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A historical approach to continental flood basalt volcanism: insights into pre-volcanic rifting, sedimentation, and early alkaline magmatism

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Abstract

Continental flood basalts are widely thought to be produced from mantle plume heads. However, plume theories do not observe any role for lithospheric rifting before flood basalt events, and consider irrelevant the fact that most, if not all, continental flood basalts have erupted through deep rifts containing thick sedimentary sequences. At best, plume theories invoke selective capture of such deep rifts or lithospheric thinspots by rising mantle plume heads. However, the fact that CFBs of the world erupted through deep, ancient rift zones, and alternative dynamical considerations of flood basalt genesis, directly lead towards a new, historical approach to flood basalt emplacement. This approach takes cognizance of the basic unity of geological history and processes, satisfactorily explains pre-volcanic rifting, sedimentation, mantle metasomatism, and early, pre-tholeiite, enriched alkaline magmatism for tens of millions of years. Both incubating and impacting plume heads ought to lead to pre-volcanic lithospheric doming which is usually not observed in flood basalts. Continental or oceanic flood basalt events instead seem to be derived by convective partial melting during sudden lithospheric pull-apart (splitting) along pre-existing lithospheric discontinuities such as deep rifts or fracture zones.
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Keywords: flood basalts; volcanism; rift zones; metasomatism; mantle plumes

1. Introduction

As well noted and emphasized by Anderson and coworkers [1–5], every continental flood basalt (CFB) province lies on the margin of a Precambrian craton. This remarkable fact immediately suggests a fundamental relationship between CFB emplacement and lithospheric rifting, with or without the instigation of mantle plumes (see e.g., various views expressed in [6]). King and Anderson [4] have pointed out that the correlation between CFB provinces and cratonic margins is far more profound than that between CFB provinces and hotspot tracks, the latter two having been interpreted as the products of giant plume heads and corresponding plume tails on moving lithosphere, in the framework of the mantle plume explanation for flood basalt volcanism (e.g., [7–12]). The classical plume head model for CFB origin [9,10,12] does not recognize any need for pre-volcanic extension. In consequence, the model invokes hotter-than-average mantle and large plume

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heads to explain the large melt volumes seen erupted in CFB provinces. In turn, it is concluded that for plume heads to grow to large sizes they must originate at the core–mantle boundary; shallower upwellings will not be big enough to generate CFB volumes [10].

The present paper emphasizes the basic fact that CFBs of the world erupted through rift basins having thick sedimentary successions and therefore a long pre-volcanic sedimentation history. The genetic implications of this relationship are that it is the major lithospheric discontinuities, such as cratonic edges, that influence, or even bring about, CFB emplacement, and connections with mantle plume heads appear unnecessary. Also, the common association of CFBs with deep rift basins, and only rarely with pre-volcanic topographic uplift, rules out mantle plume heads as the causes of CFB eruptions. The mechanism of edge-driven convective partial melting [4,5, 13,14], operating at lithospheric discontinuities, may instead be a suitable explanation for CFB events.

2. Problems with plume explanations

In the plume head model, which ascribes the origin of plumes to a thermal boundary layer at the base of the mantle, and which invokes plume heads and tails rising from there to the lithospheric levels independently of plate-scale convection and lithospheric properties, the locations of CFB provinces on the Earth's surface are expected to be random. Therefore, the very obvious relationship between all of the CFBs (Deccan, Siberian, East Greenland, West Greenland, Rajmahal, Columbia River, Parana, Namibia, and Karoo) and craton margins is coincidental in this model. Therefore, how the plume head model can reconcile it at best is to propose preferential capture of rising plume heads by craton margins, or by lithospheric rifts, discontinuities or thinspots (e.g., [15]). The other alternative is to ascribe the extension, rifting and the continental breakup themselves to the event of CFB emplacement and to the plume head (e.g., [11,16]). Thus according to Courtillot et al. [11], it is the location of the plume head that determines the location of continental break-up, and hence the location and geometry of the continent–ocean boundary.

However, some workers have even questioned the notion that plumes are at all necessary for flood basalt events. For example, King and Anderson [4] opine that the growing number of anomalous observations requiring continuous ad hoc modifications to the original plume model, or a series of special circumstances to fit the plume model into the geological settings of many CFBs, suggest that it is worthwhile considering alternatives to the strictly fluid dynamical plume models of CFB formation (see also [17]). Clearly, we need a dynamical model for CFB genesis and emplacement that satisfies all geological-field data with no special pleading.

3. A historical approach to flood basalt volcanism

3.1. The Deccan province: geological history of the Deccan rifts

The ~65 Ma Deccan flood basalt province covers today an area of 500,000 km^2 after erosion in west-central India, excluding the substantial area downfaulted into the Arabian Sea to the west of the western continental margin of India [18–22]. The province is associated with several continent-scale and smaller rift zones [22–27], namely the west coast belt, the E–W-trending Narmada–Satpura–Tapi graben–horst–graben system, the Cambay and Kachchh rifts (Fig. 1). These rift basins run along major Precambrian tectonic trends in the ancient Indian shield, and formed at different times during the Mesozoic, and are thus important Mesozoic marginal-marine basins [26].

The Kachchh (Kutch) rift initiated in the Late Triassic–Early Jurassic, and this basin has the most complete Mesozoic record with 3000-m-thick, Late Triassic to Early Cretaceous sediments deposited in two major cycles: a Middle Jurassic transgressive cycle and a Late Jurassic–Early Cretaceous regressive cycle. These sediments were intruded, covered, uplifted and folded by the Deccan Trap intrusives and flows in the Late Cretaceous–Early Paleocene [27].

Cambay rifting began in the Early Cretaceous, but subsidence took place at a greater rate during the Tertiary, and thus this basin is mainly a Tertiary basin. Wells drilled for oil and gas in the Cambay basin have penetrated thick (5000 m) Tertiary

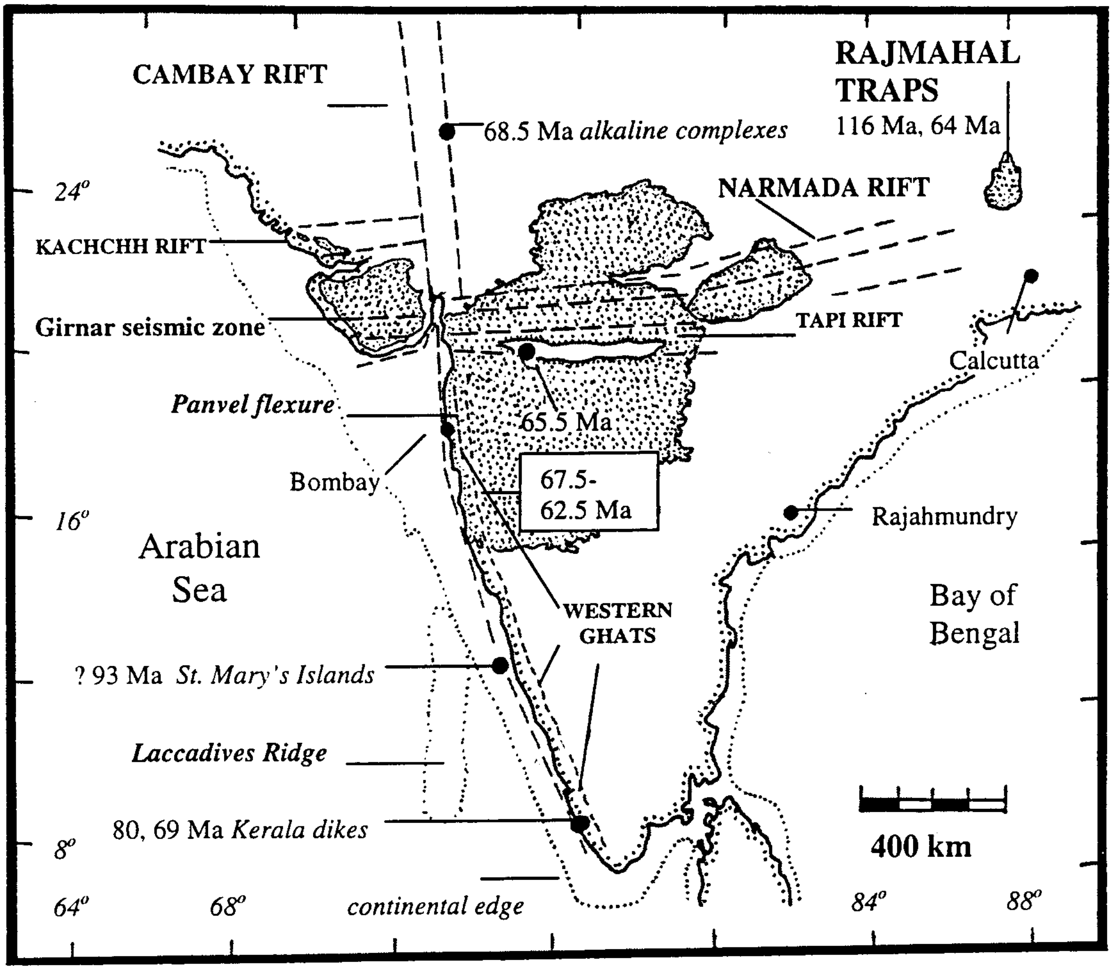


Fig. 1. Map of the Indian subcontinent showing the first-order tectonic–physiographic architecture of western and central India and the Deccan volcanic province. Note especially the various rift zones. Based on [20,22,24,27]. Numerals are published radiometric dates from various sources. The 64 Ma date shown for the Rajmahal Traps is a dike event [52], and the 65.5 Ma date from the Tapi rift is also for a dike [53].

sediments (Paleocene to Pliocene) above the Deccan Traps, and at places the basalts themselves are known to be over 4000 m thick [28]. Holes drilled in the Cambay basin have penetrated over 400 m of a Lower Cretaceous fluvio-deltaic sedimentary sequence, and Biswas [26] concluded on the basis of seismic data that at least 1200 m of Mesozoic sedimentary rocks could be expected *beneath* the Deccan Trap flows.

In the western part of the Narmada basin, shallow marine, Late Cretaceous rocks, up to 100 m thick, are exposed in scattered outcrops below the Traps, and were probably deposited in a narrow embayment in the western part of the basin as a result of a short-lived transgression during the Turonian [27]. Late Cretaceous marine sediments occur only in the Narmada basin, indicating subsidence, whereas this was a period of non-deposition and volcanic activity for the Kachchh and Cambay basins [27]. Kaila [29], based on deep seismic soundings, has postulated the presence of two hidden Mesozoic basins *below* the Traps in the Narmada–Tapi region. The northern, smaller, Narmada graben contains 1000 m of sediments, while the southern, larger, Tapi graben has 1800 m of sediments. Both are separated by a smaller horst in the subsurface.

3.2. The Siberian and East Greenland CFBs

Czamanske et al. [17] note that the Siberian flood basalts, which form the largest CFB province in the world, are underlain almost everywhere by terrigenous sedimentary rocks of the Tungusskaya Series, which includes the Tunguska coaliferous basin, thought to be the largest in the world. The Tungusskaya Series, Middle Carboniferous (~320 Ma) to Late Permian (~250 Ma) in age, varies in thickness from 100–150 m to 1400 m. No evidence of plume-related uplift can be found in the sedimentary record. (The numerical modelling of Farnetani and Richards [30] predicts pre-magmatic lithospheric uplift of a few kilometres.) The Tungusskaya Series accumulated during an environment characterized by mild but continuous subsidence, balanced by sedimentation, and accumulation of the entire volcanic sequence was accompanied by almost perfectly balanced subsidence with the preservation of flat relief, probably near sea level). Lack of surface uplift accompanying the voluminous volcanism in East Greenland has been documented by Larsen and Marcussen [31]. Thus field data suggest extensive and progressive *conditioning* of the lithosphere that would ultimately facilitate and culminate in the final rapid emplacement of a major CFB, millions or tens of millions of years later.

4. Discussion

4.1. Implications of long pre-volcanic sedimentation history for plume models

In the plume head model, all crustal extension, thinning and rifting is said to have occurred in CFB provinces *subsequent to* the eruptive episode (e.g., [9,32,33]). However, it must be appreciated that such extension, thinning and rifting may be *necessary*, for flood volcanism itself, and without a thin lithosphere melt volumes may only be small [24,34], if the lithosphere controls the extent of asthenospheric upwelling and melting (e.g., [35,36]). In plume theories it is the plume that causes lithospheric thinning and rifting, and the fact that crustal thinning, rifting and sedimentation were already underway tens of millions of years ago is irrelevant. But field data dictate that to say that it is the flood volcanism that acts as a catalyst for extension [32,33] is not realistic. What is realistic is a continuously existing tensional environment before, during, and subsequent to the eruptive episode, as it satisfies both logic and facts.

4.2. Deccan, Rajmahal, Parana and Columbia River CFBs

Indeed, the correlation of CFBs with deep sedimentary basins, often coaliferous ones, and not with pre-volcanic topographic uplifts, is an interesting one, inviting a reconsideration of the validity of both the plume impact model [9,10] and the plume incubation model [37–39]. The absence of topographic uplift preceding flood basalt volcanism is not restricted to continental flood basalts alone, but is also seen in the ocean basins. Thus, as seen above, while the largest CFB province on Earth, the Siberian Traps, shows no evidence for pre-volcanic lithospheric uplift or doming, the emplacement of the largest oceanic plateau in the world, the Ontong Java plateau in the southwestern Pacific, was accompanied by little lithospheric uplift and no subaerial emergence, despite the addition of as much as 36 km of new crust [40]. A mantle plume head origin of the Ontong Java plateau is inconceivable.

The Deccan Traps of central India are underlain by coaliferous sedimentary sequences of Gondwana age; the feeder dikes of the Rajmahal Traps of eastern India are well exposed in the Damodar valley coalfields of Gondwana age [41]. Interestingly, a 3–4 km thick sedimentary rift sequence, buried 3–5 km deep beneath the Parana flood basalts in the western part of their outcrop area, has been recently identified from a gravity survey [42]. Likewise, there was considerable thinning and rifting of the crust beneath the Columbia River province well before the volcanism [43].

From all this, it must be concluded that to say that the Siberian Traps or the Deccan Traps have been emplaced without thinning or rifting of the crust, and all thinning and rifting of the crust followed these stupendous volcanic events (e.g., [9,12]) is not supported by field data. On the contrary, significant pre-volcanism extension seems to be indicated for all continental flood basalt provinces of the world [24,44].

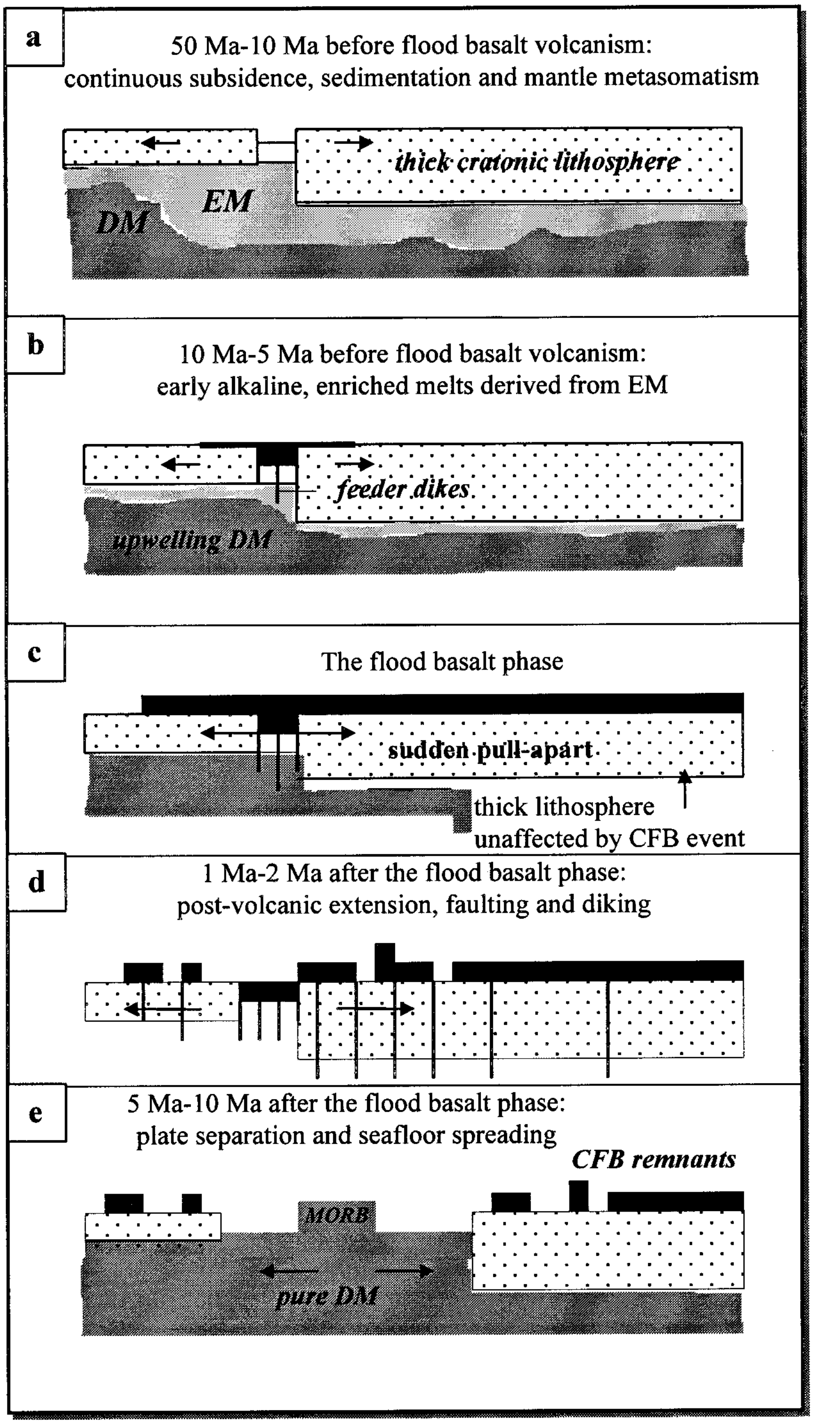
5. Mantle metasomatism, convective partial melting, and lithospheric pull-apart

The Deccan and Rajmahal CFBs obviously lie along and at the opposite ends of an ancient suture (the Narmada structure) which crosses the Indian subcontinent over 1600 km and joins two Archons [2,45,46]. Therefore, an obvious explanation for the strong correlation of locations of CFB provinces and deep rifts is the thesis that flood basalt volcanism, controlled and initiated by plate stresses, is facilitated by these rifts (which provide the most likely avenues of lithospheric pull-apart). The mechanism of convective partial melting [4,5,13,14] does not require abnormally hot mantle (unlike the plume model), and a large amount of mantle material is propelled into and processed through the melting zone rapidly, resulting in large melt volumes. The volumes and rates of volcanism are functions of various parameters like continental pull-apart rates, mantle temperature, source composition and fertility, and the presence and abundance of volatiles [2,4].

Large concentrations of volatiles in the shallow mantle reduce the solidus of the upwelling mantle, which again facilitates large-degree melting. The shallow mantle is already volatile-rich and incompatible-element-rich ('enriched mantle', EM, Fig. 2a,b), due to two possible alternative causes: (1) King and Anderson [4] point out that these regions are often the sites of previous subduction, and slab recycling and dehydration would result in concentration of volatiles, fluids and the incompatible elements they carry, at shallow levels; this is the perisphere); (2) the lithospheric discontinuity represented by the rift, which is a deep lesion in the plate, is extremely likely to have experienced volatile degassing and infiltration by incompatible-element-rich fluids which are continuously released from the deeper mantle, with pronounced mantle metasomatic effects over millions of years [47–49]. The older the crack in the plate, the longer and more pronounced is the metasomatism. Sedimentary basins often occur in these regions. The shallow mantle with widespread volatiles, and one rich in incompatible elements, is the perisphere, and acts both as a contaminant and as a melting-point-depressant of mantle melts (Fig. 2a,b). Extensive and extended (in time) metasomatization of the mantle before CFB events, and early alkaline-enriched magmas, are due to the long pre-CFB history of lithospheric rifts, and it is unnecessary to invoke mantle plumes as the agents of mantle metasomatism as Baker et al. [50] do. Besides, if the fresh mantle is anomalously warm (which is unnecessary, but by no means precluded, in this mechanism), melt volumes are even greater. This anomalously hot mantle is not necessarily a mantle plume [1,51].

Plate stresses cause pull-apart instead of lithospheric stretching and thinning, and the pre-existing small-scale convection is accentuated, rather than started, by plate separation [2,4]. Thus CFB events may be the products of lithospheric *splitting* along pre-existing discontinuities (Fig. 2c), rather than of plume-caused uniform lithospheric thinning or distributed stretching. The splitting of the lithosphere permits adiabatic ascent from great depth (>150 km) and extensive melting, and at the same time establishes a high melting column. On the other hand, the thermal and chemical erosion of the lithosphere by a hot plume head, which many plume theories propose, is dubious at best, with a rather poor mechanical aspect.

If seafloor spreading ever begins it does so after the main volcanic episode is over (Fig. 2c,d), giving the false impression that rifting occurred after the volcanism [34] (see Fig. 2e). But rifting and extension have been going on all the time (Fig. 2a–d), and all the misinterpretations that abound in the literature have resulted from the wrong idea that rifting is an instantaneous process. The beginning of mature, steady-state seafloor spreading is actually merely the culmination of rifting; the event of final plate separation. But rifting has been going on all the time, from above, and from *below*. Likewise, the long pre-volcanic sedimentation history of CFB provinces, such as the Deccan, Rajmahal, Columbia River, Siberian and Parana, suggests the operation of rifting and downfaulting tens of millions of years ago. Cognizance of this essential continuity of geological processes, represented by rifting, downfaulting, sedimentation, mantle metasomatism


a
50 Ma-10 Ma before flood basalt volcanism:
continuous subsidence, sedimentation and mantle metasomatism
thick cratonic lithosphere
EM
DM
b
10 Ma-5 Ma before flood basalt volcanism:
early alkaline, enriched melts derived from EM
feeder dikes
upwelling DM
c
The flood basalt phase
sudden pull-apart
thick lithosphere
unaffected by CFB event
d
1 Ma-2 Ma after the flood basalt phase:
post-volcanic extension, faulting and diking
e
5 Ma-10 Ma after the flood basalt phase:
plate separation and seafloor spreading
CFB remnants
MORB
pure DM

and enriched alkaline magmatism, and their final culmination, namely CFB events, brought about by lithospheric splitting, obviates the need to appeal to mantle plume heads.

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Fig. 2. (a) to (e) Cartoon depicting progressive evolution from initial rifting, downfaulting, subsidence and sedimentation, with consequent mantle metasomatism; through early pre-tholeiite alkaline phases; followed by lithospheric pull-apart and massive CFB discharge; in turn followed by seafloor spreading and eventual production of pure MORB. EM is enriched mantle, DM is depleted mantle (depleted in incompatible elements and their isotopic ratios). In this scenario, early enriched alkaline magmas derive from the EM, CFB tholeiite melts derive from the DM and are contaminated by small amounts of remaining EM (and later by continental lithosphere). Pure MORBs erupt only when EM has been completely removed and the pure DM (MORB source) has begun to be tapped, and this is when seafloor spreading has become mature and steady state. Based partly on [21].

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