an Fe-rich source). A new non-plume, plate tectonic model for Icelandic hotspot volcanism involves melting of a shallowly recycled slab of eclogitized Iapetus oceanic crust formerly trapped along the Caledonian suture. The model explains the geochemical-petrological characteristics of Icelandic basalts, and is consistent with passive upper mantle upwelling under Iceland inferred from recent seismic tomography. Based on the petrological and geochemical features of the Deccan flood basalts of the type section, in the Western Ghats, I propose that old, eclogitized oceanic crust trapped in the ancient Indian suture zones could have produced voluminous basaltic melts during the Deccan event.

Key words: Deccan volcanism, flood basalt, Iceland, eclogite, mantle plume.

Introduction: Flood Basalt Genesis in the Mantle Plume Model

The mantle plume initiation model for the origin of continental flood basalts (CFBs) (Richards et al., 1989; Campbell and Griffiths, 1990), has been widely accepted. The model postulates that intraplate, "hotspot" volcanism is caused by mantle plumes – abnormally hot upwellings that originate at the core-mantle boundary. The model is largely based on fluid dynamical experiments, which show that plumes should develop large "heads" by entrainment of surrounding mantle as they rise through the mantle, and the heads remain connected to the source region by narrow, pipe-like "tails". A plume head produces voluminous flood basalts, whereas a plume tail produces hot picritic melts. The model has been widely applied to the Deccan Traps of India, one of the largest and best examples of CFBs in the world (see Sheth, 2005 and references therein). The mainstream view is that (i) the currently active Réunion hotspot on the African plate

represents the tail phase of a deep mantle plume, and (ii) the Deccan Traps originated from the head of the same plume during late Cretaceous time when the Indian subcontinent was drifting over it. This widely accepted model has been questioned on various grounds, however (Burke, 1996; Sheth, 1999a, b, 2000, 2005).

The original plume model (Richards et al., 1989; Campbell and Griffiths, 1990), which assumed a peridotitic mantle plume, was subsequently revised. Cordery et al. (1997) found it impossible to produce the observed amounts of magma in CFBs by melting peridotitic mantle alone, and argued that mantle plumes must contain significant amounts of eclogite to be able to melt sufficiently. Eclogite (and pyroxenite) melt at much lower temperatures than peridotite (e.g., Yasuda et al., 1994, 1997; Hirschmann and Stolper, 1996). Eclogite is essentially a biminerallitic rock made up of garnet and clinopyroxene (omphacite), and accessory minerals like rutile, quartz, kyanite etc. (see Jacob, 2004 and references

therein). It is the high-pressure equivalent of basalt, and is most typically formed in subduction zones by transformation of downgoing oceanic crust (e.g., Ito and Kennedy, 1971). Plumes are now thought to constitute eclogite-peridotite mixtures, and the eclogite component required in plumes is hypothesized to represent recycled oceanic crust subducted as far down as the base of the mantle (Cordery et al., 1997), to satisfy the perceived deep (plume) origins for CFBs. Pyroxenites have been defined as ultramafic rocks made up of pyroxenes without or with olivine, the modal olivine content not exceeding 40% (Streckeisen, 1973). Pyroxenites in the sub-lithospheric mantle may also represent subducted oceanic crust (e.g., Allègre and Turcotte, 1986), and have a large range of major element compositions between peridotites and basalts (Hirschmann and Stolper, 1996).

The Alternative: Shallowly Derived Eclogite

Whereas petrologists and geochemists favouring the plume model and invoking deep recycling of slabs cite seismic tomography data as evidence for deep subduction, some experts on seismic tomography (e.g., Dziewonski, 2003, 2005) find little or no evidence for deep slab subduction. Besides, with new data, many regions traditionally considered to be classic plume areas have begun to be attributed to non-plume, upper mantle processes (see www.mantleplumes.org). A prominent example is Iceland, where recent seismic tomography work (Foulger et al., 2000, 2001) has not detected a plume in the lower mantle, and found evidence for upper mantle origin and passive upwelling instead. Iceland is the world's classic ridge-centred "hotspot" and the only part of the global mid-oceanic ridge system that is subaerial.

It has been emphasized (e.g., Anderson, 1996; Foulger et al., 2005) that mantle temperature is not the only parameter controlling melt volumes generated; mantle fertility (garnet+clinopyroxene content) or the presence of volatiles are very important as well. It is not generally appreciated that large volumes of CFB do not uniquely require high absolute temperatures. It is the temperature relative to the local solidus that is important, as well as the volume of mantle sampled, focussing effects, etc. (D.L. Anderson, pers. comm., 2004). The idea of a not-so-hot but extra-fertile source for flood basalts therefore deserves serious consideration. The anomalously thick (30 km) crust under Iceland and many unusual petrological-geochemical features of Icelandic basalts have been explained by melting of eclogite-bearing peridotite (e.g., Chauvel and Hemond, 1999; Korenaga and Kelemen, 2000), and the eclogite has recently been proposed to represent not a deeply derived plume but a shallowly

recycled slab of the Iapetus oceanic crust that was subducted (and partly trapped) when the continents of Laurentia, Baltica and Avalonia collided to form the Caledonian Suture at 440 Ma (Foulger and Anderson, 2005; Foulger et al., 2005). Warm slabs do not subduct deeply but can become neutrally buoyant at shallow depths (Oxburgh and Parmentier, 1977), and if the supercontinent above subsequently rifts apart, the eclogitic slabs, if still warm, can be entrained in the rifting-induced mass upwelling and undergo voluminous melting at normal mantle temperatures, producing much thicker crust than would be possible to get by melting peridotite alone.

In the case of CFBs too, before placing the required eclogitic source in the deep mantle, the potential availability of eclogite at shallow, upper mantle depths beneath the continents must be evaluated. The continents are geologically, structurally, and geophysically far more complex than the ocean floors. Addressing the fundamental structure and geological history of the continent in question is thus essential. Here, I propose that the mantle source of the voluminous Deccan lavas was not solely peridotite but included a basaltic component (eclogite). I also propose that, as at Iceland, the eclogitic component was not derived from a deep mantle plume but represents slabs of ancient oceanic lithosphere trapped in the old suture zones that traverse the Indian Precambrian shield.

Structure and Tectonics of the Indian Shield

India is one of the oldest continents, and has a very rich rock record from the Archaean up to the Recent. At least six Archaean to early Proterozoic cratonic nuclei, and several fold belts, are recognized in India (Naqvi and Rogers, 1987). The nuclei may have been sutured together in Archaean-Proterozoic time by proto-plate tectonic processes (e.g., Naqvi et al., 1974; Radhakrishna, 1989; but see Hamilton, 1998 for a contrary view). Several major rift zones traverse the Indian Peninsula (Fig. 1): the Godavari and Mahanadi rifts in the east, the Cambay rift in the north, the Kachchh rift in the northwest, and the E-W-trending Narmada and Tapi rifts, enclosing the Satpura horst-block in between (e.g., Biswas, 1987). Three major CFB provinces formed in India and its contiguous landmasses and oceans during the Mesozoic, all associated with continental breakup. The Deccan CFB event was associated with the breakup of India from the Seychelles microcontinent at ~65 Ma (e.g., Mahoney, 1988; Fig. 1 inset). Prior to this, the Indo-Madagascar province formed along with the breakup of Madagascar from Greater India (India plus Seychelles) at ~88 Ma (Storey et al., 1995, 1997;

Anil Kumar et al., 2001; Pande et al., 2001). Still earlier, the Rajmahal-Sylhet CFB formed at ~116–120 Ma, about 10 million years after the breakup of eastern Greater India from Australia (e.g., Kent et al., 1997). The newly formed continental margins, and the rift zones, constituted major vent areas for the Deccan CFB, as inferred from abundant mafic dyke swarms and intrusions, high heat flow, and aligned thermal springs (e.g., Sheth, 2000, 2005).

The Indian rifts run along major Precambrian tectonic trends (Katz, 1978). The Narmada zone in particular is a prominent, ancient line of weakness and has been proposed to be a Proterozoic protocontinental suture between a northern, Aravalli protocontinent and a

southern, Dharwar protocontinent (Naqvi et al., 1974; Radhakrishna, 1989). The Cambay rift, and the western continental margin of India, also developed by faulting parallel to the NNW-SSE Dharwar orogenic trend of Precambrian age (Biswas, 1987), i.e., India may have broken off from Seychelles, and Greater India from Madagascar, along what were apparently terrane boundaries. Another major Precambrian orogenic trend, the NE-SW Aravalli trend, splays out into two at its southern end: the E-W Delhi trend (along which the Kachchh rift has developed), and the main NE-SW Aravalli trend which continues right across the Cambay rift into Saurashtra (Fig. 1; Biswas, 1987).

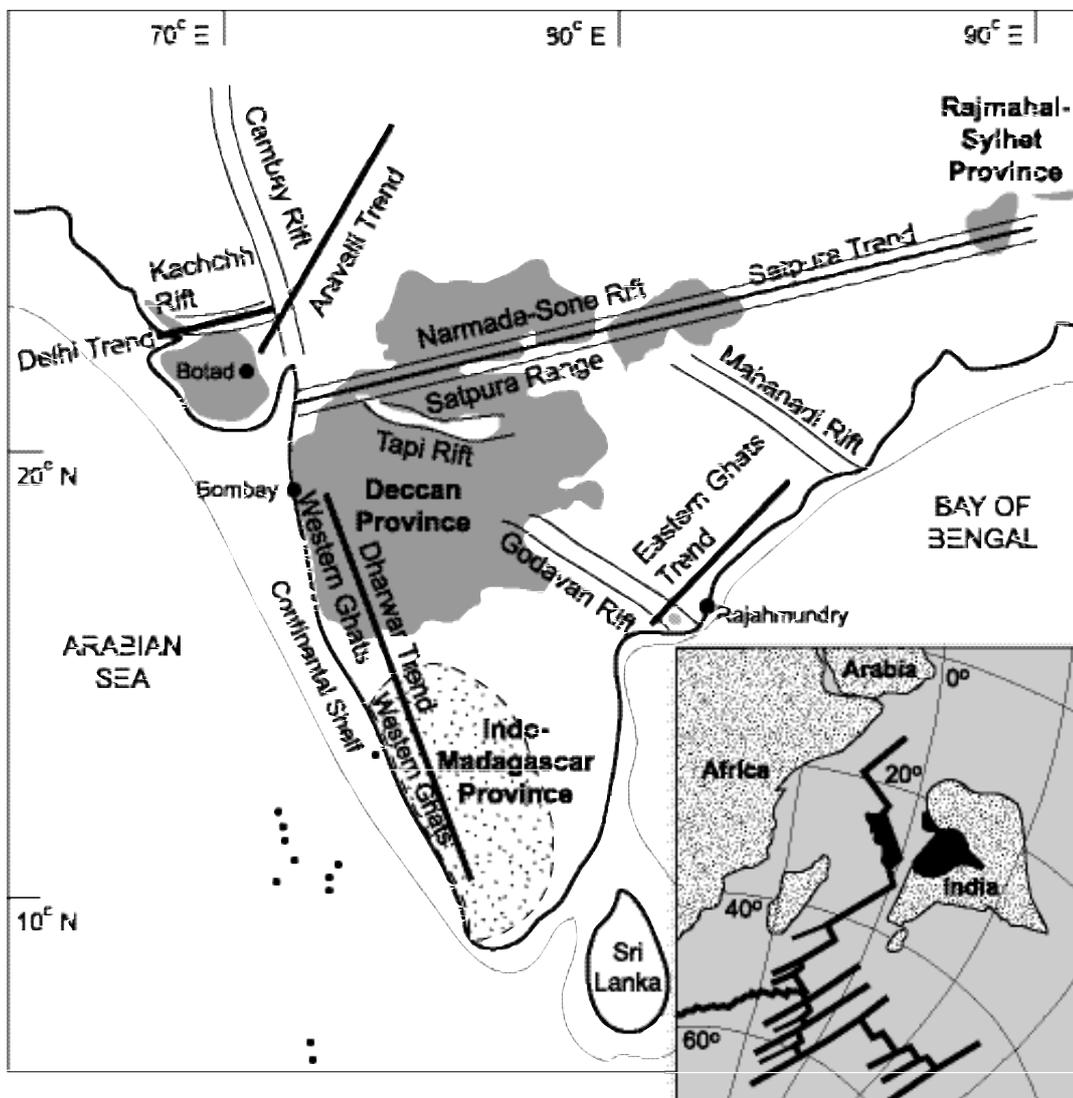


Fig. 1. Map of India showing the outcrop area of the Deccan and Rajmahal Traps (dark gray), the Indo-Madagascar province (stippled), the rift zones underlying the Deccan, the Precambrian structural trends, and some localities. The Indo-Madagascar province in India is represented mostly by dykes and minor volcanics. Based on Biswas (1987) and Sheth (2000). Inset shows the breakup of the Seychelles microcontinent from India at ~65 Ma due to a ridge jump (Norton and Sclater, 1979), at which time Deccan flood volcanism (black areas) took place.

The Deccan Tholeiites and Picrites

The Deccan lava pile is spectacularly exposed in the southwestern part of the province (Fig. 1) in the Western Ghats (Sahayadri) range, and the stratigraphic framework of this region is now known quite well from extensive field, geochemical (including isotopic) and palaeomagnetic work (e.g., see Mahoney, 1988 and references therein; Subbarao, 1988 and references therein; Lightfoot et al., 1990; Peng et al., 1994). The Western Ghats sequence is almost exclusively tholeiitic (subalkalic) (Fig. 2), with a stratigraphic thickness of ~3,000 m, and on the basis of geochemical characteristics and field markers, has been divided into three subgroups and eleven formations (Table 1). The Jawhar and Igatpuri are actually two separate formations with very similar geochemistry and petrogenetic evolution (see Subbarao, 1988 and references therein), and are therefore often grouped together. There is also no consensus regarding the formation status of the Desur, originally defined as a unit of the Panhala Formation.

Many of the formations have been subdivided into members and chemical types. Crustal contamination was a common process in the evolution of the Deccan basalts, and several distinct crustal end members were apparently involved, as attested by the arrays defined by the various formations in Nd-Sr-Pb isotopic ratio plots (Fig. 3). Table 1, based on Peng et al. (1994), lists the age-corrected (to 66 Ma) $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the basalts. Unlike most formations, the Ambenali Formation lavas are relatively little contaminated by continental lithospheric materials, with age-corrected ϵNd values of about +3 to +7, and the Mahabaleshwar Formation lavas appear to be affected by either lithospheric mantle or old granulitic crust with

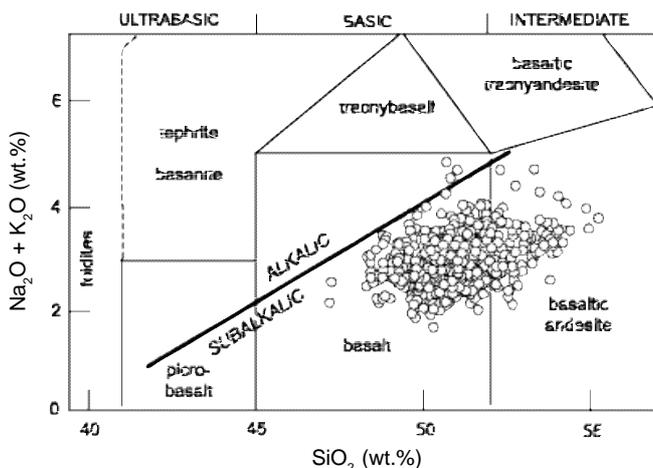


Fig. 2. Total alkali-silica diagram (Le Bas et al., 1986), showing that nearly all Western Ghats lavas (624 samples, Beane, 1988) are subalkalic basalts and basaltic andesites. Heavy diagonal line (after Macdonald and Katsura, 1964) separates the alkalic and subalkalic fields.

Table 1. The southwestern Deccan formation stratigraphy, and ranges of age-corrected Sr isotopic values for the various formations.

Group	Subgroup	Formation	$(^{87}\text{Sr}/^{86}\text{Sr})_{t=66\text{ Ma}}$
Deccan Basalt	Wai	Desur (~100 m)	0.7072–0.7080
		Panhala (>175 m)	0.7046–0.7055
		Mahabaleshwar (280 m)	0.7040–0.7055
		Ambenali (500 m)	0.7038–0.7044
		Poladpur (375 m)	0.7053–0.7110
	Lonavala	Bushe (325 m)	0.7078–0.720
		Khandala (140 m)	0.7071–0.7124
	Kalsubai	Bhimashankar (140 m)	0.7067–0.7076
		Thakurvadi (650 m)	0.7067–0.7112
		Neral (100 m)	0.7062–0.7104
		Jawhar-Igatpuri (>700 m)	0.7085–0.7128

very low $^{206}\text{Pb}/^{204}\text{Pb}$. Thick lava piles that closely resemble (chemically and isotopically) many of the Western Ghats formations, besides lava flows and dykes with compositions unlike any seen in the Western Ghats, are now known from widely spaced sections in the Deccan province (e.g., Peng et al., 1998; Mahoney et al., 2000; Sheth et al., 2004).

Intercalated basalt and picritic basalt flows are known from boreholes in the northwestern Deccan (around Botad, Fig. 1). These were postulated by Campbell and Griffiths (1990) to be high-temperature, high-melt-fraction picritic liquids derived from the axis of their conjectured plume. The picritic lavas are rich in olivine (Fo_{87-90}) and clinopyroxene phenocrysts, though close to being primary magmas with ~16 wt.% MgO (Krishnamurthy and Cox, 1977). Such liquids cannot themselves be produced from an eclogitic (olivine-free) source, because it would have less MgO than the magmas themselves. The volatile content of the source of these picritic liquids is also unknown, but H_2O and CO_2 significantly reduce the mantle solidus (e.g., Green, 1973; Hirose and Kawamoto, 1995; Gaetani and Grove, 1998). These lavas are also known to be mildly alkalic, and are therefore not the high- F picrites Campbell and Griffiths (1990) pictured them to be. Peng and Mahoney (1995), in a Nd-Sr-Pb isotopic and trace element study of these rocks, identified two distinct mixing arrays. One was postulated by them to reflect mixing between a mantle end member very similar to that for modern Réunion Island lavas, and a high- $^{208}\text{Pb}/^{204}\text{Pb}$, high- $^{207}\text{Pb}/^{204}\text{Pb}$ continental lithospheric end member. The second trend was argued by them to reflect mixing between the same continental lithospheric material and a mantle end member resembling the thick Ambenali Formation of the Western Ghats, taken by many to represent the composition of the Deccan plume head. Peng and Mahoney (1995) found, however, that both the mixing arrays include picritic members (i.e., picritic rocks were

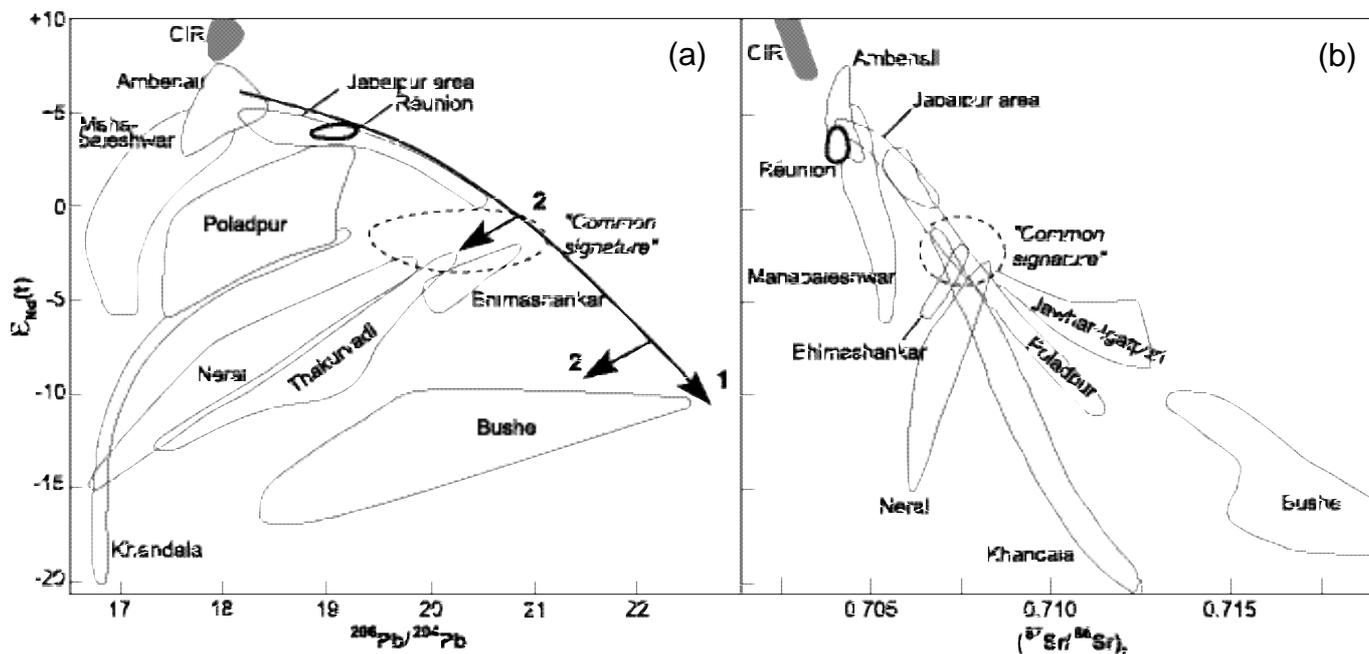


Fig. 3. (a) Fields of initial $\epsilon_{Nd}(t)$ vs. $^{206}Pb/^{204}Pb$ for individual Deccan formations from the Western Ghats. (b) Fields of initial $\epsilon_{Nd}(t)$ vs. $(^{87}Sr/^{86}Sr)_t$ for these formations. $t = 66$ Ma. Fields are also shown for present-day Central Indian Ridge (CIR) N-MORB and Réunion Island. Based on Peng et al. (1994) and Mahoney et al. (2000). The field for Jabalpur lavas is from Peng et al. (1998). The thick arrows marked 1 and 2 show the two stages of magma-lithosphere mixing conceived by Peng et al. (1994, 1998).

not confined to the mixing array involving the Réunion component alone), and the most isotopically Réunion-like lavas were in fact non-picritic. This fact, and the suggestion from trace element data that they could be high-pressure, low- F melts instead (Peng and Mahoney, 1995), is at variance with Campbell and Griffiths' (1990) picture of the Deccan plume.

Few occurrences of picritic rocks are encountered also along the western part of the Narmada rift and in the Saurashtra peninsula, south of Botad (Melluso et al., 1995; Krishnamurthy et al., 2000). Cores of olivine phenocrysts in them are forsteritic (Fo_{86-92}), and phenocryst rims more Fe-rich. One sample (ANK) of Krishnamurthy et al. (2000) has a olivine phenocryst rim composition Fo_{60} and groundmass olivines of Fo_{84-72} compositions. Another flow contains Fo_{83} phenocrysts and Fo_{64} groundmass olivines. Clearly, only some of these existed as picritic liquids, but many of them are mildly alkalic or transitional, rich in TiO_2 (>1.8%), K_2O and P_2O_5 (Krishnamurthy et al., 2000). On the other hand, picritic basalts of the Western Ghats show a huge range in olivine compositions, Fo_{84-43} (Krishnamurthy et al., 2000), and the Western Ghats tholeiites have an average olivine composition Fo_{77} (Sen, 2001). The picritic basalts of the Western Ghats are enriched in cumulus olivine and clinopyroxene and do not represent liquid compositions (Beane and Hooper, 1988; Krishnamurthy et al., 2000). Most of the samples shown on figure 2 are quite evolved, with MgO in the range 4–7 wt.%.

Melting of Eclogite-Peridotite Mixtures

Few experimental petrological data on the Deccan lavas exist. Sen (1988) studied some tholeiites from the Western Ghats that were nearly aphyric, and contained 9–10% MgO, 9–10% FeO, 10–11% CaO, and 16–17% Al_2O_3 . He argued that they had undergone little or no olivine fractionation, and were likely generated from a heterogeneous but dominantly N-MORB-type mantle at 10–15 kb (~35–50 km). He suggested that the much more abundant and more evolved Deccan lavas (with 4–7 % MgO) are products of substantial gabbro fractionation. Later, he suggested (Sen, 1995) that the Deccan primary magmas were picritic and formed over the pressure range of 2 to 3 GPa.

An eclogite-bearing source has not been evaluated for the Deccan so far. If the eclogite-peridotite mixed source model is valid for the Deccan, it means that the large Deccan lava volumes produced and erupted were due to higher source fertility (garnet+clinopyroxene content), not high temperatures. Arguments for a large mantle thermal anomaly based on large erupted volume alone (e.g., White and McKenzie, 1989) can be discounted. Eclogite, like pyroxenite, has a much lower melting point than peridotite, and earlier work (Yoder and Tilley, 1962; Ito and Kennedy, 1974; Yasuda et al., 1994) also suggested a much narrower (as little as 75–100°C) melting range for eclogite than peridotite (Fig. 4). Recent work (Yaxley,

2000) indicates that eclogite and eclogite-peridotite mixtures can have a melting interval as wide as or wider than peridotite (Fig. 5a), displaced overall to significantly lower temperatures at all pressures. (Note, however, the liquidus minimum on figure 5a, corresponding to a 30:70 wt.% eclogite:peridotite mixture for which the melting interval is only 250°C, compared to 400°C for the pure peridotite composition). During adiabatic upwelling of a mixed eclogite-peridotite source, the eclogite would melt earlier (at higher pressure) than the peridotite because its solidus temperature is considerably lower than that of peridotite, at least for upper mantle depths (e.g., Yasuda et al., 1994). This is in part because the effect of increased Fe and alkalis is to lower the solidus. Thus, the addition of basalt to peridotite reduces its solidus and liquidus, which results in melting beginning at a lower temperature in the basalt-peridotite mixture, and in melt fractions being higher for a given temperature (Fig. 5b). Compared to fertile peridotite, a mantle source consisting of ~30 wt.% eclogite mixed with ~70% peridotite has substantially higher melt productivity during adiabatic ascent in the upper mantle (Yaxley, 2000).

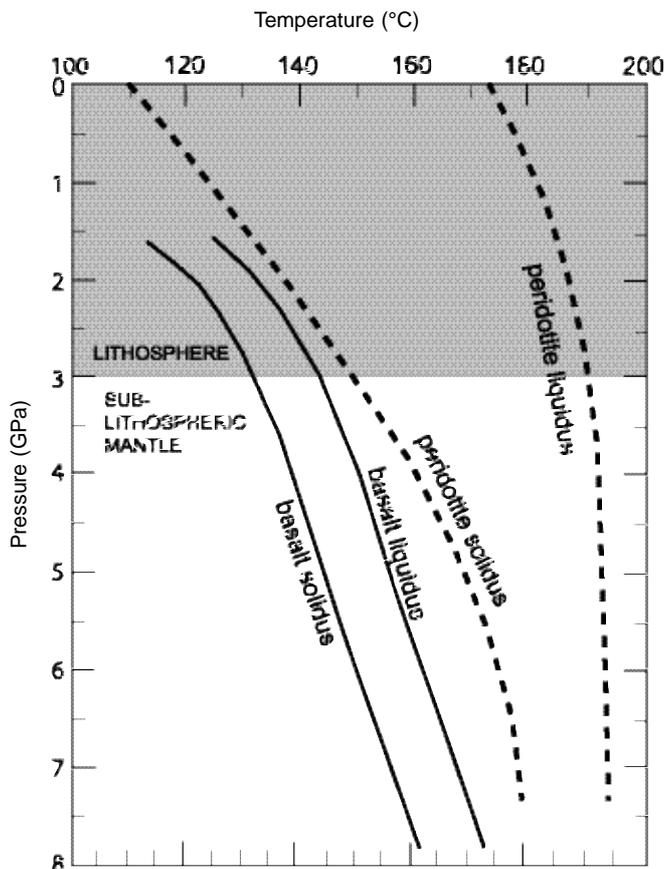


Fig. 4. Solidus and liquidus curves for anhydrous fertile peridotite (McKenzie and Bickle, 1988) and average MORB (Yasuda et al., 1994) in pressure-temperature space. Taken from Yaxley (2000).

I show below that the petrological characteristics of the Deccan tholeiites may be interpreted as indicating an excess basaltic component in their mantle source, with which many of their geochemical signatures are also consistent.

An Fe-rich Source for the Thakurvadi Formation Lavas?

Beane and Hooper (1988) described several flows from the Neral and Thakurvadi Formations that have apparently fractionated a mineral assemblage dominated by olivine. Olivine accumulation at the base of several of these flows, by crystal settling, is also clearly observed in outcrop. At Malshej Ghat, 125 km NE of Bombay, they observed that the bottom one metre of a flow unit is clearly enriched in olivine phenocrysts (1–3 mm in size), but the upper part of the unit is nearly aphyric. The olivine phenocrysts have cores as Mg-rich as Fo_{84} and rims of Fo_{74} , and an estimated average composition of Fo_{76} . Beane and Hooper (1988) found that the picrite basalt layer (their sample SAM-017, with 15.63 % MgO) can be derived by adding about 29 % of the olivine phenocrysts to the aphyric sample, and calculated that the parental melts of these picrites (with which Fo_{84} olivine cores would be in equilibrium) would have contained 9–10% MgO. As noted by them, these liquids represent the most primitive liquids for which we have direct evidence in the Western Ghats, and such magmas cannot have been in equilibrium with mantle peridotite.

I performed calculations (Table 2) of incremental addition of equilibrium olivine to a whole-rock composition represented by the aphyric lava sample SAM-018 of Beane and Hooper (1988). This sample can be interpreted as a “daughter liquid” (DL) of more magnesian magmas. I calculated thirty-five successive “parental liquid” (PL) compositions, each by adding 1 wt.% equilibrium olivine (Roeder and Emslie, 1970) to the previous liquid composition. Five of these parental liquid compositions, with which olivines containing 79.4, 83.9, 84.3, 90.0 and 91.0 Fo% respectively would be in equilibrium, are given. SAM-018 (DL) has a Mg# value of only 52.6, where $Mg\# = [\text{atomic Mg}/(\text{Mg} + \text{Fe}^{2+})] \times 100$, assuming $\text{Fe}^{3+}/\text{Fe}^{2+} = 0.16$. SAM-018 (DL) has equilibrium olivine with Fo% of 78.7, and could be derived by 9 or 10 wt.% olivine fractionation from a parental magma represented by PL9 or PL10 respectively (equilibrium olivine in both is $\sim Fo_{84}$). Peridotite-mantle-derived picritic primary magmas should crystallize equilibrium olivines with $Fo\% > 90$ (typically ~ 91), and should have whole-rock Mg# values of 75 (Basaltic Volcanism Study Project, 1981). PL30 and PL35 are two such calculated parental liquids with Fo_{90} and Fo_{91} equilibrium olivine

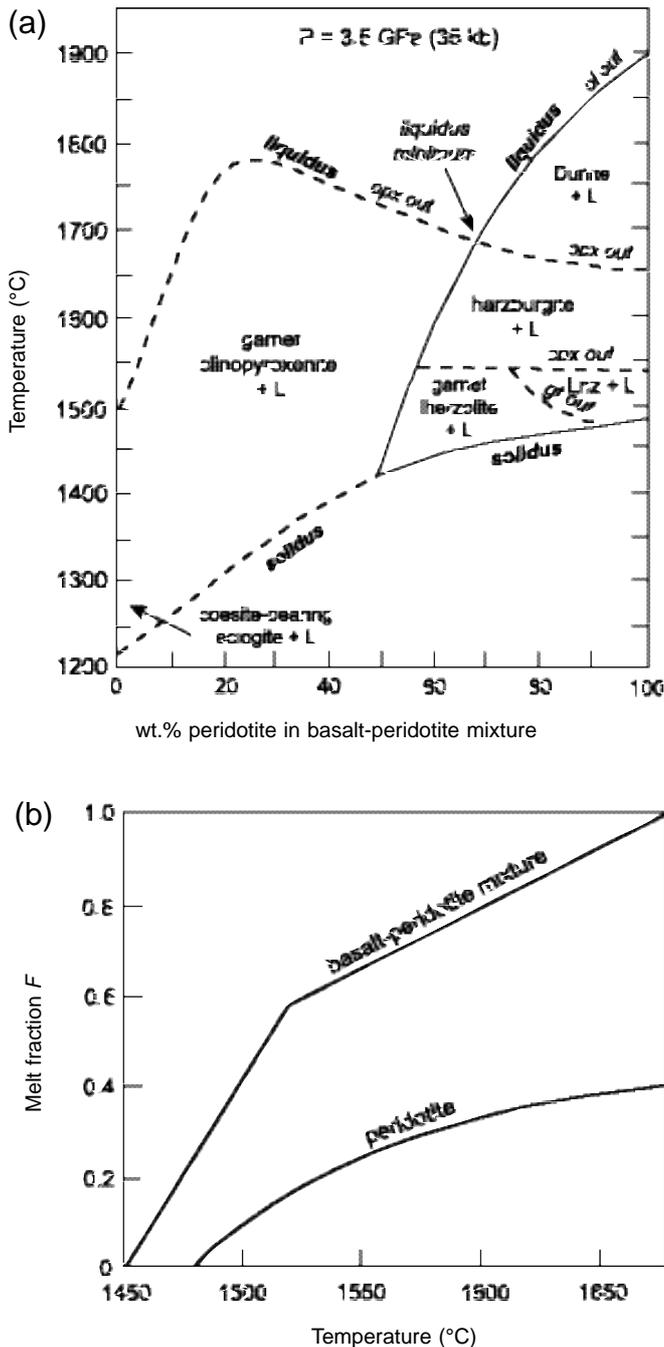


Fig. 5. (a) Phase relationships on the compositional join eclogite-peridotite. The specific samples studied are GA1 (average altered oceanic crust, Yaxley and Green, 1994) and MPY90 (peridotite), and their various mixtures. Whole-rock compositions of these can be found in Yaxley (2000). L=liquid; gt=garnet; opx=orthopyroxene; cpx=clinopyroxene; ol=olivine. (b) Curves of melt fraction F vs. temperature for a 30:70 wt.% mixture of average altered oceanic crust and fertile peridotite, and for pure peridotite. The peridotite curve is based on McKenzie and Bickle (1988), and the basalt-peridotite line is an approximate estimate for the liquidus minimum composition shown in (a). The higher average dF/dT and lower solidus of the mixed rock results in much higher melt productivity compared to peridotite for a given temperature. After Foulger and Anderson (2005).

respectively. Assuming that SAM-018 is derived by fractionation alone from a parental, primary magma like PL35, 35 wt.% olivine fractionation is required. The required amount of fractionation is much more if clinopyroxene, plagioclase, and iron oxides were considered besides olivine, because these other minerals would deplete MgO in daughter liquids to a much lesser degree than olivine alone would. Huge piles of cumulates should then be expected in the subsurface under the Deccan. Cox (1980) indeed suggested extensive crustal or subcrustal sill complexes and cumulate layers, and strongly argued for the derivation of Deccan basalts from picritic parent liquids (Cox, 1999). He considered only a peridotite mantle source probable.

Crustal Contamination, Peridotitic Source, or Eclogite-bearing Peridotite Source?

The possibility suggested here is that Deccan lavas like SAM-018, in which the most magnesian olivine phenocryst cores are only Fo_{84} , were derived from primary magmas that would crystallize equilibrium olivine with $84 \leq Fo\% < 91$ compositions, i.e., primary magmas that were not in equilibrium with peridotite but were in equilibrium with a more Fe-rich source than peridotite. Note that the Fe-rich cores of olivines in these lavas cannot be ascribed to their having assimilated continental crust. There is agreement (e.g., Cox and Mitchell, 1988; Sen, 1995, 2001) that crustal contamination of the Deccan basalts had a relatively minor effect on their major element compositions, which were instead largely controlled by fractional crystallization and magma mixing. If, therefore, the lavas with Fo_{84} olivine cores are not much fractionated (so near-primary), they are showing us the low olivine Fo content of the mantle source with which they equilibrated, which clearly would not be peridotite. Unfortunately, there is no way to prove that they are primary or near-primary. One has the choice here of interpreting them so, or as highly fractionated daughters of parental magmas with Fo_{91} olivines. For the former case, thick dunite layers in the subsurface are not required or expected, and for the latter case they are essential. High-resolution seismic studies might be able to image such dunite layers if they exist.

What then are the amounts of fractional crystallization likely to be undergone by the Deccan flood basalts? Plagioclase is a very common phenocryst in many, and olivine and clinopyroxene phenocrysts are by no means rare. Substantial gabbro fractionation at shallow depths is indicated (e.g., Mahoney, 1988; Sen, 1988, 2001 and references therein). I suggest that many of the Deccan basalt lavas, while they may be the result of gabbro fractionation, have undergone much less of early olivine

Table 2. Calculated whole-rock and equilibrium olivine compositions for successive parental liquids of the lava SAM-018 (DL).

Oxide wt. %	DL	PL1	PL9	PL10	PL30	PL35
SiO ₂	49.04	48.94	48.23	48.15	46.71	46.41
TiO ₂	2.32	2.30	2.14	2.12	1.72	1.62
Al ₂ O ₃	15.05	14.90	13.74	13.60	11.10	10.55
FeO(T)	13.02	13.09	13.44	13.45	13.17	12.97
MnO	0.19	0.19	0.17	0.17	0.14	0.13
MgO	6.89	7.23	10.00	10.35	17.07	18.67
CaO	10.92	10.81	9.97	9.87	8.06	7.66
Na ₂ O	1.90	1.88	1.72	1.70	1.35	1.30
K ₂ O	0.40	0.40	0.36	0.36	0.30	0.28
P ₂ O ₅	0.26	0.25	0.23	0.23	0.19	0.18
Total	99.99	99.99	100.00	100.00	99.81	99.77
Mg#	52.6	53.6	60.9	61.8	73.0	75.2
Fo%	78.7	79.4	83.9	84.3	90.0	91.0

fractionation than would be required for melts of normal peridotite. What this means is that the primary magmas that were produced in the mantle were already Fe-rich compared to “normal” peridotite melts.

In the AFM diagram (Fig. 6), the Western Ghats lavas define a marked tholeiitic trend (Fe-enrichment). This trend does not, of course, mean an Fe-rich source. However, the relatively evolved, Fe-rich compositions of a large majority of the Deccan tholeiites have been hitherto interpreted as a result of advanced fractional crystallization. A relatively Fe-rich source (compared to normal peridotite) and the appropriate Fe-rich primary magmas, as argued here, would mean the following:

(i) Required amounts of fractional crystallization are relatively small. Yasuda et al. (1997) and Cordery et al. (1997) made the same argument, that the amounts of fractionation necessary to derive the erupted basalts from picritic parents could be significantly reduced if the mantle source (in their model an upwelling mantle plume) contained eclogite and the primary magmas were not picrites to begin with.

(ii) The volume of total magma generated is considerably smaller than that estimated from peridotite melting models. The latter require huge amounts of magma ($\geq 50\%$) to be not erupted but left as cumulates in the subsurface.

(iii) Even accepting that magma volume produced is related to mantle temperature alone (which is not correct), the lesser total magma volume that is produced in the new model makes a thermal anomaly still less necessary.

Recent experimental work (Yaxley, 2000) shows that hybrid basalt (eclogite)-peridotite mixtures with $< 45 \pm 5$ wt.% of the basaltic component will produce primary melts that crystallize more Fe-rich olivine ($Fo\% < 89-90$) than normal peridotite melts. A near-solidus primary liquid in equilibrium with a source containing Fo_{84-85} olivine (a 45:55 eclogite:peridotite source) would contain $\sim 9-15\%$ MgO, and a near-solidus

primary liquid in equilibrium with a source containing Fo_{90} olivine (a peridotite source) would contain $\sim 16-22\%$ MgO (Yaxley, 2000). The former type of primary liquid is what Beane and Hooper (1988) calculated as a parental liquid for the Deccan lava SAM-018. Figure 7 shows that for 1 GPa (10 kb) pressure corresponding to about 35 km depth, olivines of composition $Fo_{84.6}$ would correspond to an FeO(T)/MgO ratio of 1, and the MgO concentration in the primary liquid would be $\sim 11\%$ (cf. Beane and Hooper, 1988). Yaxley (2000) stated that a hybrid source composition consisting of ~ 30 wt.% basalt mixed with ~ 70 wt.% peridotite produces substantially more melt (compared to normal fertile peridotite) during adiabatic ascent in the upper mantle. The melts of such a mixed source are picritic and nepheline-normative at relatively high pressures and low degrees of melting, and become hypersthene-normative picrites or olivine tholeiites at higher degrees of melting and lower pressures. The Deccan tholeiites, such as those of the Western Ghats, may therefore be moderately fractionated daughters of relatively low-MgO olivine tholeiite primary magmas, rather than highly fractionated daughters of picritic liquids.

Trace Element Modelling of the Ambenali Magma Type

Unlike lavas of some of the lower formations in the Western Ghats, lavas of the Ambenali Formation are

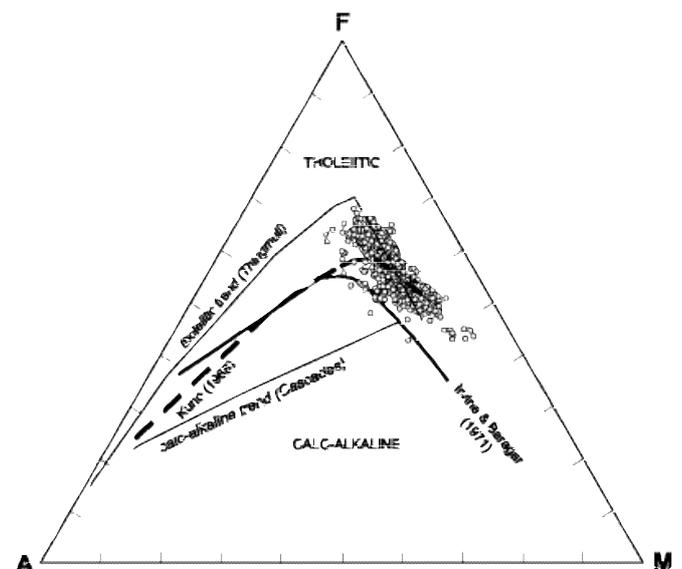


Fig. 6. AFM diagram for Deccan lavas (624 samples, Beane, 1988) of the Western Ghats section. A represents total alkalis, F is total iron as FeO, and M is MgO, all calculated on an anhydrous basis. Also shown are the classical calc-alkaline trend of the Cascades (U.S.A.) and tholeiitic trend of Thingmuli Volcano (Iceland). Dividing lines for the tholeiitic and calc-alkaline fields after Kuno (1968) and Irvine and Baragar (1971).

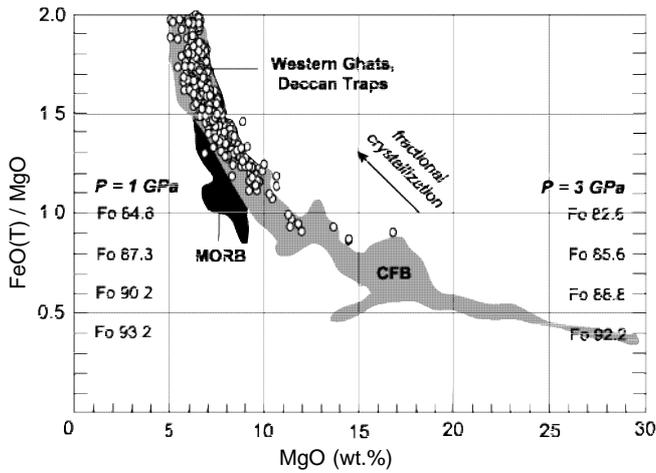


Fig. 7. Plot of FeO(T)/MgO vs. MgO (wt.%) for Deccan lavas from the Western Ghats (Beane, 1988). Samples with values of FeO(T)/MgO up to 2.0 only are shown (the highest value is 4.5) to enable easy comparison with MORB and CFB data shown by Yaxley (2000); olivine compositions in equilibrium with primary liquids at 1 GPa and 3 GPa (Yaxley, 2000) are also shown. Notice that CFB, including the Western Ghats lavas, are generally systematically higher in FeO(T)/MgO relative to MORB for the same MgO value (i.e., same degree of fractionation).

known to be little contaminated by continental lithospheric material. (All Ambenali lavas are by no means uncontaminated, as shown by the range of initial ϵNd values from about +7 to +3; Fig. 3). The Ambenali lavas resemble evolved transitional (T)-MORB in terms of major elements and compatible trace elements; i.e., they are ferrobasalts or “Fe-Ti” basalts with a broadly T- or enriched (E)-MORB-like incompatible element signature (e.g., Mahoney, 1988). They are taken by many (see Peng and Mahoney, 1995) to represent the composition of the Deccan plume head. Primitive-mantle-normalized patterns of Ambenali lavas show small Nb peaks, and have $\text{Nb}_N/\text{La}_N > 1$. Mahabaleshwar lavas have higher Nb concentrations than the Ambenali, though they have $\text{Nb}_N/\text{La}_N < 1$ (Fig. 8a). The Mahabaleshwar component has been variously argued to be old enriched lithospheric mantle or ancient granulitic crust with low $^{206}\text{Pb}/^{204}\text{Pb}$ (Fig. 3). The Mahabaleshwar component is thought not to be ocean island mantle, because the lower limit of the Mahabaleshwar Fm. ($^{206}\text{Pb}/^{204}\text{Pb}$ as low as ~ 16.7) is much lower than observed in modern oceanic lavas (Peng et al., 1994). Could the Ambenali magma type basically be N-MORB-type magma contaminated by small amounts of Nb-enriched (possibly phlogopite-bearing) continental lithospheric mantle, as Sheth (1999b) argued? Or, could the Ambenali magma type represent a blend of N-MORB magma with magma derived from ancient recycled crust?

To evaluate further whether the Deccan magmas, particularly the Ambenali magmas, could be blends of

magmas derived from peridotite and eclogite, and specifically the model of such eclogite representing ancient oceanic crust, I carried out batch melting calculations on a particular eclogite composition and attempted matching either the batch partial melts themselves, or suitable mixtures of these melts and N-MORB, to the average Ambenali composition. Oceanic crust, after its formation at a ridge, undergoes hydrothermal alteration and low-degree metamorphism, and during subduction, progressively transforms into amphibolite and eclogite (e.g., Poli, 1993). For the trace element composition of average altered oceanic crust before dewatering, I used the data of Zhang et al. (2004). The mobilities of various elements during dehydration and eclogitization were determined by Kogiso et al. (1997), who used an amphibolite as the starting material. Percent mobility is simply the concentration in starting material minus the concentration in final products, divided by the concentration in starting material (and multiplied by 100). Note that several elements in table 3 have high mobilities exceeding 50%, and the mobility of Pb is as high as 84.6%. (Mobility of Y is -0.5% , which means Y was enriched in the experimental run products compared to the starting material.) Using these mobility values I calculated the concentrations of these elements in dehydrated, eclogitized oceanic crust (the assumed source material in my calculations). I then calculated batch melts of varying degree (5% to 90%) using the distribution coefficients provided by Klemme et al. (2002), for eclogites having 50:50, 90:10, and 10:90 modal proportion of clinopyroxene and garnet.

For the same degree of batch melting, roughly the same concentrations of the various elements in the partial melts were obtained for all three eclogite types. The patterns of batch melts of the eclogite, and their mixtures with N-MORB, shown in figure 8b, closely mimic the pattern of the source eclogite itself, for all of the highly incompatible elements. In all cases, patterns that come closest to the Ambenali pattern are of a 10% batch melt, and of a 50:50 bulk mixture of a 5% batch melt and N-MORB. They are rather similar to the Ambenali in a few characteristics (e.g., normalized $\text{Nb}/\text{La} > 1$, a feature of the eclogite itself), but are glaringly different in their Rb, U and Pb values. The patterns of the batch melts and their mixtures, with relatively high Rb and their U peaks and large Pb troughs, contrast strongly with that of the Ambenali which has relatively low Rb, a small trough at U and no significant trough (or peak) at Pb. It is not clear to what extent the lower Rb and U concentrations in the Ambenali can be ascribed to subaerial alteration (this may seem an ad hoc explanation), but it is well-known that altered oceanic crust acquires a much higher U/Pb ratio than unaltered oceanic crust, given the high mobility of

Pb in seawater (e.g., Kogiso et al., 1997). As regards the Pb troughs in the batch melts and the mixtures (Fig. 8b), I speculate that the nearly flat Ambenali pattern at Pb reflects contamination of eclogitized-crust-derived magmas with originally lower Pb by small amounts of continental lithosphere. Peng et al. (1998) noted that Pb is highly enriched in most types of continental crust, and the Pb concentration of a mantle-derived magma may be dramatically affected by small amounts of continental crustal contamination.

In figure 8b, the pattern for the 5% batch melt mostly lies above the Ambenali pattern. Increasing the melt fraction shifts the partial melts towards the source eclogite composition. The pattern for the 20% batch melt is situated below the Ambenali pattern, and therefore, no bulk mixture of the 20% (or any higher-degree) batch melt with N-MORB can reproduce the Ambenali composition. Clearly, if these results are to be believed, the maximum proportion of eclogite in the mantle source of the Deccan Traps is restricted to ~20%. The results are clearly far from spectacular, though several uncertainties and assumptions were involved. For one, the source eclogite is assumed to consist only of clinopyroxene and garnet, but even small amounts of rutile in the eclogite can significantly affect the concentrations of elements such as Nb, Ta and Ti in the partial melts (e.g., Ryerson and Watson, 1987; Klemme et al., 2002). It is also not clear to what extent N-MORB is a suitable mixing end member. Further modelling, desirably with more realistic source compositions (modal, chemical, and also isotopic), seems called for. (A serious handicap is the near-absence of crustal or lithospheric mantle xenoliths, of whatever kind, in the Deccan lavas.) Below I explore other aspects of the model.

Identifying a Recycled Component in the Western Ghats Lavas: the ΔNb Parameter

Nb peaks are exhibited by primitive-mantle-normalized multi-element patterns of many ocean island basalts, and depict the recycled oceanic crust component, thought by many to be a mantle plume. The prevailing view is that subducting oceanic crust dehydrates at shallow depths and loses most of its large-ion-lithophile element (LILE) inventory, whereas the high-field-strength elements (HFSE) such as Ti and Nb (compatible in a mineral such as rutile) are retained by the slab as it transforms to eclogite and travels to the deep mantle (e.g., Hofmann and White, 1982; Hofmann et al., 1986; McDonough, 1991). Mantle plumes upwelling from the deep mantle are therefore thought to have inherent excess Nb.

Table 3. Data and results of batch melting calculations.

	average oceanic crust (ppm)	element mobility (%)	Eclo- gitized oceanic crust (ppm) C_o	bulk D	Amben- nali avg. (PMN)	N- MORB (PMN)	5% batch melt (ppm) C_L	10% batch melt (ppm) C_L	20% batch melt (ppm) C_L
Rb	12	63.0	4.44	0.002	5.20	0.88	134.72	68.68	34.68
Ba	26	52.5	12.35	0.0010	8.44	0.90	34.68	17.51	8.80
Th	0.27	37.7	0.17	0.004	11.76	1.41	37.17	19.31	9.84
U	0.14	29.1	0.10	0.007	10.95	2.24	84.06	44.80	23.16
Nb	2	3.6	1.93	0.015	17.50	3.27	42.13	23.85	12.77
La	2.50	56.1	1.10	0.017	16.16	3.64	24.21	13.89	7.50
Ce	7.50	50.7	3.70	0.034	14.59	4.23	25.33	15.96	9.17
Pb	0.20	84.6	0.03	0.156	14.00	4.23	2.13	1.76	1.30
Sr	110	40.8	65.1	0.043	10.14	4.27	33.96	22.24	13.16
Nd	7.30	30.9	5.05	n.a.	13.74	5.39	-	-	-
Zr	74	(≈ 0)	74	0.24	12.59	6.61	23.77	20.91	16.85
Sm	2.60	13.6	2.25	0.23	12.88	5.92	18.87	16.51	13.20
Y	28	-0.5	28.14	1.7	7.82	6.15	3.71	3.79	3.96
Yb	3.10	1.4	3.06	n.a.	5.58	6.19	-	-	-

Notes: Element concentrations in average altered oceanic crust (in parts per million) are for an undewatered state of the crust (Zhang et al., 2004). Percent mobilities of elements are those calculated by Kogiso et al. (1997) for subducted, dehydrated, eclogitized oceanic crust. Although they did not measure Zr, the mobility of Zr is here assumed to be zero since Zr (like Nb) is a very alteration-resistant element. Bulk D (distribution coefficient) values for the elements are for the case of partial melting of eclogite containing 50% modal clinopyroxene and 50% modal garnet (Klemme et al., 2002). n.a. means value not available. PMN means value normalized by concentration in primitive mantle; primitive mantle normalizing values and N-MORB values are from Sun and McDonough (1989). The batch melting equation (Shaw, 1970) is $C_L = C_o / [D(1 - F) + F]$, where C_o is the concentration in original (source) rock, C_L the concentration in liquid (partial melt), D is the bulk distribution coefficient, and F is the melt fraction with values between 0 and 1. Note that the C_L values tabulated are actual concentrations in ppm.

There are two caveats to using the high Nb concentrations observed in many ocean island basalts to infer a source enriched in Nb. One is provided by the study of Ionov and Hofmann (1995) of mantle xenoliths from Central Asia. Ionov and Hofmann (1995) argued that, during subduction and dehydration of a slab, Nb is not retained by the slab but is given off like the LILE, and is concentrated in hydrous minerals like phlogopite which crystallize in the mantle wedge under open system conditions. If this phlogopite-bearing mantle is melted later on and the phlogopite consumed in melting, the magma produced would have a high Nb content (Sheth, 1999b). Workers subsequent to Ionov and Hofmann (1995), however, have argued that Nb is largely immobile during slab dehydration (e.g., Kogiso et al., 1997). The other caveat is that Nb is a highly incompatible element in the anhydrous peridotite assemblage and would be strongly enriched in its initial low-degree partial melts (Sun and McDonough, 1989; Baksi, 2001).

Both these caveats (phlogopite-bearing mantle source and low-degree melting) do not hold for the voluminous

Deccan flood basalts that are almost entirely subalkalic and therefore not low- F melts. These caveats also do not hold for Icelandic tholeiites and normal mid-ocean ridge basalts (N-MORB). Fitton et al. (1997) showed that Icelandic basalts and normal mid-ocean ridge basalts (N-MORB) define parallel tight arrays on a plot of $\log(\text{Nb}/\text{Y})$ vs. $\log(\text{Zr}/\text{Y})$, with N-MORB relatively poor in Nb (Fig. 9). The upper and lower bounds of the Icelandic basalt array are given by the following equations respectively:

$$\log(\text{Nb}/\text{Y}) = 1.92 \log(\text{Zr}/\text{Y}) - 1.176$$

$$\log(\text{Nb}/\text{Y}) = 1.92 \log(\text{Zr}/\text{Y}) - 1.740$$

Fitton et al. (1997) defined a parameter ΔNb based on this diagram as follows:

$$\Delta\text{Nb} = 1.74 + \log(\text{Nb}/\text{Y}) - 1.92 \log(\text{Zr}/\text{Y})$$

ΔNb is a fundamental source characteristic and is insensitive to the effects of variable degrees of partial melting, source depletion through melt removal, and subsequent alteration. N-MORB have negative ΔNb values and Icelandic basalts have positive ΔNb values. Contamination of N-MORB magmas with continental crust can also never produce positive ΔNb values in the contaminated melts, because both N-MORB and the continental crust are depleted in Nb relative to other

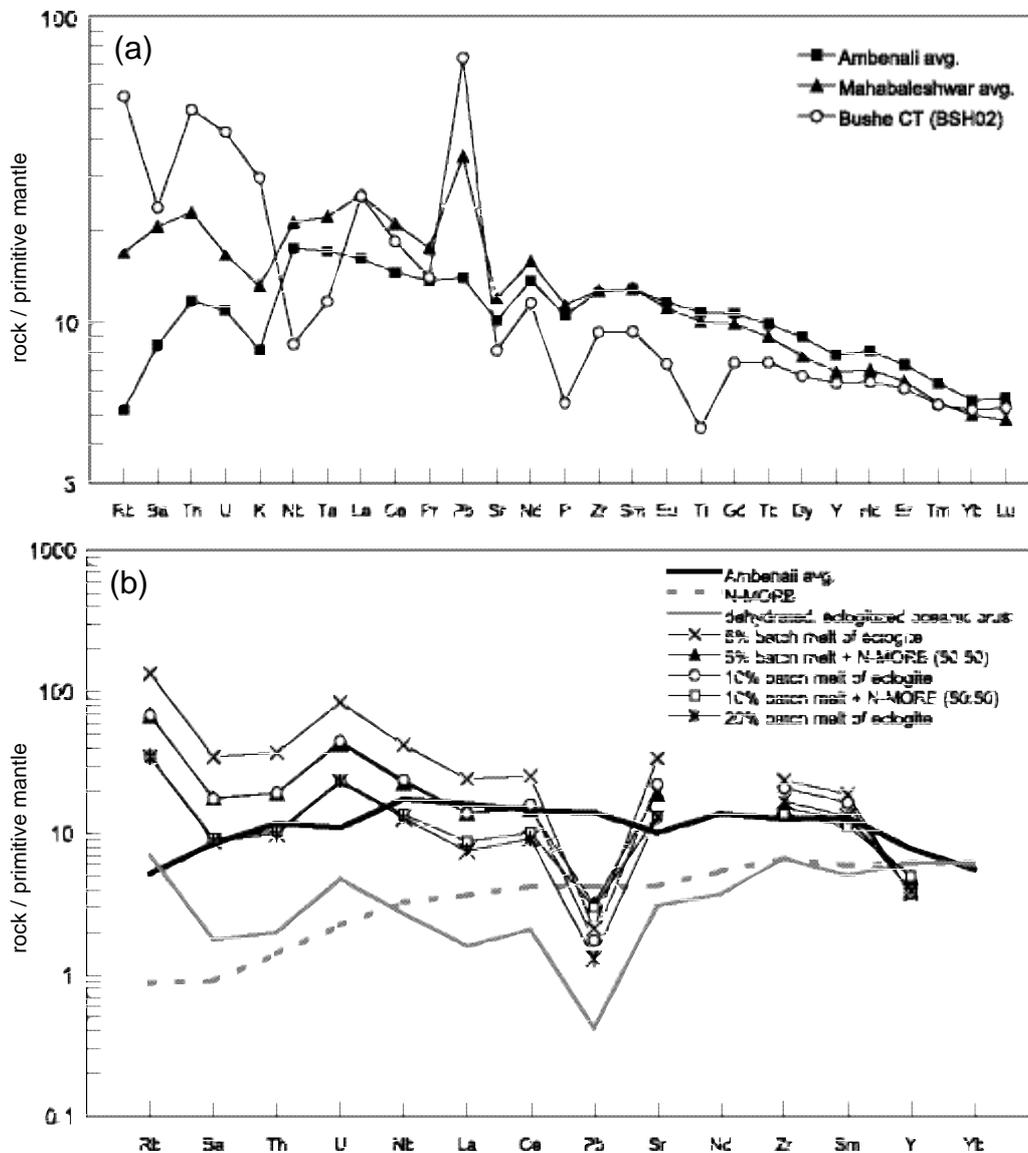


Fig. 8. (a) Primitive-mantle-normalized (values from Sun and McDonough, 1989) multi-element patterns for average Ambenali and Mahabaleshwar Formation lavas and the Bushe Chemical Type (sample BSH02 of Beane, 1988). The pronounced Nb-Ta troughs of the Bushe pattern are a result of crustal contamination (e.g., Mahoney, 1988). (b) Comparison of primitive-mantle-normalized multi-element patterns for the Ambenali magma type, N-MORB, eclogitized oceanic crust, and its various batch melts and their mixtures with N-MORB.

incompatible elements (e.g., both have primitive-mantle-normalized Nb/La < 1) and the continental crust has a ΔNb value equal to zero or slightly negative. The ΔNb value for an individual basalt sample shows the excess or deficiency in Nb of the mantle source of that basalt relative to the lower bound of the Iceland array. Positive values of ΔNb imply an Icelandic mantle source and negative values a depleted upper mantle source. Samples with $\Delta\text{Nb} = -1$ and $+1$ have respectively one-tenth and ten times the Nb contents of samples with the same Zr/Y falling on the $\Delta\text{Nb} = 0$ reference line. Baksi (2001), on the basis of this diagram, argued for deep-mantle plume components in many continental and oceanic flood basalts and ocean island lavas. However, inherent excess Nb in a mantle source, though it may indicate recycled oceanic crust, still provides no depth constraints. A shallowly recycled (upper mantle) eclogitic slab, or a slab of ancient eclogite residing within the continental lithosphere, would satisfy the observations equally well. I therefore take positive ΔNb values of lavas (and thereby mantle sources) as simply a signature of Nb-enriched, eclogitized oceanic crust, not a deep plume.

Continental basalts may be significantly contaminated by continental crust, and depending on the degree and type of contamination and the nature of the contaminant, they can have their ΔNb values lowered variably. Figure 9 shows the positions of the Deccan basalts of the Western Ghats on the $\log(\text{Nb}/\text{Y})$ vs. $\log(\text{Zr}/\text{Y})$ diagram. I have combined the basalts of Jawhar to Poladpur formations to avoid cluttering, but plotted the Ambenali and Mahabaleshwar Formation basalts separately, the reason for which will be immediately clear. The Jawhar to Poladpur Fm. basalts considered together (Fig. 9), or when plotted individually (not shown), straddle the $\Delta\text{Nb} = 0$ boundary line. Significant crustal contamination has occurred in the petrogenetic evolution of many Jawhar to Poladpur Fm. basalts (e.g., Beane et al., 1986; Peng et al., 1994), and can be told from many criteria, one of them Sr isotopic ratios (Table 1). Therefore the positions of many samples below the $\Delta\text{Nb} = 0$ line is not surprising. On the other hand, the aphyric basalt SAM-018 from the Thakurvadi Formation, for which I considered an eclogite-bearing mantle source possible, has a ΔNb value of $+0.07$. (Unfortunately, isotopic data are not yet available for this sample.)

The remarkable feature in figure 9 is that nearly all Ambenali and all Mahabaleshwar Fm. basalts plot right within the bounds of the Icelandic array. Very few (2 of 52) Ambenali samples have negative ΔNb values and the rest have positive values, and all Mahabaleshwar samples (13) have positive ΔNb values (Fig. 10). These can be ascribed neither to unusual (e.g., phlogopite-rich) mantle

sources nor to low- F melting, as both Ambenali and Mahabaleshwar Formations are wholly made up of subalkalic tholeiites, and are in fact two of the thickest formations of the Western Ghats (Table 1). Also, the positive ΔNb values of all Mahabaleshwar lavas mean that if they were contaminated by granulitic crust, as suggested by their $^{206}\text{Pb}/^{204}\text{Pb}$ ratios, this contamination was insufficient to bring down their ΔNb to zero or negative values, and the ΔNb values of the magmas before contamination would have been even more strongly positive. Alternatively, it is possible that the contaminant granulite itself did not have a strongly negative ΔNb value. A simple interpretation of the observations is that the Ambenali and Mahabaleshwar Formations have a recycled oceanic crust component in them. A relatively fusible eclogite (or pyroxenite) component, of the type postulated in this paper, can explain well the large volumes of these lavas.

The Volume of Eclogite and Eclogite-generated Melt

The continental lithosphere was already at least 150–200 km- thick well in the Archaean as evidenced by Archaean diamonds (e.g., Boyd et al., 1985). Accreting protocontinental nuclei of India may easily have been 150 km thick, and could hold a slab of oceanic crust that, if in a steeply inclined or vertical position, could be at least this high (cf. Foulger et al., 2005). The average thickness of the modern oceanic crust is 7 ± 1 km (e.g., White et al., 1992), of which the basaltic part (pillow basalts and sheeted dykes) makes up ~ 2 km (Boudier and Nicolas, 1985; Nicolas, 1989). Archaean oceanic crust may have been significantly thicker, warmer and more

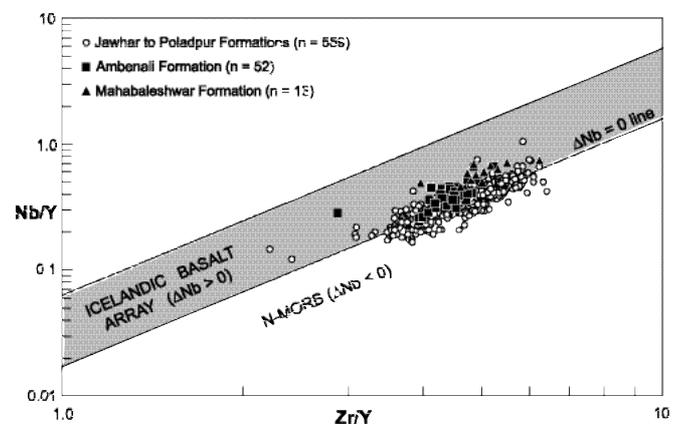


Fig. 9. The Western Ghats lavas, Deccan Traps (Beane, 1988) on the $\log(\text{Nb}/\text{Y})$ vs. $\log(\text{Zr}/\text{Y})$ diagram of Fitton et al. (1997). The Icelandic basalt array is also shown. Samples plotting above the $\Delta\text{Nb} = 0$ line (lower bound of the Iceland array) are thought to have a recycled oceanic crust component.

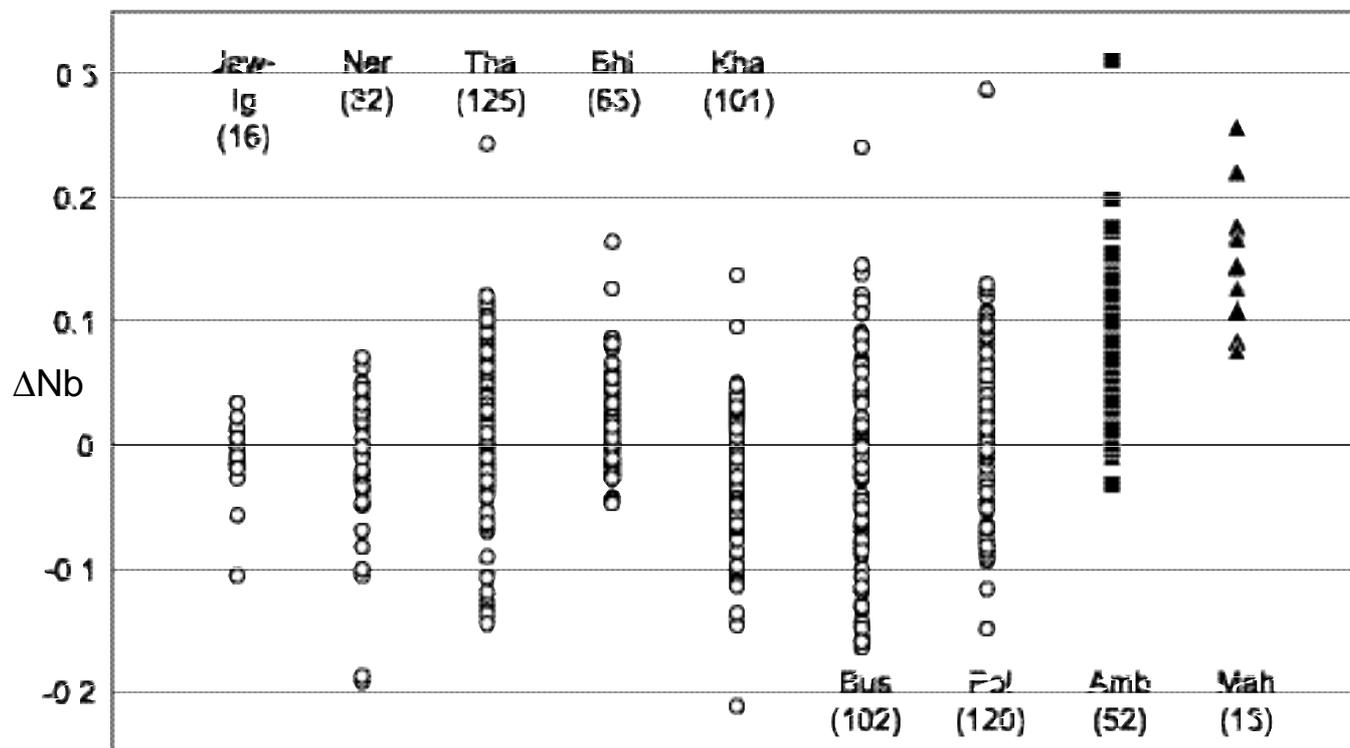


Fig. 10. Range of ΔNb values calculated for lavas of the various Western Ghats formations, using the formula of Fitton et al. (1997) and the data of Beane (1988).

buoyant owing to a hotter Archaean mantle (e.g., Bickle, 1978; Campbell and Jarvis, 1984; Hamilton, 1998 and references therein). A thickness of 5 km is considered here a reasonable assumption for a flat, vertical slab, but this thickness would be effectively larger if the slab were imbricated (Foulger et al., 2005).

Assuming that a vertical or near-vertical, 150 km-deep, 5 km-thick basaltic layer in an ancient suture zone (such as the Narmada zone) melted over a length of 500 km of the suture zone, and that total melting was achieved, the magma volume produced would be $0.375 \times 10^6 \text{ km}^3$. Assuming an additional such slab along the western Indian continental margin and its total melting, the total volume obtained is $0.75 \times 10^6 \text{ km}^3$. This is half the estimated original volume of the Deccan ($1.5 \times 10^6 \text{ km}^3$), assuming an original area for Deccan of $1.5 \times 10^6 \text{ km}^2$ (Wadia, 1975) and a reasonable original average thickness of 1 km over this entire area. Thus half the volume of the Deccan would have come from eclogite alone. The assumption of total melting of the eclogite may be unrealistic, though the considerably lower solidus and liquidus of eclogite compared to peridotite mean that heat conduction out of the ambient peridotite into the eclogite should be effective in melting it to high melt fractions. Even if it were assumed that the eclogite melts to 50%, one-fourth the total volume of the Deccan lavas would come from it. Note that

although eclogite and basalt have the same chemical composition, it is not necessary to achieve total melting of eclogite to produce a liquid of basaltic composition, as each melt fraction yields in general a basaltic composition (Yoder, 1976), excepting the near-solidus eclogite partial melts that are highly siliceous (rhyodacite or dacite, Yaxley and Green, 1998).

It is assumed that all magma formed was erupted, i.e., no magma was trapped in dykes, magma chambers, etc. This assumption is more or less valid, because the density factor is less serious for such magmas than for picritic liquids. Picritic liquids, due to their high density, must pond at subcrustal or midcrustal depths to crystallize and fractionate olivine, and only then can they rise upward through the effective density filter that is the continental crust (Stolper and Walker, 1980). If one-fourth the total erupted volume of the Deccan lavas (a conservative estimate) came from eclogite alone, this volume is quite considerable.

A Physical Model for Melting the Eclogite

Although eclogite-rich plumes have been proposed (e.g., Cordery et al., 1997; Takahashi et al., 1998), an important problem is that adding large amounts of eclogite to a peridotitic plume creates negative buoyancy in the

plume, given the higher density (3.4–3.5 gm/cm³; Ito and Kennedy, 1971) of eclogite than of peridotite (3.3 g/cm³). Thus eclogite-rich plumes cannot upwell (O'Hara et al., 2003). Plume proponents have tried to circumvent this problem by proposing appropriately higher temperatures (greater thermal buoyancy) for plumes (e.g., Cordery et al., 1997), but such plumes should encounter their solidus at great depth and will still not be able to upwell (O'Hara et al., 2003). Therefore, if substantial amounts of eclogite exist within peridotite, the tendency of the mass would be to *sink*, not upwell.

I propose delamination of eclogite to avoid the paradox of upwelling, dense eclogite-rich plumes. Delamination means the removal of the lower lithosphere and its incorporation into the asthenosphere. Delamination causes lithospheric thinning, so that ambient mantle can convectively flow toward the thin lithosphere (e.g., Czamanske et al., 1998), upwell into the gap, undergo decompression, and melt. The delaminated lithosphere can itself melt (e.g., Smith, 1993). Elkins-Tanton (2005) mentions two necessary conditions for delamination to occur: (1) The lower lithosphere becomes gravitationally unstable, i.e., is denser than the material underlying it, and (2) The viscosity of the lower lithosphere is reduced sufficiently for it to flow downward under the influence of gravity (Elkins-Tanton et al., 2002). Numerical modelling work (Elkins-Tanton, 2005) suggests that, over a range of lithospheric thicknesses and mantle potential temperatures, these processes can create a wide range of melt volumes, even up to the size of a flood basalt province, and that delamination is a viable process for the Siberian flood basalts.

I suggest that the onset of crustal extension and lithospheric rifting along India's ancient sutures, well before the flood basalt phase in the Deccan Traps (see Sheth, 1999a, 2000), led to the realization of both the required conditions mentioned above (Fig. 11). In this model, as the lithosphere begins to rift along the ancient suture, the eclogite trapped along the suture becomes suspended in the mantle, and begins to sink bodily. As it sinks, ambient asthenospheric peridotitic mantle flows into the gap created, depressurizes adiabatically, and melts. If the eclogite is originally hydrated, it begins to dehydrate as it heats up, and the water released into the surrounding upwelling peridotite causes further melting of it. Melting of the eclogite will ensue when it is sufficiently heated, and melts of eclogite will blend with melts of peridotite to yield *Fe-rich primary magmas*.

Yasuda et al. (1997), who proposed a composite (eclogite-peridotite) upwelling plume model, made the important point that eclogite melts extensively before the peridotite begins to melt, but the melts cannot escape the

source region until peridotite melting allows large-scale melt connectivity, at which point large volumes of melt may be released cataclastically. They also showed that the major element compositions of hybrid magmas derived by melting of such mixed mantle sources is comparable to that of CFBs, and argued that some CFBs could be near-primary magmas.

Notably, the model of Yasuda et al. (1997) involved upwelling, not sinking, eclogite. How about the sinking eclogite in the model proposed here? One can notice that dehydration and partial melting of such sinking eclogite should make it cooler and harder to melt further. I note, however, that the residual eclogite would be considerably lighter compared to the original unmelted rock, and at this point it would be entrained into the mass upwelling of asthenospheric peridotite. As both rise, the residual eclogite will become a heat sink – it will draw heat diffusively from the surrounding peridotite, heat up, and because of the heating and continuous decompression, will melt much more on ascent (Fig. 12). The idea is based on the work of Hirschmann and Stolper (1996) who, based on many major and trace element and isotopic grounds, argued for the presence of garnet pyroxenite in the source of MORB. Pyroxenite, like eclogite, is a relatively fusible mantle rock, and pyroxenite in the sub-lithospheric mantle may represent subducted basaltic crust. An upwelling mixture of pyroxenite and host peridotite (Fig. 12) has much greater melt productivity over the same depth interval than pure peridotite, because of the low-melting pyroxenite component in the mixture. Such a mixture can also have much greater melt productivity than upwelling pyroxenite, the reason being diffusion of heat out of the host peridotite and into the enclosed pyroxenite. As worked out by Sleep (1984), such thermal diffusion is efficient and rapid as long as the mantle heterogeneity that is being heated does not exceed a few kilometres in size. It would appear that the results of Hirschmann and Stolper (1996) would also apply equally well to eclogite, and the thermal requirements for melting a substantial mass of eclogite in my model would be met with.

Discussion and Conclusions

As for Iceland, a Fe-rich mantle source has been proposed for the Columbia River CFB of western U.S.A. (Wright et al., 1988; Takahashi et al., 1998) and argued to represent ancient oceanic crust subducted and recycled via a deep mantle plume (Takahashi et al., 1998). It is pertinent that this CFB, the only post-Precambrian CFB in North America, is situated on a tectonic boundary adjacent to the only craton in North America, the Wyoming Craton (Anderson et al., 1992). A more appropriate model

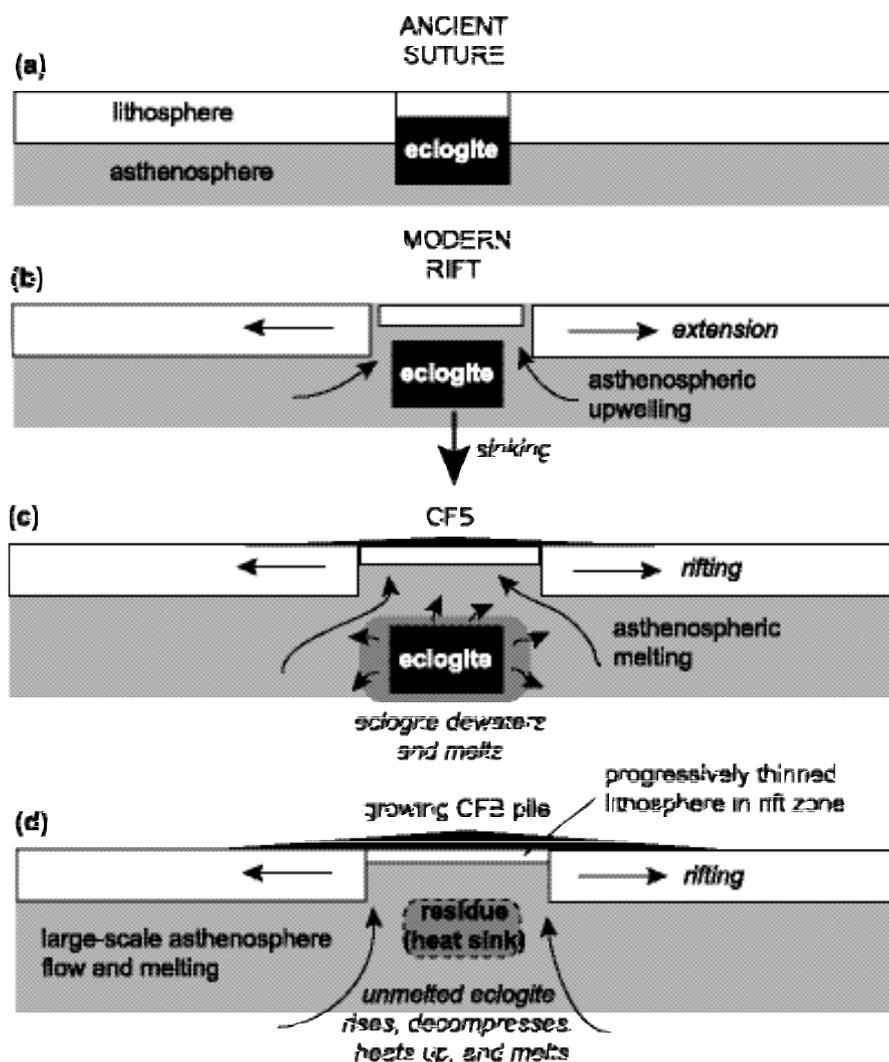


Fig. 11. Schematic model (not to scale) to illustrate the proposed mechanism of delamination of eclogite. (a) Eclogite exists stably along an old suture zone. (b) Lithospheric extension and rifting begin, and the eclogite delaminates and sinks. Surrounding asthenospheric mantle flows into the gap, decompresses and melts. (c) Continued sinking of eclogite leads to its dehydration and melting, while the water released by the eclogite promotes melting in the asthenospheric mantle above. Modified after Elkins-Tanton (2004). (d) The residue of partial melting of eclogite gets entrained into the mass flow of asthenosphere and ascends; as it ascends it decompresses, heats up due to thermal diffusion out of the host peridotite, and melts much more.

for this CFB may be that of Smith (1992), involving back-arc convection and pyroxenite melting. In fact, Smith (1993) showed a close correlation between the locations of CFB provinces, hotspot tracks, and ancient sutures. He even noted the association of the Deccan and Rajmahal Traps with sutures in India and emphasized the contributions to ocean island volcanism from enriched mantle delaminated from under sutures.

The garnet peridotite or pyrolite plume model, which has long been popular in models of large-volume basaltic magmatism, ascribes excess magmatism to higher-than-average temperatures. More recent models of petrogenesis emphasize the petrological diversity of the mantle and include important roles for eclogite or pyroxenite, besides

volatiles (especially CO_2) (e.g., Presnall et al., 2002; Foulger et al., 2005), and do not require high absolute temperatures. Gibson et al. (2000) and Gibson (2002) consider that several CFBs probably had Fe-rich (eclogite-bearing) mantle sources but, believing that CFBs are derived from mantle plume heads, they propose that the required eclogite represents deeply recycled oceanic crust entrained within uprising plumes. The observations are then explained by invoking "plume head heterogeneity", but structural and petrological complexities of the continents have generally remained neglected in the plume model. The plume model, focussed as it is on the deep mantle, assumes no continents, no geology, no fracture zones, no lateral temperature variations in the

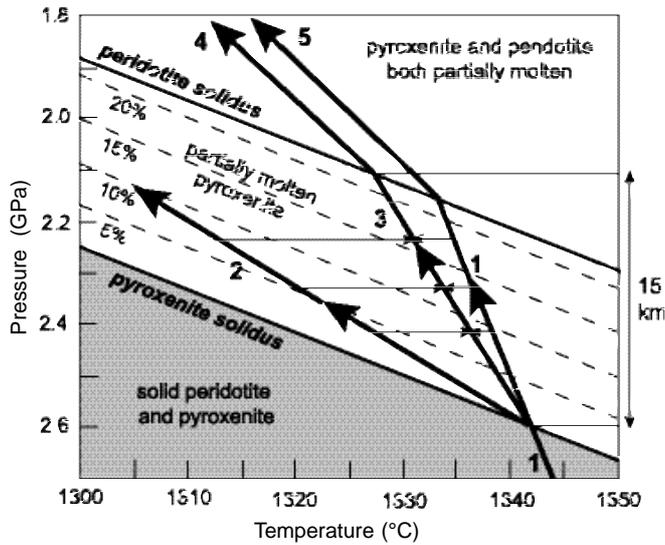


Fig. 12. Schematic diagram, slightly modified from Hirschmann and Stolper (1996), showing thermal equilibration between pyroxenite and host peridotite in upwelling mantle. Heavy lines with arrowheads show the paths of upwelling mantle. 1 is an adiabat for an upwelling mass of pyroxenite-bearing peridotite. When it intersects the pyroxenite solidus, the pyroxenite begins melting but the host peridotite remains solid. The latent heat of melting cools the residual pyroxenite (trajectory 2, gentler than 1) unless cooling is compensated by thermal diffusion out of the peridotite. The dashed lines are isopleths of constant melt fraction in the pyroxenite. If the peridotite loses no heat, it continues to upwell along the adiabat 1 until it touches its own solidus and begins melting. It will now follow trajectory 5. If, however, thermal diffusion out of the peridotite into the pyroxenite is efficient, both will thermally equilibrate (along the small horizontal converging arrows) and the upwelling mass made up of both, with the same temperature throughout, will follow the curve marked 3. After intersecting the peridotite solidus, the mass will follow curve 4. If instead of pyroxenite the upwelling peridotite contained eclogite, qualitatively the same effects should be observed.

mantle (so no mantle convection), and no internal heating (Anderson, 1996).

The model I have proposed here, of an excess basaltic component in the source of the Deccan flood basalts, and its derivation from ancient oceanic crust preserved within the Indian continental lithosphere, is based on the possible Fe-rich mantle sources for the voluminous Deccan basalts, and first-order structural-tectonic features of the Indian subcontinent. It is worth exploring in detail. I conclude, as I have done previously based on many types of data (Sheth, 1999a, b, 2000, 2005), that CFB events like the Deccan do not require, and are not consistent with, the deep mantle plume model. The original plume model has ascribed CFBs such as the Deccan to high mantle temperatures alone. Important roles for mantle with extra fertility or volatile content are now increasingly recognized, but recent plume models simply assume

plumes to have these required attributes (e.g., Cordery et al., 1997; Baker et al., 1998; Gibson et al., 2000; Gibson, 2002). The key point is, when volatiles are considered, easily fusible and fertile mantle invoked, and continental geology paid due attention, one may no longer need deep mantle plumes.

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