Towards understanding Deccan volcanism

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Abstract

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Abstract

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1. Introduction

Large igneous provinces are some of the Earth’s greatest volcanic events with huge volumes (> 500,000 km$^3$) of predominantly basaltic lavas covering vast continental and ocean-floor regions (Bryan & Ernst 2008, Self et al. 2014). Over Earth history, LIPs have a frequent correlation with severe climate and ecosystem perturbations including mass extinctions (Clapham & Renne 2019). However, we still lack a good understanding of one of the most fundamental questions related to LIPs: How do LIPs erupt, and what is their eruption rate compared to modern analogs? Furthermore, how does their eruption style and rate vary spatially and temporally across a LIP. In principle, these properties can be most directly constrained from volcanological features of the lava flows and associated dikes and vents. However, in practice, this is difficult to achieve for many LIPs due to the lack of present-day exposure and difficult physical accessibility. The Deccan Traps LIP (henceforth, Deccan), one of the best-preserved large continental flood basalt (CFB) provinces, is an exception to these limitations. Along with the Columbia River Basalt (CRB) province, it provides a unique opportunity to understand how the huge thickness and extent of lava flows associated with LIPs erupt (Self et al. 1998, 2020).

The Deccan erupted around 66 Ma years ago within an overall duration of about 8-10 Ma (Mahoney et al. 2002, Pande et al. 2017, Sprain et al. 2019). The eruption of the Deccan is associated with the passage of the Indian plate over the Réunion hotspot (Duncan & Pyle 1988, Richards et al. 1989, Hooper et al. 2010, Krishnamurthy 2020). However, most of the exposed subaerial volume was emplaced in a much-more-limited ~ < 1 Ma-interval around the Cretaceous-Paleogene boundary (Schoene et al. 2019, Sprain et al. 2019, Kale et al. 2020b, and references therein). The present-day subaerial extent of Deccan lava flows on the Indian subcontinent is about 500,000 km$^2$ (Figure 1, GSI District Resource Map (2001))
along with a significant volume offshore in the Arabian Sea (Fainstein et al. 2019, Kumar & Chaubey 2019), and some small-volume Deccan-related intrusions in the Seychelles (Devey & Stephens 1991, Owen-Smith et al. 2013, Shellnutt et al. 2017). Estimates of the total pre-erosional Deccan lava flow volume range from 1 to 2 x 10^6 km^3 (Sukheswala 1981, Sen 2001, Jay & Widdowson 2008). On the eastern side of the main Deccan Plateau, distal exposures of Deccan are the flow-fields and dikes in the Mandla region (extending to the eastern Damodar Valley) and the Rajahmundry Traps (and flows offshore in the Bay of Bengal) (Srivastava et al. 2020, Fendley et al. 2020) (Figure 1). On the western side, the Deccan lavas may have extended out to > 1000 km from the present west coast of peninsula India to the present-day Seychelles Bank before it was rifted away after ~ 62-64 Ma (Devey & Stephens 1991, Shellnutt et al. 2017). Given these uncertainties, it is perhaps misleading within our present knowledge to predicate any time/volume “rate” estimates about Deccan volcanism on the full province scale. On a local/regional scale, however, the volcanological features of the lava flows can provide constraints on eruption rates. A striking feature of the Deccan (and LIPs in general) is that the vast majority (>> 95%) of the lavas are pahoehoe (pH) akin to those in Iceland and, to a lesser extent, Hawai’i (Self et al. 1998, Duraiswami & Shaikh 2013a, Kale et al. 2020a).

In this review, we start with briefly reviewing some basic facts about the Deccan CFB, specifically the tectonic structure of the underlying Indian plate (section 2.1, Figure 1) as well as the chemo- (Figure 2) and litho-stratigraphy (section 2.2, Supplementary Figure SM2) developed in the Western Ghats region over the past few decades (e.g., Beane et al. 1986, GSI District Resource Map 2001). These form the basis of Deccan’s spatial sub-division and regional comparisons of volcanological properties. Additionally, Indian basement exerts a first order control on both where Deccan flows likely erupted from and how far they spread (section 5). This is followed by our focus – synthesis of volcanological information for the Deccan based on extensive work done by many Indian and international researchers over the past few decades. Almost all Deccan lava flows are tholeiitic basalts (including picritic flows) with a small (< 1%) volume of silicic units in outlying regions (as presently exposed, Supplementary Figure SM1, GSI District Resource Map (2001)). Hence, we will exclusively focus here on the volumetrically dominant basaltic component (Figure 3). To ensure a consistent usage, we first describe some basic terminology for LIP lava flows followed by a description of the primary Deccan lava flow features (section 4, Figures 3 and 4; Supplementary Figure SM3). We next describe the present constraints on the Deccan flow-field-scale eruptive rates and eruptive locations based on the spatial distribution and orientations of potential feeder dikes (section 5, Figures 5; Supplementary Figure SM4 and SM5). We end with a brief discussion of how all these observations can inform us regarding the crustal magmatic systems of LIPs (Figure 6) and how the Deccan volcanological constraints can be combined into a conceptual model of LIP lava flow-fields (Figures 7).

2. Province scale perspective

2.1. Tectonic zones and sub-provinces

Deccan basalts are primarily exposed as sub-horizontal stacks of lava flows throughout the Deccan sub-provinces and do not display any significant dips except in some fractured zones (e.g., Panvel flexure in the Western Ghat region, Figure 1; Kale et al. (2020b)). Regional southerly dips of up to 2-3° are seen in the western areas (Beane et al. 1986, Mitchell & Wid-
dowson 1991) over a > 100-km scale. Geophysical studies have shown that the crust below the Deccan is composed of multiple cratonic blocks (principally Western Dharwar Craton, Eastern Dharwar Craton, Bastar Craton, and the Bundelkhand Craton – see Figure 1 for locations) and basins (Gondwana as well as Meso-Neoproterozoic basins) (Brahmam & Negi 1973, Kaila 1988, Harinarayana 2007, Kale et al. 2017). The cratonic boundaries are zones of structural discontinuities which subdivide the Deccan structurally into six subprovinces having different cratonic segments underlying them (Figure 1): Western Deccan (including Western Ghat region), Central Deccan (with a potentially heterogeneous crust based on crustal xenoliths in dikes; (Ray et al. 2008)), Kutchh-Saurashtra subprovince, Malwa subprovince, Mandla subprovince, and the Satpura subprovince. Some of the structural zones (shown in Figure 1 by dashed lines and dotted regions) have a long history of active deformation preceding the Deccan and extending to modern times (Peshwa & Kale 1997, Rajaram et al. 2017). For instance, the ENE-WSE trending Central India Tectonic zone (CITZ) was active during time-periods ranging from Late Archean to Permo-Carboniferous (Shankar 1991, Valdiya 2015). The post-Deccan activity of these zones is clearly illustrated by regional fracture zones cutting across the multiple Deccan flows, especially in the Tapi valley (Peshwa et al. 1987), and recent intra-plate seismicity in these regions (Pandey 2020). This post-Deccan deformation is critical for interpreting Deccan stratigraphy since stacks of lavas south of the Tapi and Narmada valleys (see Figures 1 and 2 in SD-2 Kale et al. (2020b)) occurring at comparable altitudes differ significantly. This illustrates that in this region, as well as in some Western Deccan Plateau regions (Kale et al. 2017), elevation-based lava flow correlations need careful fault correction.

2.1.1. Deccan Basement Topography. Eruptive models of the Deccan (Cox & Mitchell 1988, Watts & Cox 1989, Jay et al. 2009, Richards et al. 2015) consider that palaeotopographic undulations below the Deccan were filled by the earliest lava flows and subsequent flows were emplaced on a relative smooth surface with very little or no hindrance to the lateral spread of the lava, except the slightly undulating top of the flow-field underneath. But, is this a good approximation? Topographic undulations of the order of 200-300 m are observed along the fringes of the province (Auden 1954). Deep seismic soundings (Kaila 1988), gravity profiles (Brahmam & Negi 1973), and other geophysical studies have also demonstrated similar undulations across the province below the lavas (Patro & Sarma 2007, Harinarayana 2007, Murty et al. 2014, Rajaram et al. 2017). Such undulations have also been reported from Mandla lobe (Solanki et al. 1996) and Tapi valley (Deshmukh et al. 1996). Recent deep bore hole drilling in the Koyna-Warna region of the Western Deccan province (Sinha et al. 2017, Gupta et al. 2017) has highlighted that the Archean crust directly underlying Deccan may have had palaeo-topographic undulations of about 200m over ~ 20 km distances (some of this topography may be due to post-Deccan faulting and tectonics during subsidence; Subbarao & Courtillot (2017)). Analogously, Jay et al. (2009) interpret 90 m of syn-emplacement topography across the area that is now the Mahabaleshwar Plateau towards the end of the main Deccan eruptive phase (see Figure 4A). If the Indian basement (and the subsequent Deccan lavas atop them) did have substantial topography, long-distance chemostratigraphic correlations, as shown in Figure 2, between Western Ghat flows and Central Deccan flows will need revision (Kale et al. 2020b). The presence of substantial basement topography also has strong implications for flow morphology since it is easier to change lava flow morphology, flow field structure as well as lobe thicknesses if lava is flowing over a steeply sloped basement (Patil et al. 2020).
2.1.2. Chemostratigraphy. Uniformity across the vast Deccan province, due to the predominant basaltic flows (see small silicic regions in Supplementary Figure SM1), has made it difficult to stratigraphically analyze and correlate single flows across exposures 10s of km away. Geochemical studies, initiated during 1980s, resulted in the chemical characterization of Deccan lava flows (e.g., Najafi et al. 1981, Sreenivasa Rao et al. 1985, Mahoney et al. 1982, Cox & Hawkesworth 1985) and became the basis for the chemostratigraphic classification of the Deccan (Figures 2A and Figures 2B) that is presently actively used (e.g., Beane et al. 1986, Devey & Lightfoot 1986, Subbarao 1988, Lightfoot et al. 1990, Mitchell & Widdowson 1991). Starting with Beane et al. (1986), the Western Ghat Deccan lavas were divided into ten formations and three sub-groups. The chemostratigraphic classification is a hybrid scheme that relies in part on regionally observed variations in the element composition and element ratios of the lavas, as well as the presence of units with distinctive petrographic characters easily identifiable in the field (notably, plagioclase-phyric megaphorphyritic units locally known as giant plagioclase basalts, or GPBs; Shandilya et al. (2020)). Measurements of radiogenic isotopes (notably from the Sr, Nd, and Pb systems) showed sharp transitions across formational boundaries (see Figure 2B), lending further support to the chemostratigraphic scheme (e.g., Peng et al. 1994, 1998, Basu et al. 2020). Subsequent workers (Mitchell & Widdowson 1991, Mahoney et al. 2000, Khadri et al. 1999) extended this classification to include new units, mapped across a wide area of the Deccan (Figure 2, after Subbarao et al. (2000) and some individual stratigraphic sections – see Supplementary Text for more info). Some of the Western Ghats geochemical formations have been extended 100s of km laterally into the central Deccan (e.g., the Khandala and Poladpur formations Peng et al. 1998, Melluso et al. 2004, Peng et al. 2014), the south-eastern Deccan (e.g., the Poladpur, Ambenali, and Mahabaleshwar formations Jay & Widdowson 2008, Kumar et al. 2010), and the Rajahmundry Traps < about 1000 km from the Western Ghats (Self et al. 2008, Fendley et al. 2020). Thus, the Deccan may have been typically associated with individual lava flows 100s of km long, and hence large individual eruptive episodes of greater than 1000s of km³ akin to other LIPs such as CRB (Vye-Brown et al. 2013, Bryan & Ferrari 2013). The compositional ranges defined in the Western Ghats (and consistent with Central Deccan flows) were used for correlating dikes and lavas in the other sub-provinces of the Deccan, with varying degrees of success (e.g., Mahoney et al. 2000, Chenet et al. 2009, Vanderklyusen et al. 2011, Ganguly et al. 2014, Shrivastava et al. 2014, Sheth et al. 2019). Although lavas with major and trace element compositions broadly similar to Western Ghats geochemical formations have been found in these regions, they don’t always have the same stratigraphic sequence and/or measured ages (e.g., Shrivastava et al. 2014, Sheth et al. 2018, Melluso et al. 2006, Sheth et al. 2013, Peng et al. 1998, Hooper & Subbarao 1999, Mahoney et al. 2000, Devey & Stephens 1991) suggesting that Deccan geochemical formations should typically not be extended across sub-provinces (except through the Western-Central Deccan region). This conclusion is further supported by different Pb isotopes in Deccan flows across sub-provinces even if the lava compositions are otherwise similar (Peng et al. 1998, Mahoney 1988, Mahoney et al. 2000, Peng et al. 2014, Vanderklyusen et al. 2011, Sheth et al. 2018). Considering the structure of the Indian crust underlying the Deccan (as discussed in the previous subsection) and these observations, we posit that most lava flows within a Deccan sub-province were not fed overland from the Western Ghats. Instead, each sub-province (with the exception of the Central Deccan) had a distinct upper crust magmatic plumbing system with different crustal assimilants.
2.2. Lithostratigraphy

To allow mapping based on field observations alone, the Geological Survey of India devised an alternative lithostratigraphic classification schema (see Supplementary Figure SM2). It is based on field mapping of the lava characters (simple, compound, and a’a’ flows) and the exposed continuation of the flows supplemented sparsely with chemical signatures (in terms of crustal contamination) of the lava units. The results of this voluminous work were compiled as District Resources Map series, published between 1999 and 2005, and recognizes four primary independent groups (Supplementary Figure SM2) for different parts of the Deccan with a number of other smaller regional formations (GSI District Resource Map 2001, Raju 2016, GSI Bhukosh 2020 (accessed December 1, 2020). The relative stratigraphic positions of these groups with respect to each other (across sub-provinces) remain undefined. Like the chemostratigraphic classification, the lithostratigraphic classification also uses GPBs (named as M1 to M4) as marker horizons to separate the formations in the Western Ghats (Godbole et al. 1996, Shandilya et al. 2020). Since most of the recent geochronological and paleomagnetic studies were done utilizing the chemostratigraphic framework, there is an increasing focus on correlating these two Deccan stratigraphic frameworks. However, at present, this remains an area of active research (Kale et al. 2020b).

3. How were Deccan lavas emplaced?

3.1. Terminology for lava bodies

In general, we know that lava flows or lava flow-fields largely consist of sheet (and other) phh lava lobes in all CFB provinces (Self et al. 1998, Thordarson & Self 1998) and the Deccan is no exception (Self et al. 2006, Jay et al. 2009, Self et al. 2020). Only the CRB has whole flow-fields defined and Deccan flows (sensu lato) are only known in section and have rarely been correlated over large distances (> ~ 100 km; Choubey 1973, Shandilya et al. 2020) except for the Rajahmundry Traps (Fendley et al. (2020); Figure 1). Because of the lack of defined flow-fields in the Deccan, we also use the term eruption package to describe the products of a single eruption in section. A lava flow is composed of many individual lobes; one or more lava flows make up an eruption package or flow-field, which should be bounded top and bottom by weathering and/or erosion surfaces (indicated sometimes, though not exclusively, by red boles), demonstrating a hiatus in lava emplacement at that place. A nice example of this is seen in the lowermost Rajahmundry Traps flow (Figure 3B) where the flow field (flow field only has one flow) consists of multiple lobes and the flow field is bounded by thick sediment horizons above and below.

In continental flood basalt provinces, flow lobes can vary in size from tens of cm to kms in width, and tens of cm to ~ 200 m in thickness (Self et al. 1997, Thordarson & Self 1998, Vye-Brown et al. 2013). Where a single flow lobe is a large-scale feature, i.e., wider than an outcrop (> 100 m or more) and ~ 10 m, or greater, thick, the term sheet flow lobe (shortened to sheet lobe) is used. We term occurrences of Deccan lavas dominated by small lobes (< ~ 10 m down to 0.5 m thick) as “small scale phh eruptive units”; they are commonly referred to as “compound flows” in the literature. These share characteristics with so-called hummocky phh flow-fields of Hon et al. (1994), also called lobate flows by Kale et al. (2020a). Areas of “compound flows” (Figure 3C) in the Deccan were identified earlier by Deshmukh (1988), and later Bondre et al. (2000), Duraiswami et al. (2001), Bondre et al. 

Self et al.
These observations confirmed that the common structures and characteristics of the lavas support that they were emplaced by the process of inflation, as they contain several distinctive features of inflated pāhoehoe (Self et al. 1998). This is reflected in the threefold division of the lobes into basal zone, core, and upper crustal zone, and internal features such as horizontal vesicular sheets and pipe vesicles, with surface ropes, and tumuli (Figure 3). We now have information that shows that all Deccan formations contain both “compound flows” and sheet lobes in varying proportions (Self et al. (2020) Figure 4B) and that no mechanistic interpretations should be placed on the presence or absence of these lava types (see also Bondre et al. (2004)). Based on analysis of flow-fields in the CRB, as well as work on other CFBs, it is better to assume that eruption packages are a single simple lava unit at any one outcrop are, in fact, part of a compound eruption package because single lobes can be seen to change character to multiple lobes or abut other lobes laterally (e.g., Vye-Brown et al. 2013, Duraiswami et al. 2017, Patil et al. 2020); Figure 4A. All eruption packages and flow-fields that have been identified so far in the Deccan and other flood basalt provinces (e.g., Walker 1971, Thordarson & Self 1998, Vye-Brown et al. 2013, Dole et al. 2020) are therefore “compound”. We thus generally avoid using the terms “simple” and “compound” lava lobes for outcrop scale and instead prefer using sheet lobes and hummocky pāhoehoe based on lobe thicknesses.

3.1.1. Structure of inflated pāhoehoe sheet lobes. Sheet lobes in the Deccan lavas have an internal structure (Figure 3A inset), as with other flood-basalt provinces, see Self et al. (1998). The upper crustal zone of Deccan sheet lobes often has ragged, and sometimes large (10-15 cm), vesicles, while others have rounder and smaller vesicles. Upper crusts are almost always more susceptible to alteration and weathering due to the vesicular nature, while the core lava is generally non- or poorly vesicular and better preserved. Bulk vesicularity of the core increases towards the core/upper crust boundary where mega-vesicles and bell-jar vesicles may be observed. Also, segregation features such as horizontal vesicular sheets and vesicle cylinders can also infrequently be seen in the Deccan sheet lobe upper crusts/cores (c.f., Thordarson & Self 1998, Hartley & Thordarson 2009) and help to pick out the core-upper crust transition. Cores of sheet lobes are often jointed, which is usually crude and poorly developed in the Deccan and is rarely well-developed, giving columnar joints with a variety of widths. Some joints may have formed due to water interaction with the cooling lobe to produce a variety of different patterns such as fanning columnar joints (e.g., Lyle 2000) (Figure 3B), secondary sets of joints perpendicular to the main jointing (Moore, 2019), and poorly vesicular (quenched) lava. Often little detail can be observed due to alteration. Features observed in sheet lobes tens of meters thick from the Deccan and CRB appear to be like those seen in meter-scale Icelandic and Hawaiian lobes (Self et al. (1998), Figure 3E). If, based on CRB and Deccan dimensions, sheet-lobes have areas between 4 and 10 km², and a major flow field (say, of Roza flow, CRB, volume, some 1300 km³ of lava; Thordarson & Self (1998)) has an area of 40,300 km², then a flow field is likely made of around 4,000 to 10,000 sheet-lobes.

Very few logged Deccan sheet lobes unequivocally possess rubbly pāhoehoe tops to the upper crustal zone (the “broken-top pahohoe” of Walker (1999)). These are defined by uppermost zones of brittlely fragmented vesicular pāhoehoe crust, which have been identified in several other basaltic provinces (Guilbaud et al. 2005, Keszthelyi et al. 2006, and references therein). Sen (2017) describes rubbly pāhoehoe lava units in the lower formations of the Deccan just east of the Western Ghats but sees them as transitional changes within a normal pāhoehoe flow. Duraiswami
et al. (2008) find more rubbly-topped lobes in the Deccan than we do, and this needs to be resolved with more careful flow lobe textural characterization. Since flow-top weathering can lead to additional fracturing and partial crust collapse into the underlying vesicular zone, identifying clear rubbly phh tops in the Deccan can be challenging and remains an avenue for future work.

3.1.2. Deccan flow lobe thickness distributions. We characterize broad volcanological characteristics of the Deccan lava flows using the lobe thickness measurements based on detailed stratigraphic logs in the Western Ghats (see Supplementary Figure SM3 for logs from Jay (2005)) as well as some other datasets across other Deccan sub-provinces. The flow lobe thicknesses from these logs, plotted in Figure 4A, illustrate that even for sections within ~50 km distance, the flow morphology and lobe thickness can make it very challenging to track individual lobes (and, by extension, flows) from outcrop to outcrop. Additionally, the weathering horizons are typically thin (< 1 m, typically 20-30 cm) and are also spatially heterogeneous clearly indicating that each successive flow field did not completely, and uniformly, overlap the previous one. In Figure 4B (see Self et al. (2020), for data and references), we show Deccan-scale lava lobe thickness distribution for the Western Ghats region - middle (Lonavala) subgroup has one modal lobe thickness of ~18 m and another at ~50 m; lowest (Kalsubai) subgroup has smallest modal lobe thickness and coarse tail extending towards 50 m; the upper (Wai) subgroup has the same median thickness as the middle subgroup and a coarse tail extending towards 100 m. Each subgroup has small lobes and with highest percentage in Kalsubai. The lobe thickness distribution is broadly similar for the Koyna cores which predominantly have the Wai subgroup flows. Following convention from previous subsections, we separate flow lobe thickness by each sub-group: Killari-Central Deccan (Wai subgroup but with thick sheet lobes), Malwa & Narmada-Tapi Rift Zone (similar to Wai subgroup), and North-Western Deccan-Saurashtra (similar to Kalsubai with pre-dominantly hummocky phh). Although the lack of a process-scale model for inflated lobes makes it difficult to relate lobe thickness to eruption rate (Self et al. 1998, Rader et al. 2017), the overall similarly between Malwa, Narmada-Tapi, and Wai subgroup, and Mandla & Central Deccan to a lesser extent, indicates overall similar eruptive dynamics. Furthermore, there is a clear temporal progression in flow properties from the Kalsubai (and potentially Saurashtra) to Lonavala and Wai subgroups though more log sections are needed to test this further since majority of the data is from the upper formations.

4. Deccan Traps – How were they erupted; where were the eruptive centers?

The location of eruptive vents in CFB provinces is best identified by the presence of near-vent volcanic facies, such as spatter ramparts and pyroclastic deposits produced by fire-fountaining events. Because they are easily weathered and have restricted areal extents, such deposits are rarely preserved. The CRB and North Atlantic Magmatic Province (Greenland sections) are the only LIPs where vent systems and near-vent deposits have been unambiguously identified feeding a large-scale flow-field (e.g., Thordarson & Self 1998, Brown et al. 2014, Peate et al. 2003, Larsen et al. 1999) although there are a number of other smaller vent complexes in many CFBs (e.g., Siberian Traps; Karoo and Ferrar CFBs, North Atlantic Magmatic Province Ross et al. 2005, and references therein). Interestingly, Deccan is relatively unique among CFBs with only a small amount of mafic volcaniclastic deposits (Ross
et al. 2005) though some of these may be presently offshore or are weathered component of red bole weathering horizons (Duraiswami et al. 2020). In the Deccan, previous workers have relied upon three primary lines of indirect evidence to infer the location of eruptive vents: (a) spatial distribution of lava flow morphologies, although this has been challenged (Bondre et al. 2004) as discussed above; (b) morphology of the volcanic edifice (if any) and location of the thickest sections (which need not be proximal, as the CRB amply shows); and (c) location of dike systems (see Supplementary Figure SM4 for some individual dike images as well as satellite images showing multiple long dikes). In the Deccan, we only have exposure of the near surface/shallow crust (< 2-3 km depth; e.g., Auden (1949), Agashe & Gupte (1971)); there are no exposures of deeper parts of the magmatic system in contrast to some older LIPs. Also, most of the observed intrusive structures are dike with only a few sills reported (e.g., Chakla-Delakhari Sill; Pachmarhi Sill; Mahad Sill, Sheth et al. (2009a), Ganguly et al. (2014), Duraiswami & Shaikh (2013b), See Supplementary Figure SM1). Evidence for fissure-fed activity from dikes has recently been presented (Das & Mallik 2020), but that this is the most common mode of eruption in the Deccan province is still an assumption.

4.1. Deccan Dike Distribution

At province scale, a large number of dike segments have been mapped based on a combination of field work (GSI 1:50k maps) as well as satellite image analysis and digital elevation maps (GSI District Resource Map 2001, Raju 2016, Jagannathan & members 2010, GSI Bhukosh 2020 (accessed December 1, 2020). This combined dataset (~ 29,000 segments) is shown in Figures 5 and 6 where the dike segments are colored by dike orientations and segment lengths respectively. The longest single mapped dike is ~ 79 km (Sheth et al. 2019) though it is possible that longer Deccan single dikes exist and they have been mapped as distinct dike segments due to erosional breaks and/or lack of access. Thus, we would advise some caution in interpreting the dike segment length distribution since it is likely biased against long dikes. Overall, the Deccan dikes have a strong ENE-WSW preferred orientation (Figure 5, lower right inset) and a high dike line density (number density weighted by dike lengths) in some regions in the Narmada-Tapi rift zone and Saurashtra (Figure 5, main map inset). Additionally, the Figures clearly illustrate the lack of mapped dikes in a large portion of the Central Deccan, especially in the South-Eastern region. Finally, we do not expect every dike to have directly fed a lava flow. In contrast to the CRB Roza vent flow-field system (Thordarson & Self 1998), the feeder relation of Deccan dike has also not physically seen and dike top terminations are typically truncated due to erosion. Consequently, it is unclear if a dike terminated in the crust/lava flow pile or if it fed lava flows directly. The feeder relationship has been inferred based only on the chemical affinity between dikes and lava flows (Vanderkluysen et al. 2011).

Based on the underlying tectonics as well as the pattern of dominant dike orientations, we divide the dikes into four main dike swarms (e.g., Auden 1949, West 1959, Beane et al. 1986, Dessai & Viegas 1995, Hooper 1990, Ray et al. 2007, Sheth et al. 2009b, Vanderkluysen et al. 2011, Sheth et al. 2019, Cucciniello et al. 2020) - Narmada-Tapi swarm, Coastal Dike Swarm, Central Deccan dike swarm, Saurashtra dike swarm (Figure 5). Each of the four dike swarms is composed of a number of sub-swarms of 100s of dike segments (Vanderkluysen et al. 2011, Sheth & Cañón-Tapia 2015).

There are only a few measurements of dike thickness in the Deccan. Based on existing
The four primary Deccan dike swarms are:

1. **Narmada-Tapi swarm** (Median length – 954 m): Dikes generally strike ENE-WSW, parallel to the rift-and-graben structure where the Narmada and Tapi rivers flow (Figure 5, see top panel). This pattern of dike alignment with the CITZ highlights the contribution of pre-existing zones of crustal deformation in the eruption of Deccan lavas. It is noteworthy that some Deccan Age dikes have been found in the eastern India extending past the Mandla Lobe (Figure 5, Srivastava et al. (2020)) further illustrating the role of Indian tectonics on crustal transport of Deccan magma.

2. **Coastal Dike Swarm** (Median length – 990 m): N-S striking (approximately parallel to the west coast) dike swarm extending from the coast to the Western Ghat escarpment with a local maxima in dike line density (see Supplementary Figure SM5).

3. **Central Deccan swarm** (analogous to the Nasik-Pune swarm, Median length – 2330 m): The dike segments, on average, exhibit weak preferred directions compared to the other sub major swarms and also are much longer (Figures 5&6). In addition, the dike density is typically lower than other swarms suggesting that dikes in this region are longer, but sparser.

4. **Saurashtra dike swarm** (Median length - 890 m) : Similar to the Narmada-Tapi swarm, the dikes generally strike ENE-WSW in this region though there is more orientation spread and cross cutting dikes (Figure 5, see top panel). The southern Saurashtra region in particular has a high dike density (Supplementary Figure SM5 inset). For convenience, we have grouped dikes in Kutchh with Saurashtra.

Datasets, Deccan dikes have a wide range of thickness from 1 to 62 m (median of ∼10-20 m for different subswarms) and lengths (1 km to 79 km) (Ray et al. 2007, Bondre et al. 2006, Sheth et al. 2019), except for the Goa dike sub-swarm (part of the Coastal swarm), where dikes are shorter (< 200 m) and thinner on average (∼6 m) (Gadgil et al. 2019). A significant fraction of dikes, especially the thick (> a few m) ones, show evidence of multiple magma injections in the form of multiple columnar-jointed rows (2-5 injections) (see discussion in Sheth & Cañón-Tapia (2015)) (see Supplementary Figure SM4A for some pictures). We find that the log-normal density distribution provides the best fit to the dike segment length data akin to other LIPs (e.g., CRB Chief Joseph Dike Swarm, Morriss et al. (2020); Supplementary Figure SM5). The systematic underprediction of the dike number density at small dike lengths is likely an artifact of single dikes being broken into multiple segments thus biasing the data. Further computational analysis of the dike dataset in combination with remote sensing, geochemical analysis, and field observations can help ascertain the real number of independent dikes in the Deccan Traps and their spatial pattern.

To ascertain feeder relationships between dikes and flows, Vanderkluysen et al. (2011) conducted a province-scale study of dike chemical and isotopic compositions. They found that many dikes do not feed any known flows, particularly in the Narmada-Tapi swarm. These authors concluded that the Narmada-Tapi and Nasik-Pune swarms were the principal...
source areas for lavas of the Kalaubai and Lonavala Subgroups, while the Central Deccan swarm (and, to a lesser degree, the coastal swarm) was the main locus of feeder dikes to Wai Subgroup lavas. Sheth et al. (2019) presented evidence for long-distance (> 500 km) crustal magma transport in dikes of the Narmada-Tapi swarm. However, given the relative scarcity of dikes in the main Deccan east of Sangamner (Supplementary Figure SM5), and the presence of flows in the eastern and southern Deccan (including Rajahmundry) that are both synchronous and geochemically identical to those of the Western Ghats, it is apparent that surficial lava flows must have traveled hundreds of kilometers across the main Deccan before occasionally spilling off the plateau and following ancient depressions eastwards (e.g., Jay & Widdowson 2008, Self et al. 2008, Vanderkluysen et al. 2011). Flows of the Ambenali Formation found in the eastern Deccan (Jay & Widdowson 2008), would have traveled no less than 475 km (the distance between the westernmost known feeder and its easternmost extent). Lavas of the same formation would have traveled 900 km, as the crow flies, to reach Rajahmundry, contending for the longest known lava flows on Earth (Self et al. 2008, Fendley et al. 2020). In conclusion, the dike spatial pattern provides further support for considering the Western and Central Deccan sub-regions as part of the same flow stratigraphy (Figure 1 & 2) while the other sub-provinces may have distinct crustal magmatic systems.

4.2. Deccan eruptions and Réunion plume motion

Since the Deccan is associated with Réunion mantle plume (Richards et al. 1989), it has been hypothesized that the eruptive centers for Deccan migrated southwards following the plume track during the emplacement of the Western Ghat chemostratigraphic sequence. With an eruptive timeline to ∼ 800,000 years (Sprain et al. 2019, Schoene et al. 2019), the Indian plate moves only 150 km (assuming a superfast plate motion of 18 cm/yr, Pusok & Stegman (2020)). Thus, if the plume was centered at Surat (southern Saurashtra) when the Igatpuri Fm. eruptions start, it would have only reached Nasik (∼ 150 km NE of Mumbai) by the time of the Mahabaleshwar Fm. If the crustal magmatic system mirrored this plume motion, the resulting stress pattern does not match the observed dike spatial distribution and orientation pattern (Figure 5). We instead posit that initial magmatic system was established underneath the Narmada-Tapi rift zone which was already under extension prior to Deccan (Pandey 2020). The dikes and the shallow plumbing system followed pre-existing tectonic structures early in the eruptions, and then progressively developed its own feeder system centered on the plume head with increasing melt flux. Correspondingly, the plume-induced stress superseded other regional extensional forces leading to more varied dike orientations (Central Dike Swarm, Richards et al. (2015), Vanderkluysen et al. (2011)). Additionally, the dike emplacement itself lead to significant near-surface strain with a peak value of ∼ 2.5% in the Narmada-Tapi region (Using a typical dike thickness of ∼ 10 m, and dike linear number density; Supplementary Figure SM5 Inset) One potential line of evidence from the dike distribution supporting this hypothesis is that first, the lava flows in the Narmada-Tapi Rift zone and Malwa region are older than most of the Western Ghats sequence with Chron 30N polarity as well as extending through Chron 29R to Chron 29N at least (Schöbel et al. 2014)). This suggests that the volcanism was longer lived in Malwa. The proposed model of Deccan magmatic evolution can be directly tested with future geochemical mapping, paleomagnetism, and dating of dikes.
5. What are the Deccan lava Eruption rates?

Despite improved geochronological age precision of order 0.1 - 0.01%, the absolute age uncertainty is still of order 10,000 kyr (for KPB age samples)(Sprain et al. 2019, Schoene et al. 2019) which is too large to resolve individual flow-fields. Hence, other indirect methods are necessary to estimate Deccan eruptive rates.

5.1. Volcanological Constraints

Early studies of CFB flow-fields proposed that individual flow-fields were emplaced within timescale of a few days to weeks, with a correspondingly huge eruption rate (Shaw & Swanson 1970, Mangan et al. 1986, Tolan 1989). However, work on lava flow-fields in the CRB province (e.g., Self et al. 1998, Vye-Brown et al. 2013, and references therein) has illustrated a strong similarity between CFB lava flows and modern, especially Icelandic, lava flows despite the significantly different spatial scale. As a consequence, it is suggested that CFB flows were emplaced as inflated compound pāhoehoe flow-fields with eruption rates similar to the highest observed for Iceland (e.g., Laki 1783; 8,700 m$^3$/s Thordarson & Self 1993, Guilbaud et al. 2005), but sustained over years to decades (e.g., Ho & Cashman 1997, Keszthelyi & Self 1998, Self et al. 1998, Anderson et al. 1999, Bryan et al. 2010, Keszthelyi et al. 2006). Using the mean eruption rate of 4000 m$^3$/s for the first two months of the Laki 1783 eruption, a 5000 km$^3$ Deccan flow field would be emplaced in ~ 40 years. In practice, the actual emplacement times are longer since magma flux would be expected to fluctuate during an eruption. Rader et al. (2017) have argued that effusive flux variations (of factor ~ 2-5) are a requirement for the formation of inflated sheet lobes. In both CRB and Deccan flood basalts, the presence of multiple vesicular horizons in the upper crust of a single flow-lobe may be evidence of this cyclic inflation (Hon et al. 1994, Cashman & Kuahkaua 1997). One potential challenge with using constraints on the effusion rate at the vent location to estimate the duration of a CFB flow field is that each flow field may be fed by a long fissure system (e.g., ~ 180 km for the CRB Roza flow; Thordarson & Self 1998, Brown et al. 2014). If a fissure is active along a significant fraction of its length, the total time-period for CFB emplacement will be short despite the restricted effusion rate. However, the volcanological estimates of minimum lobe emplacement duration based on the Hon et al. (1994) scaling for the thickness of lobes’ upper crust are typically > 10 years for most CRB flow-fields (and would be similar for Deccan given similar lobe crust thickness) (Thordarson & Self 1998, Vye-Brown et al. 2013). These estimates are minimum estimates for the duration of a CFB field since they assume that the thickest lobe was inflating throughout an eruption, and they ignore time-elapsed between lobe superposition. If instead, different lobes undergo inflation at different times and/or have some time-hiatus between them, the total duration of a CFB field would be longer (order centuries) (see Vye-Brown et al. 2013 for a more detailed discussion of other model uncertainties). Thus, we can conclude that individual Deccan, and CFB, flow-fields are emplaced over long time-periods by sustained eruptions from a single/a few active vents or short fissure segments.

5.2. Paleomagnetic secular variation

A common method to directly estimate inter-flow emplacement rates is to utilize the secular variation of Earth’s magnetic field. Consequently, paleomagnetic directions recorded in successive lava flows (in a stratigraphic sequence) display variations in field position (Chenet...
et al. 2008, 2009). Typically, if two (or more) flows have similar field directions within a 5-10 degree threshold, they are assigned to a directional group and assumed to have been emplaced very rapidly (within ~ 400 years) using estimates of modern secular variation (Chenet et al. 2009). The number and stratigraphic distribution of directional groups (DGs) thus provides a high-resolution estimate of LIP eruptions. Based on a large study in the Western Ghats region, Chenet et al. (2009) concluded that the whole stratigraphy erupted in 30 major eruptive periods along with 41 individual lava units. They estimated that the volume of each eruptive period is between 1000 to 20,000 km$^3$ while individual lava unit’s volume is typically 1300 km$^3$. Each of these 71 units has a duration of 10-100 years based on the secular variation analysis. Thus, Chenet et al. (2009) concluded that the active eruptive period for the Western Ghats Deccan lava flow was very short ranging from 1000 to 7000 years. However, this time estimate is based one key simplifying assumptions about the pattern of geomagnetic secular variation: ignoring the quasi-cyclic (with a time scale of ~ 10 kyr) nature of paleosecular variation (Panovska et al. 2018). This quasi-cyclicity can introduce spurious correlations wherein lava flows separated by multiple secular variation cycles still have a small difference in paleomagnetic directions. The two key characteristics of these type of “spurious” DGs is that firstly each DGs typically only have 2 lava flow members, and secondly a substantial fraction of flows are not part of any DG. For Deccan, the DGs found by Chenet et al. (2008, 2009) satisfy both these characteristics especially when only considering DGs for a single continuous stratigraphic section (e.g., in the Wai-Panchgani section, only ~ 50% flows are part of a DG). Additionally, an analysis of the detailed stratigraphic logs from Jay (2005) with the DGs shows that many Deccan DGs encompass interbedded weathering horizons (red boles, shown in Figure 4A) which may take 1000s of years to form (Sheldon 2003). Finally, maximum thickness of boles is less than 1.5 m, with most boles being inter-formational rather than between geochemical or lithologic formations. Thus, we conclude that the long-term eruptive tempo was likely not as pulsed (intermittent) as initially inferred by (Chenet et al. 2009). Instead, Deccan flow field eruptions were spaced more uniformly during the Deccan main phase eruptions (Sprain et al. 2019, Schoene et al. 2019).

5.3. Hg chemostratigraphy

Another indirect method to estimate the eruptive rate of the Deccan at flow-field scale resolution is the use of mercury (Hg) chemostratigraphy (e.g., Font et al. 2016, Keller et al. 2018, Percival et al. 2018, Fendley et al. 2019). Hg is emitted as a vapor during volcanic eruptions, as well as through passive degassing, and volcanism is the dominant source of Hg to the environment (see Fendley et al. (2019) for more discussion). Increases in Hg concentration, therefore, may indicate inflation of the global Hg budget due to flood basalt eruptions. Using high resolution terrestrial Hg chemostratigraphic records, Fendley et al. (2019) estimated that Deccan eruptions lasted on the order of centuries and released 500–3000 megagrams Hg/yr, corresponding to ~ 50–250 km$^3$/yr of lava. These estimates are very consistent with the volcanological estimates from the previous subsection. Additionally, the frequency of Hg peaks in some high resolution terrestrial and marine records spanning the Deccan eruptive time period suggest that eruptions occur every 3-6 thousand years on average. However, further analysis of the Hg records is required to constrain the eruptive history accurately and constrain the duration eruptive hiatus (if any) and eruption pulses. In particular, such analysis must account for variable sedimentation rates, record sampling
resolution, and lithological variations for different Hg records (Fendley et al. 2019).

5.4. Implications for Deccan magmatic architecture

The eruptive rate constraints discussed in the previous subsections as well as the dike distributions provide significant constraints on the crustal magmatic architecture underlying the Deccan. Cox (1980) proposed one of the first semi-quantitative magmatic models for Deccan consisting of a large (multi-km thick) crustal sill complex at/or close to Moho depth as the primary melt accumulation location, along with an elaborate network of dikes and sills for feeding surface lava flows. More recently, Black & Manga (2017) and Ernst et al. (2019) proposed a similar structural model for a CFB magmatic system with an extensive primary underplated magma reservoir(s) spanning hundreds of km laterally and up to 20 km in thickness. The magma is then envisioned to ascend both laterally outward and vertically through the crust via a large number of dikes (radiating, linear, or circumferential). During this transport, the magma can periodically accumulate in mafic-ultramafic intrusions of various shapes (e.g., multiple km thick upper-to-mid crustal sills: 2060 Ma Bushveld and 2710 Ma Stillwater complexes). However, using a series of thermo-mechanical models, Mittal & Richards (2021) showed that the presence of just a few large crustal magma reservoirs is inconsistent with the eruptive rate constraints since large magma chambers erupt too quickly (LIP eruptions in hours-days rather than years). They instead propose that CFB eruptions are fed from a number of smaller (∼10^2 - 10^5.5 km^3) interconnected magma reservoirs present throughout the crust consistent with the paradigm of a transcrustal magmatic system (Figure 6). This magmatic plumbing architecture permits; (a) large volume efficient eruptive episodes with 10-100s of years duration; (b) relatively short time-periods separating eruptive episodes (1000s of years) since multiple mechanisms can trigger eruptions (via magma recharge or volatile exsolution, as opposed to long term (10^5 - 10^6 year) accumulation of buoyancy overpressure; (c) lack of large upper-crustal intrusive bodies in various geophysical datasets; and (d) marked geochemical changes between and within individual eruptive episodes as observed in various CFB sections. It also provides a potential explanation for the observed similarity in the chemical compositions of the flows occurring in different sub-provinces, though sub-provinces are underlain by different cratonic blocks.

6. Summary - CFB flow-fields

The various parts of a CFB flow-field have not been illustrated before carefully; Figure 7 is an attempt to do so for a Deccan flow field, or any CFB flow-field for that matter. It is based on what has been observed and reported for Deccan lavas by innumerable authors, plus observations by the authors in Iceland and the CRB province. For the Deccan in particular, no clear large lava tubes have been identified (Duraiswami et al. 2004, Pawar et al. 2015). The components of the flow-field are laid out as they would occur, proximally to distally, but the scale is difficult to represent. Deccan (and many other CFB) flow-fields are probably so huge (thousands of km^3), for the most part, that the sheer extent is difficult to represent on a single-page sketch.
FUTURE ISSUES

1. Constraining total Deccan eruptive volumes: An estimate of the Deccan eruptive volume and eruption rates accounting for erosion, subsidence below surface (especially lavas presently offshore western coast, (Bhattacharya & Yatheesh 2015, Kumar & Chaubey 2019)), and rifting from India (when & how much) is critical, basic information needed to assess the Earth system impacts of Deccan volcanism and relationship with the Chicxulub impactor.

2. Testing the robustness of the chem/litho-stratigraphic framework: Key challenges that need to be addressed are (i) better statistical tools to distinguish formations with overlapping compositions and incorporating isotopic measurements, (ii) correcting the Western Ghat Escarpment bias in sampling and systematically analyzing the datasets for each sub-province while accounting for spatial compositional variations in the sub-Trappean Deccan crust, and (iii) ground-testing the results by physically tracing single flow-fields/chemical formations across long distances.

3. Quantitative observations of Deccan flow-fields: Detailed field, petrological, and geochemical analysis of individual Deccan lavas are need to constrain the volume and spatial extent of individual eruptions as well as any along flow volcanological and geochemical variations. These observations would help answer first order questions: How do LIP flows traverse long distances without freezing; What was their true eruption rate and are there differences in the style of eruption between the sub-provinces.

4. Ascertaining the vent location for Deccan lavas: A better constraint on Deccan vent locations is needed to answer critical questions related to eruption style: Did individual flow-fields erupt from a single vent or multiple vents at the same time? Was there one vent area for most of the Deccan, or were there single vents for each formation? Did different sub-provinces have separate magmatic plumbing systems and eruptive histories?
Figure 1
Simplified geologic map of peninsula India showing distribution of main outcrops of Deccan Volcanic Province (DVP) and main sub-provinces (Deccan Plateau including the Western Ghats), Satpura region, Mandla Lobe, Malwa Plateau, and Kutchh-Saurashtra region (blue color). Figure also shows major sedimentary basins, Proterozoic mobile belts, and major cratons (after Kale et al., 2020a) - 1: Western Dharwar Craton, 2: Eastern Dharwar Craton, 3: Bastar Craton, 4: Eastern Ghats Belt, 5: Singhbhum Craton, 6: Bundelkhand Craton, 7: Aravalli Craton. Primary tectonic faults (Barmer-Cambay rift zone, Central India Tectonic Zone (CITZ), Pranhita-Godavari rift zone (PGR), Kurduwadi Lineament zone (KLZ), Western Ghats Escarpment, Koyna Fracture Zone) and lineaments (dashed lines, Rajaram et al. (2017)) in Central India related to pre-existing Indian crustal features are also labelled. The 45 symbol on the map shows location of Deccan-associated Behradli Kimberlite (Lehmann et al. 2010).

7. Figures
Figure 2
A Spatial map for geochemical formations – using estimates from Subbarao et al. (2000). Points show locations of individual formation stratigraphic sections from Jay et al. (2009), Talusani (2010), Kumar et al. (2010), Peng et al. (2014) (see Supplemental Text for label numbers). B Composite section of Western Ghats lava flow stratigraphy showing geochemically defined formations. Magnetic polarity of lavas is expressed at right, R – chron 29r; N = chron 29n, after Jay et al. (2009). Isotopic range of lavas after Kale et al. (2020b).
Nera Formation (fig-карта для масштаба).

Figure 3A. Thick SLs in Mahabalshwar Formation at Arthur’s Seat, Maharastra; top and bottom and main layers marked. Inset is cartoon through hypothetical sheet flow lobe, after Thordarson & Self (1998), showing common arrangement of internal physical features (not resolvable in cliff at right); right face: UC – upper crustal zone; C – core; LC – lower crustal zone; HVZ – horizontal vesicular zone; MVZ – megavesicle zone; VC – vesicle cylinders; PV – pipe vesicles; BVZ – basal vesicular zone. Left face shows typical form and arrangement of cooling joints. B: Rough (outlined lobe cores) 10-meter-scale lobes atop ~ >30 m thick, entablature-jointed sheet-lobe from Rajahmundry Traps (likely Ambenali Formation); carbonate unit marks flow top. C: Multiple small, highly vesicular hummocky-pahoehoe lobes in Ellora Caves, Maharashtra. D: Deccan Thalghat (Jawahar Formation) hummocky-pahoehoe lobes, after Thordarson & Self (1998); note the lack of sharp interface with the overlying non-GPB basalt. E: Filled pipe-vertical vesicles in probable Triassic Formation lobe (cluster for scale); fill the core with similar roped...
Figure 4
A. Plots of lobe thickness in each Deccan lava formation vs elevation above mean sea level for traverses in central Western Ghats area; width of bar = lobe thickness. Formations are shown by bar color; + open dots = with small lobes; + stars = small-lobe-dominated. Red vertical lines show boles (weathering horizons; note bole line thickness is not to scale). Plots given from N to S (top to bottom) represent distance of ∼80 km – no lobe-thickness trend with distance is seen. B. Univariate kernel density estimator to calculate probability density function (PDF) of lava lobe thicknesses in accumulated formations within each Deccan subgroup as well as some outlying sub-provinces. Key feature of interest is that all formations have both small and sheet lobe dominated lava flow-fields.
Figure 5
Spatial distribution of ~ 29,000 Deccan-associated dike segments (using GSI 1:50 k geologic maps and NGLM dike dataset) with colors denoting dike orientation. Insets A and B show regional zoom-in for Saurashtra and Narmada-Tapi swarms each with multiple overlapping dike orientations. Figure also shows rose diagram for each dike subregion as well as for the whole dataset (in bottom right). For each dike orientation bin in rose diagram, color bars illustrate corresponding dike length distribution histogram.
Figure 6

Conceptual model for magmatic structure of a continental flood basalt sequence such as Deccan in three stages: Early Stage Flood Basalts (Panel A), Main Stage Flood Basalts (Panel B), and Late Stage Flood Basalts (Panel C). The most voluminous surface eruptions occur during Main Stage Flood Basalts while the maximum passive degassing typically occurs towards end of Early Stage CFBs.
Cartoon of generic phh lava flow-field; caption to be supplied when finished. Key point is that all flow-fields in most Deccan formations have both small and sheet lobe dominated lava flows. (This is a draft figure and will be replaced in the final reviewed Annual Review version with a graphic illustration).
DISCLOSURE STATEMENT
The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

8. Supplementary Material
8.1. Supplementary Text

8.2. Supplementary Figures SM1-SM5

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**Lithostratigraphic Classifications Of The Deccan Volcanic Province, India**

**Western subprovince**

- **Group**: Sahyadri
- **Subgroup**: Bombay, Borivali, Elephanta, Khandala, Mahabaleshwar
- **Formation**: M4 (GPB) - Purandargarh, Diveghat, Karla

**Satpura (Central) subprovince**

- **Group**: Satpura
- **Formation**: Karanja, Buldhana, Chikhli, Ajanta

**Other subprovinces**

- **Formation**: Mandla, Kankaria- Pirukheri, Malwa, Indore

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**Figure 9**

SM2: Spatial map for Deccan lithological formations (following GSI 1:50k geologic maps). Note that stratigraphy for three outlying areas has different names and relationship of units to those of Western Ghat-Central Deccan province is unclear. In the Mandla, Malwa, and Saurashtra region, the lithostratigraphic formations are sometime less well defined – hence, we only show the primary formations with large spatial regions on the map. The stratigraphic order of the formations is shown on the right following Kale et al. 2020a. We do not compare the lithostratigraphic and chemo-stratigraphic formations (even if they have the same name) with each other given the present uncertainty correlating them.

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**LITERATURE CITED**


Bhattacharya G, Yatheesh V. 2015. Plate-tectonic evolution of the deep ocean basins adjoining
Figure 10: A. Dike pictures from Deccan Traps: (i) Single injection basaltic dike near Igatpuri, Western Ghats; (ii) multiple injection dyke (with three columnar-jointed sets) near Satara, Maharashtra. Dike edge is not visible in this picture; (iii) Multiple injection dike (near Thanepada) from the Nadurbar-Dhule dike swarm; dike has 10-columnar-jointed rows and dike-host flow interface is not exposed. B. Google Earth Satellite images showing regions from each of the four Deccan dike swarms (the dikes are the curvilinear features in the images). The images clearly illustrate the high dike spatial density in some regions and a number of intersecting dikes (e.g., star shaped pattern in left part of Figure B(iii)).
Figure 11
SM4: Excerpts from lithostratigraphic logs (Jay, 2005) showing features of lavas in selected parts of seven traverses representing typical features of DVP lava formations. Key gives identification of lava features, together with paleomagnetic polarity signature and formation/chemotype [see Jay et al., 2009]; m asl - height above sea level. No correlations between lavas are indicated by placement of logs in this figure. Logs except Matheran show types of sheet lobes and hummocky-pahoehoe plotted in Figure 3 of main text.
Figure 12: SM5: Spatial distribution of ~29,000 Deccan-associated dike segments (using GSI 1:50 k geologic maps and NGLM dike dataset) with colors denoting dike segment length. Inset in main figure shows spatial map of overall dike density weighted by dike segment length. For each sub-region, corresponding figure shows PDF of dike length (and best-fit lognormal distribution) as well as polar plot of (2x) dike orientation and (log_{10}) dike segment length.
the western continental margin of India—a proposed model for the early opening scenario. In *Petroleum geosciences: Indian contexts*. Springer, 1–61


Brown RJ, Blake S, Thordarson T, Self S. 2014. Pyroclastic edifices record vigorous lava fountains during the emplacement of a flood basalt flow field, Roza member, Columbia River basalt province, USA. *Bulletin* 126:875–891


Deshmukh S, Sano T, Fujii T, Nair K, Yede Kar D, et al. 1996. Chemical stratigraphy and geochemistry of the basalt flows from the central and eastern parts of the Deccan volcanic province of


Duraiswami RA, Shaikh TN. 2013a. Geology of the saucer-shaped sill near mahad, western deccan traps, india, and its significance to the flood basalt model. Bulletin of Volcanology 75


GSI Bhukosh. 2020 (accessed December 1, 2020). Bhukosh


Melluso L, Mahoney JJ, Dallai L. 2006. Mantle sources and crustal input as recorded in high-mg deccan traps basalts of gujarat (india). *Lithos* 89:259–274


32 Sel et al.
suite records the culmination of deccan traps continental flood volcanism. Lithos 182:33–47
Patro B, Sarma S. 2007. Trap thickness and the subtrappean structures related to mode of eruption in the deccan plateau of india: results from magnetotellurics. Earth, planets and space 59:75–81


Self S, Mittal T, JAY AE. 2020. Thickness characteristics of pāhoehoe lavas in the deccan province, western ghats, India, and in continental flood basalt provinces elsewhere


West W. 1959. The source of the deccan trap flows. J. Geol. Soc. India 1:44–52