The Deccan Volcanic Province: Thoughts about its genesis

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1. Impetus for this contribution

The Deccan volcanic province (DVP) is one of the world's largest LIPs and perhaps the best studied continental flood basalt (CFB). However, its genesis and evolution are still poorly understood.

Recently, *Sheth* (1999) convincingly refuted the plume model as a basis for the genesis of the DVP (see The Deccan beyond the plume hypothesis). However, his suggestion that the DVP and Laccadive-Chagos ridge formed as a consequence of southward crack propagation along the Vishnu fracture zone is not consistent with data concerning the geomagmatic and tectonic history of the Indian peninsular plate. The current status of knowledge thus represents a shortfall of understanding. The need to fill this gap in our knowledge, and to establish a genetic model for the DVP based on the vast volumes of existing scientific data, was the impetus for the present contribution.

2. Introduction

The DVP is one of the Earth's giant continental flood basalts and has a total exposed area of about half a million square kilometers, between latitudes 16° - 24° N and longitudes 70° - 77° E. In the northwestern, central and southern Indian peninsula, the approximate volume of the DVP is about 2×10^6 km^3 and its estimated age is 64-65 Ma. It is generally believed that the DVP originated during Gondwanaland breakup as part of the Seychelles-India separation event. Another important belief concerning this CFB is that it is the "head" of a plume which is currently active as Reunion volcanism, with the "tail" consisting of the rather irregular chain of volcanic islands extending from Reunion to and along the Laccadive-Maldive-Chagos ridges. The latter model has been refuted convincingly, as mentioned above. However, a viable alternative model has not yet been proposed. In this contribution we attempt to provide an alternative hypothesis based on existing geological information about the DVP.

3. The Deccan volcanic province: existing scientific data

The DVP erupted on the Archean-Proterozoic shield areas of south, north-west and central India and the adjoining offshore area off the west coast (Figure 1) (*Devey & Stephens*, 1991). The volcanics cover two cratonic areas – the Dharwar craton of the south Indian shield and the central Indian craton. Apart from this, the DVP is associated with four major rift zones of peninsular India (Figure 1). It is juxtaposed with the east-west-running Narmada-Satpura-Tapi rift which is a horst-and-graben-type rift zone that trends ENE-WSW for > 1600 km along central India (*Mishra*, 1977). In northwest India, the DVP is in contact with the Cambay, Kutch and West Coast rifts.

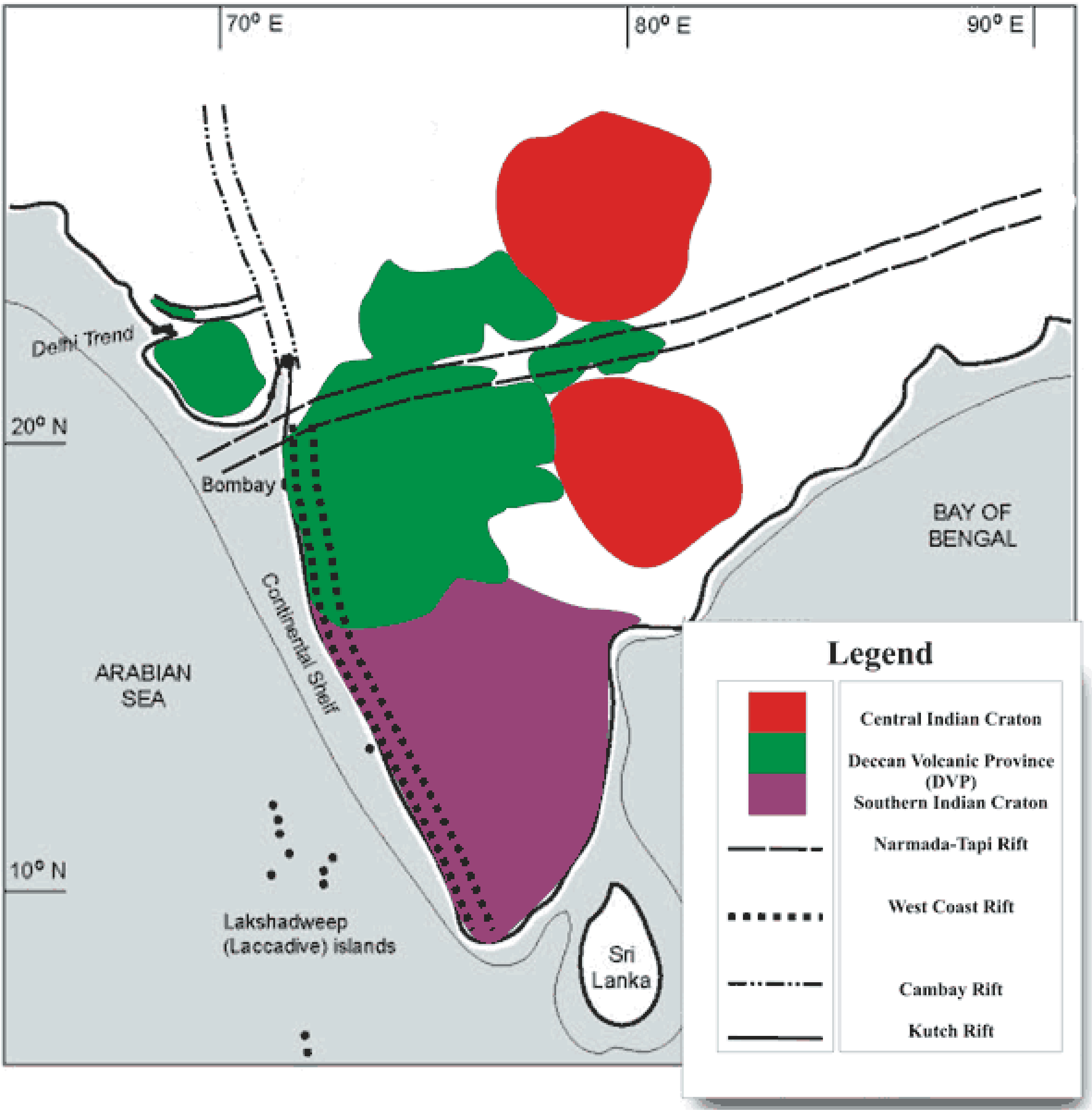

Figure 1: Geological map showing the location of the Deccan volcanic province and its relationship with the geo-tectonic features of the region. Modified after Sheth (2005).

To evaluate the causes of DVP genesis, it is essential to understand the geological context of its hosts. Therefore, to interpret the data from the Deccan volcanics, we first review the nature of the hosts.

Along the West Coast rift, the south Indian shield witnessed several prior phases of magmatism before it hosted the Deccan volcanics. The first recorded event occurred at 678 Ma when gabbro, granophyre and anorthosite magmatism occurred (*Nair & Vidyadharan*, 1982). This was followed by granitic plutonism, almost 128 My later, *i.e.*, at 550 Ma (*Soman et al.*, 1983). Subsequently, the region hosted pegmatitic intrusions at 460 Ma (*Soman et al.*, 1982). These pegmatites mark the end of the major phases of the magmatic episode because there was then a complete hiatus of magmatic events in the region until 93 Ma (date averaged from six differing K-Ar dates), *i.e.*, for more than 350 My! At 93 Ma, the West Coast region again experienced magmatism, this time involving rhyolitic and dacitic volcanics (*Valsangkar et al.*, 1980). This was followed by vast mafic volcanism and plutonism which resulted in the DVP and associated dyke swarms during the period 64-65 Ma, and covered the huge area mentioned above.

Along the Narmada-Tapi rift zone, prior to the Deccan episode, no major magmatic event is reported. Instead, the horst (Satpura) and grabens (Narmada and Tapi) paved the way for enormous sedimentation, which gave rise to the Mahakoshal group of rocks (*Chanda & Bhattacharya*, 1966). These metasediments recorded several phases of shearing implying that the Narmada – Tapi rift is associated with intense shear deformation along an east-west trend. These metasediments are followed by Jurassic-early Cretaceous sediments on top of which the Deccan volcanics lie (*Chanda & Bhattacharya*, op.cit).

The tectonics of the northwest Indian peninsula and the offshore region are inter-related. The summary of the tectonic history of this region given here is based on the studies of several workers (*Glennie*, 1932; *Qureshy*, 1971; *Owen*, 1976; *Kaila et al.*, 1979; 1981; *Biswas*, 1982; 1987; *Harbison & Bassinger*, 1973; *Gupta et al.*, 1998). As shown in Figure 1, four major rift zones are in contact with the Deccan volcanics, the Narmada-Tapi rift, the West Coast rift, the Cambay rift and the Kutch rift. Kutch rifting occurred in the late Triassic to early Jurrasic followed by early Cretaceous Cambay rifting. The Narmada-Tapi and West Coast rifts were reactivated in the late Cretaceous. The Narmada-Tapi rift zone is believed to be extending along its trend into the offshore area of the Indian west coast.

Concerning geophysics (*Chandrasekharam*, 1985), the Bouguer gravity anomaly pattern and seismic profiles along the West Coast rift indicate:

- thinning of the continental crust along the western coast. This implies delamination of the lithosphere beneath the west coast,
- rifting of the coast in a horst-and-graben pattern, and
- shear displacement of the West Coast fault.

Deep Seismic Sounding (DSS) investigations have been carried out in the Indian peninsula (*Reddy et al.*, 1999). This study indicates that the crust seems to become thinner (24 km) towards the northern parts of the west coast, that is north of 15°N. The west coast was also characterized by upwarp of the Moho during the late Cretaceous period.

Vertical crustal movements are recognized along the West Coast rift, and shear displacement along the Narmada-Tapi rift zone and its extension into the offshore areas (*Biswas*, 1982).

4. The new proposed hypothesis: an effort to bridge the gap in knowledge

4.A: *The first phase of magmatism, 678 to 460 Ma*: Of the four rifts, only the West Coast rift exclusively hosts magmatic rocks older than the Deccan volcanic event at 64-65 Ma. These magmatic rocks, which formed at 678-460 Ma, show a clear trend of fractional melting (gabbro-rhyolite to pegmatites). This implies the presence of a magma chamber beneath the Indian lithosphere under the west coast. In this magma chamber, magma could have remained stored and preserved its primary chemistry. The primary magma could have risen from its depth of segregation which was beneath or within the west coast lithosphere, but certainly not deeper than 200 km because the first magmatic event was gabbroic. *The hiatus in igneous activity* from 460 Ma to 93 Ma along the West Coast rift indicates that during this period the magma pressure in the chamber was less than lithospheric, and/or the temperature was too low for magma to cross the liquidus of its compositions. By 93 Ma, that is 350 My later, this problem was removed.

4.B *The beginning of the second phase of igneous activity, at 93 Ma*: This phase, along the West Coast rift, is marked by a magmatic event which was not plutonic, like previous ones, but rather volcanic. Unlike the previous episode, it began with magma of felsic composition – the rhyolites. It is relevant to note that Madagascar-Indian plate breakup took place at around 93 Ma. This breakup also occurred along the western continental margin of India. Obviously, such a megascale rifting event will leave its signature in the form of volcanic, not plutonic activity, which can explain the simultaneous rhyolitic volcanism. The composition, felsic instead of mafic, probably indicates that the temperature was too low to melt mafic components in the magma chamber beneath the West Coast region, but elevated enough to produce the rhyolitic melts, *i.e.*, it was around 1000°C.

4.C *The Deccan volcanism, at 64-65 Ma*: The second event of this phase is the Deccan volcanism which occurred after a hiatus of 30 Ma. Also, after exactly the same hiatus, and at the same time of 64-65 Ma, the Indian plate experienced breakup from yet another partner at Gondwanaland time – the Seychelles. This probably indicates that the second stage of magmatism, which began at 93 Ma, was controlled by the breakup events between Gondwanaland microplates and the Indian plate. Also, it shows that the breakup process was a gradual and progressive phenomenon, starting with Madagascar-India separation and, after another 30 My, Seychelles-India separation. Since this process controlled West Coast magmatism, which tectonism is expected to do, we deduce that the magmatism was also progressive. Thus, we conclude that (i) the rhyolitic volcanism at 93 Ma resulted from Madagascar-India breakup, and (ii) that this breakup event was a continuous process which led to Seychelles-India breakup after another 30 My and to Deccan volcanism at the same time. The progressive chemical trend of the volcanics, i.e., from *rhyolite to basalt*, indicates gradual progressive increase in temperature and/or gradual progressive lowering of the liquidus in the magma chamber as a result of gradual progressive rifting/breakup of the Indian plate with Madagascar and the Seychelles respectively.

The shift from *plutonism* during first phase to *volcanism* during the second phase perhaps indicates the presence of direct, uninterrupted conduits from the magma chamber to the surface of the continental crust during the second phase. This is what is expected during extensive rifting events such as Madagascar-India and Seychelles-India separation which did not occur during the first phase.

The *large volume of the Deccan volcanics* and the *high rate of volcanism* during the Deccan episode indicate:

a.

a. higher rate of adiabatic decompression due to continental scale rifting,

b. consequently, higher rate of melting of magma in the chamber,

c. further, continental delamination of the western continental crust due to elevation in temperature and decrease in viscosity caused by the presence of a heat source in the form of a magma chamber at its base, and

d. a direct plumbing system between the melt and the surface, during eruption.

Considering that the West Coast and Narmada-Tapi rift zones were reactivated at the time of Deccan volcanism and the Cambay and Kutch rifts were also available as direct conduits for the upward movement of melt, we infer that the presence of these four rifts and geophysical evidence of lithosphere thinning beneath the westen coast explains the size, volume and eruption rate of the Deccan volcanics.

The *geochemical variation within the Deccan volcanics*, as mentioned above, perhaps indicates differences in the chemistry of the host rocks. For example, along the Narmada-Tapi rift zone the magmatic melt must have interacted with the host sediments, which are Mahakoshal Jurassics along with Archean metamorphics. Similarly along the West Coast, Cambay and Kutch rifts, the melt would have interacted with Archean-Precambrian metamorphics. Consequential changes in the chemistry would be reflected in the geochemistry of the DVP volcanics.

4.D Post Deccan

4.D.1: 61 Ma*:* The rifting which had started at 93 Ma resulted in the opening of the Carlsberg ridge at about 61 Ma. Deccan volcanism also continued, as suggested by the age of DVP rocks from the Bombay area (*Sheth & Ray*, 2002). This is the time when the Laccadive ridge also experienced Deccan volcanism.

4.D.2: 55-50 Ma: Sea-floor spreading along the Carlsberg ridge resulted in the emplacement of ocean floor between the ridge and the continental margin of the Indian West Coast. Deccan volcanism along the West Coast rift produced the Maldive ridge at around 55 Ma and the Chagos ridge at around 50 Ma. Clearly, the Maldive and Chagos ridges formed by interaction of the West Coast rift magma with Carlsberg ridge mantle magma because the Laccadive ridge, at 61 Ma, is characterised by melt with the same chemistry as melt from the magma chamber beneath the western continental crust of India.

The locations of these ridges mark the position of India at a given point in time. At this time, the

Indian plate was moving northwards at a velocity of 18-19 cm/year. Thus, the position of Indian plate was controlled by (a) its own velocity in a northerly direction, and (b) the speed of Carlsberg ridge propagation.

4.D.3: 45-35 Ma: By this time, the northward movement of India had slowed considerably because the Indian plate had collided with the Eurasian plate. As a result, intraplate tectonics were solely responsible for deformational events. Along the West Coast rift, two types of forces were important (Figure 2), the north-south-trending West Coast and Cambay rift forces and the east-west-trending Narmada-Tapi rift force. The net vector force of these two combined resulted in shearing and stretching along the West Coast rift zone (Figure 2). Simultaneously, isostatic balancing forces resulting from the emplacement of a huge volume of volcanics resulted in vertical movements along the west coast. These conclusions are based on the fact that the West Coast rift is bounded by intersecting sets of faults and fractures which extend up to the Laccadive ridge (Figure 2). The fracture system north of 16°N formed during the late Cretaceous whereas the systems to the south of 16°N formed during the middle to late Tertiary. This indicates that deformation along the coast had started in the late Cretaceous and gradually progressed southwards during the late Tertiary. Probably, the combined outcome of these forces resulted in Laccadive ridge separation (due to stretching), southward displacement (due to shearing) and subsidence (due to isostatic balancing) during the late Tertiary.

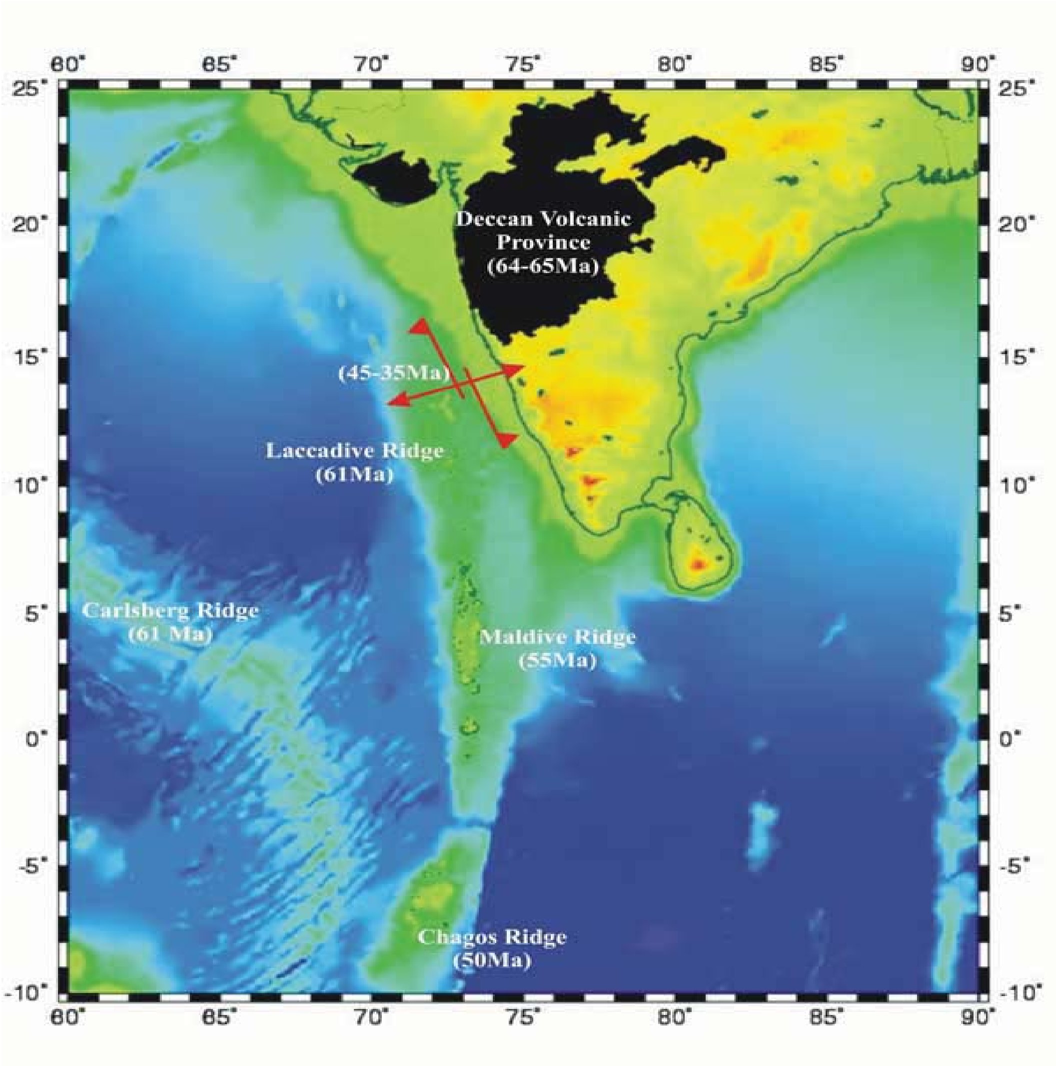

Figure 2: Diagrammatic representation of the proposed hypothesis described herein for the geological history of the Indian plate from 65 Ma onwards. The major stress directions along western continental margin of India 45-35 Ma are indicated by red arrows.

Summary

We propose that a magma chamber underlies the West Coast rift of the Indian peninsular. In support of this idea, we point to evidence for continuous magmatism along the west coast at 678 – 460 Ma, which shows a continuous trend of fractional melting. This was followed by a lull in magmatism for almost 350 My. Magmatism started again at around 93 Ma when Madagascar broke away from the Indian plate. Since that rifting took place along the west continental margin of India (i.e. today's western coast), we conclude that the associated magmatism along the western continental margin of the Indian plate was related to Madagascar-India break up. Rifting led to decompression which in turn led to partial melting in the magma chamber beneath the western continental margin of India. This is supported by the fact that magmatism during this phase started with felsic volcanism and not mafic.

As rifting proceeded along the western margin of the Indian plate, the rate of partial melting in the magma chamber increased proportionately leading to the mafic Deccan volcanism. The high rate of Deccan volcanism was due to the fact that along with the West Coast rift, three other deep crustal rifts were activated simultaneously. This could have been due to continuous rifting along the west coast from 93 Ma onwards. We propose that the high volume of Deccan volcanism was because:

1. The magma chamber accumulated magma for almost 350 My, between 460 Ma and 93 Ma, during which time magma was added to the chamber and crystallized, and

2. Delamination of the Indian continental crust occurred above the magma chamber.

We envisage the magma chamber process to be as follows. A huge magma chamber progressively accumulates melt, first from the underlying mantle and eventually from both mantle and continental crust (by delamination). The molten material solidifies with time and remains in the chamber during the period 460-93 Ma. When continental breakup of greater India starts (including Madagascar rifting away) the solified magma begins to melt. Since the melting point of felsic components is lowest, these are melted first and rhyolites typically comprise the first phase of volcanics. Alkaline magma is not initially formed because it has a higher melting point.

Following Deccan volcanism, the Carlsberg ridge formed and the Indian plate continued to move north. The systematic time progression of volcanism between the Carlsberg ridge and the Indian plate is due to sea floor spreading and *not* to plate movement above hotspot.

When the Indian plate collided with the Eurasian plate, its velocity decreased considerably and intraplate forces started to play a lead role. The main forces were then an EW force along the Narmada-Tapi rift and a NS force along the West Coast rift. The combined affect of these forces led to rifting and shearing along the West Coast rift and resulted in subsidence, pull-apart and *en echelon* deformation along the Laccadive ridge.

To reiterate, the proposition that ~ 10^6 km^3 of Deccan basalts was erupted from a magma chamber in which it was stored is radical. However, there are several strong points that support this suggestion:

1. The long history of magmatism along the same zone which culminated in the eruption of the Deccan Traps,

2. A lull in the magmatism for 350 My and its subsequent reactivation,

3. DSS results which show that the Moho upwarped beneath the west coast during the late Cretaceous. This could be associated with formation of the magma chamber,

4. Continental scale rifting (Seychelles-India) and Deccan volcanism are contemporaneous. The timing of the major phase of Deccan volcanism is considered to be ~ 66-62 Ma (*Courtillot et al.*, 1986; *Venkatesan et al.*, 1993) and the timing of Seychelles-India breakup is also thought to be late Cretaceous (*Biswas*, 1982). Note that the breakup of Gondwanaland was a continuous process which started (in the case of greater India) with the separation of Madagascar (at ~ 93 Ma) and by 63 Ma, Seychelles also separated from mainland India (*Biswas*, 1982; *Gombos et al.*, 1995). The breakup of Seychelles-India is thought to be the main rifting phase associated with Deccan flood basalt eruption and the

available data suggest that they were contemporaneous. This age data provides strong evidence in favor of stored magma which underwent progressive melting, in proportion to advancement in rifting (and consequent lowering of liquidus of the magma in the chamber), and resulted in volcanism whose rate and volume corresponded to the rate and scale of rifting.

5. The time of reactivation of the deep crustal continental rifts coincided with breakup events elsewhere in greater India,

6. The volcanism in the second phase started out felsic and gradually became mafic over a 30-My period, which points toward progressive lowering of the liquidus, and not a sudden increase in temperature, and

7. Geophysical evidence points towards thinning of the continental crust north of 15°N, that is exactly beneath the Deccan volcanic province. This provides additional support for the existence of delaminated continental crust there.

We offer these ideas for further work and discussion.

Acknowledgments

The authors appreciate the continuous encouragement, valuable discussions and critical comments of Dr. Harsh K. Gupta, Secretary, Department of Ocean Development, Government of India and Dr. P.C. Pandey, Director, NCAOR. The authors are thankful to Prof. John J. Mahoney who very kindly provided his critical comments which helped us to improve the manuscript. We were inspired to work on the Deccan by the thought-provoking arguments and iconoclastic views of Dr. H. C. Sheth. We thank our colleagues at NCAOR for their remarkable contribution all through the brainstorming sessions and discussions of the Deccan.

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Discussion

Tuesday, 29th March, 2005: Hetu Sheth
This article is very welcome, and I appreciate that the authors are seeking alternate explanations for the magnificent Deccan volcanic province of India. I believe, however, that elements of the alternative model proposed here are untenable. I offer the following specific comments which I am sure will be taken constructively, because we have the same goal. All references cited here can be found in *Sheth* (2005).

1. The authors state that "[Sheth's] suggestion that the DVP and Laccadive-Chagos ridge formed as a consequence of southward crack propagation along the Vishnu fracture zone is not consistent with data concerning the geomagmatic and tectonic history of the Indian peninsular plate". It is not clear what they mean by this. If the Ar-Ar dates obtained on the Laccadive-Chagos Ridge rocks are to be believed (*Baksi*, 1999, 2005 gives reasons not to believe them), then southward crack propagation in a northerly moving plate, as proposed by *Sheth* (2005), is a good alternative to a plate moving over a fixed plume. If these dates should not be believed (a movement I shall support), I am happier because then I don't have to explain the "track" by southward crack propagation either. It is simply a leaky fracture zone without evidence of systematic age progression, like many others scattered worldwide.

2. The present volume of the Deccan is not 2 x 10^6 km^3. This may have been the original volume.

3. The authors use 93 Ma as the valid age of the St. Mary's Islands felsic volcanics, related to India-Madagascar breakup. However, this date, obtained by *Valsangkar et al.* (1981), was only an average of six widely differing K-Ar dates, and may have no geological meaning as pointed out by *Pande et al.* (2001). *Torsvik et al.* (2001, Terra Nova) obtained direct U-Pb zircon ages of ~ 90 Ma on these volcanics, and *Pande et al.* (2001) got excellent crystallization ages of ~ 85 Ma on them by the Ar-Ar technique.

4. 93 Ma vs. 85 Ma is an important point. If the former is correct, then the St. Mary's Islands rhyodacites are at the beginning of the Indo-Madagascar province. If their age is 85 Ma, however, they are at or near the end of the Indo-Madagascar province. This has important implications for mantle and crustal dynamics and sources, and of course the environmental effects of such volcanic episodes. In the Deccan, many/most felsic rocks appear to postdate the "flood basalt" episode (*Sheth et al.*, 2001; *Sheth & Ray*, 2002), similar to the 85 Ma St. Mary's Islands rhyodacites and Indo-Madagascar flood basalts case.

5. The latest geophysical/seismological studies (M*ohan & Ravi Kumar, 2*004) do not support the widespread and long-held view (partly based on deep seismic soundings) that the basement crust along the western Indian coast is greatly thinned. *Mohan & Ravi Kumar* (2004) find that this crust is of normal shield thickness (36 – 40 km). *Singh* (1998) arrived at a similar conclusion for the Navsari

area based on gravity modelling. Some sort of fracture/structural boundary control through normal-thickness crust is apparently at work.

6. Fractional melting is not what the authors think it is. Fractional melting, as opposed to batch melting, means that small melt fractions are removed from their source rock as soon as they are formed, and do not react with the residue. The production of rhyolites from the partial melting of a basaltic source does not mean the melting was fractional.

7. A frozen magma chamber that rested under the western Indian coast for 300 Myr is a difficult idea to embrace. Surely, the early magmatic events would have left a depleted residue there, but such residues would be difficult to melt. If a frozen magma chamber, do the authors envisage it to be basaltic/gabbroic in composition? Its partial melting then could not produce the voluminous basaltic magmatism of the Indo-Madagascar and Deccan provinces. The authors have overlooked the enormous volumes of basalts in the former, which outcrop mostly in Madagascar.

8. The partial melting of such a magma chamber could have produced felsic volcanism; however, this usually involves or is aided by hydrous melting. Where did the water come from, at 90 Ma and 65 Ma? And how did the 90-85 Ma Indo-Madagascar event leave sufficient fertile source rock to be melted at 65 Ma?

9. What is the mechanism of continental crustal delamination that the authors propose? What would have made it denser than the underlying mantle to enable it to sink?

10. An alkalic magma does not necessarily have a higher temperature (not melting point) than a tholeiitic one. Melting points, or rather solidi, are for source rocks, not for magmas. Tholeiitic magmas are favoured by higher-degree melting, shallower depths, and hydrous melting. Primary alkalic magmas are favoured by lower-degree melting, greater depths, and CO_2 in the mantle source. (ome magmas are also alkalic due to contamination by lithosphere, or advanced fractional crystallization. Indeed, at low values of lithospheric extension and mantle decompression, the first magmas to form are expected to be deep, low-melt-fraction, volatile-rich alkalic, mafic magmas.

I hope these comments are useful.

Tuesday, 4th May, 2005: Anju Tiwary
In reply to Hetu's comments:

1. We would be interested in more specifics regarding Hetu's perception of the origin and evolution of the Vishnu fracture zone.

2. The number we quote for the present volume of the Deccan is been taken from published work, as mentioned in our article. We use the number quoted in "*Flood basalts, mantle plumes and mass extinctions*" by Steve Self and Mike Rampino, and available on the website http://www.geolsoc.org.uk/template.cfm?name=fbasalts

3 and 4. Our purpose in using the V*alsangkar et al. (1*981) reference was to let the reader know that the India-Madagascar separation is widely accepted to be at ~ 90 Ma, as is evident from several other articles (*Storey et al.* 1995; *Plummer*, 1995; *Gombos et al.*, 1995; *Raval & Veeraswamy*, 2003). It is beyond the scope of this article to discuss the issue of "reliability of ages" of rhyolites at St.Mary's Island or whether they are related to the timing of India-Madagascar separation or not.

5: As far as crustal thickness is concerned, we are looking from a holistic point of view concerning how the crustal thickness varies northwards from the Indian shield along the major west coast trends. There are numerous published studies on this issue. A recent seismological study carried out by *Gupta et al.* (2003) shows northward "crustal thinning" (with respect to the southern Indian shield) along pre-existing trends. Taking most of the published geophysical work in the region (DSS, Gravity, Magnetotellurics, and Receiver Function Analysis) into account the northward reduction in crustal thickness is very clear (*Reddy et al.* 1999; *Kaila et al.*, 1992; *Kaila & Krishna,* 1992; *Chandrasekharam*, 1985; *Gupta et al.,* 2003). *Gupta et al.* (2003) presented the regional picture (between latitudes 20°N-80°N) based on the receiver-function analysis whereas the work carried out by *Mohan & Ravi Kumar* (2004) focuses mainly in the central part of the Deccan Traps (between 20°N and 18.3°N). Moreover, we must also keep in mind that the non-uniqueness involved in the receiver-function analyses before embarking upon any particular number. In view of all this, one must consider the constraints on the crustal thickness from multiple geophysical techniques.

6: The definition of fractional melting and batch melting is given here to avoid confusion. This definition is taken from the book *Igneous Petrogenesis* by Marjorie Wilson, page 59.

Equilibrium or Batch melting: the partial melt formed continually reacts and equilibrates with the crystalline residue until the moment of segregation. Up to this point the bulk composition of the system remains constant.
Fractional or Rayleigh melting: the partial melt is continuously removed from the system as soon as it is formed, so that no reaction with the crystalline residue is possible. For this type of partial melting the bulk composition of the system is continuously changing.

Therefore, through batch melting it is not possible to get rhyolitic melt from the source of basaltic composition but fractional melting of basalt can produce rhyolitic melt because the melt gets out of the system instead of further reacting with it to reach equilibration.

7: Our article clearly states that due to the geological history of intermittent magmatism, it is viable to conjecture (a) magma chamber(s) beneath the west coast fault. Since a magma chamber cannot remain completely isolated from its surroundings, whatever the time span of its dormant phase, it is not possible to deduce the primary composition of magma chamber. The processes of magma mixing, contamination and partial melting/fractional crystallization would obviously overlap in time. Hence, it is not possible to comment on the composition of the magma chamber during its evolution between 460 Ma and 93 Ma. However, the primary melt would be EMORB, that is erupted during the first phase of magmatism at 670 Ma.

The question of the volume of the Deccan volcanic province is not difficult to answer, if one takes into consideration the complete geological evolution of the Western Indian Peninsula. We would like to know Hetu's views about the geochemistry of the continental crust and lithosphere beneath west coast fault Does he think that this fault is a palaeo-suture? If so, then shouldn't there be underplated and obducted fossil oceanic crust? That would provide a source for voluminous basalt.

8: First, we would like to correct the view that partial melting of basalt has to be aided by hydrous melt to produce felsic volcanism. The presence of water decreases the melting point temperatures of mafic minerals, so felsic volcanics are produced at lower temperatures. If hydrous phases are not present, then felsic volcanics are produced from basaltic material at higher temperatures than in hydrous conditions.

Our reply is the same regarding fertile sources as for huge basaltic volumes. The underplated and obducted oceanic crust which occupied the western continental fault lithosphere had to be of the Precambrian Era and therefore enriched.

9: The presence of underplated oceanic crustal material would make it denser and allow sinking.

10: It is incorrect to assume that tholeiitic or alkaline magma characterizes conditions as mentioned by Hetu. Tholeiitic and/or alkaline magmas are found in virtually all kinds of tectonic settings and conditions (Page 11, table 1.3 of *Igneous Petrogenesis* by Marjorie Wilson).

Regarding melting points, Hetu is right that melting points are for solid phases and but then we consider that magma from 460 Ma and later fluxes in the chambers were solidified by 93 Ma. So, we are indeed talking about melting points.

We thank Hetu for his comments.

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