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Deccan volcanism at K-Pg time

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ABSTRACT

The last major mass extinctions in Earth history (e.g., end-Guadalupian, end-Permian, end-Triassic, and end-Cretaceous) are all correlated closely in time with the main-phase eruptions of major flood basalt provinces (Emeishan, Siberian, Central Atlantic Magmatic Province, and Deccan Traps, respectively). The causal relationship between flood volcanism and mass extinction is not clear, but likely involves the climate effects of outgassed volatile species such as CO_2, SO_2, Cl, F, etc., from some combination of magma and country rocks. In a surprising "coincidence," the end-Cretaceous (K-Pg boundary) micro-faunal extinction also corresponds precisely in time to what may have been the largest meteor impact of the past billion years of Earth history, the Chicxulub crater at 66.05 Ma. The Deccan Traps eruptions were under way well before K-Pg/Chicxulub time and are most likely the result of the mantle plume "head" that initiated the presently active Reunion hotspot track—thus the Deccan Traps were clearly not generated, fundamentally, by the impact. However, recent high-precision $^{40}Ar/^{39}Ar$ geochronology indicates that conspicuous changes in basalt geochemistry, lava flow morphology, emplacement mode, and a possible 50% increase in eruption rate at the Lonavala/Wai subgroup transition in the Deccan Traps lava group corresponded, within radioisotopic age precision, to the K-Pg boundary and the Chicxulub impact. This has led to the testable hypothesis that the

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M_w ~11 seismic disturbance of the Chicxulub impact may have affected the Deccan eruptions. Here we review a broad landscape of evidence regarding Deccan volcanism and its relation to the K-Pg boundary and attempt to define what we see as the most important questions than can and should be answered by further research to better understand both the onshore and largely unknown offshore components of Deccan-related volcanism, and what their climate and environmental impacts at K-Pg time may have been.

INTRODUCTION

The geological record suggests that the most conspicuous mass extinction events of at least the past 300 million years of Earth history are causally related to flood basalt volcanism (although not all flood basalts are associated with mass extinctions). The end-Guadalupian (ca. 260 Ma), the end-Permian (ca. 250 Ma), the end-Triassic (ca. 200 Ma), and the end-Cretaceous, or K-Pg (ca. 66Ma) mass extinction events correspond very closely in time to the "main-phase" eruptions of the Emeishan Traps, Siberian Traps, Central Atlantic Magmatic Province, and the Deccan Traps, respectively (see, e.g., Clapham and Renne, 2019; Courtillot and Renne, 2003; Ernst et al., 2020; Kasbohm et al., 2020). It is generally assumed that flood volcanism disrupts the climate and biosphere due to volcanic outgassing (CO_2, SO_2, Cl) and/or outgassing of the subcrustal country rocks intruded by the magma, but there is no agreement upon which gaseous species cause the most environmental perturbation, or how this leads to ecological damage and extinction (Jones et al., 2016). In addition, a number of flood basalt provinces, especially oceanic plateaus, do not correspond to large extinction events and currently there is no clear correlation between erupted volume and extinction intensity (see, e.g., Clapham and Renne, 2019, and references therein).

The most enigmatic (and recent) case of correlation between flood basalt volcanism and mass extinction is that of the K-Pg mass extinction, which exterminated the non-avian dinosaurs as well as several other lineages. At least in terms of the marine micro-faunal records, the K-Pg mass extinction corresponded precisely with the Chicxulub impact at 66.05 Ma (Alvarez et al. 1980; Hildebrand et al., 1991; Sprain et al., 2018; Hull et al., 2020), as well as the main-phase eruptions of the Deccan Traps (Renne et al., 2015; Schoene et al., 2014, 2019; Sprain et al., 2019). So far, no convincing evidence has been found for large impacts corresponding to the other three mass extinctions mentioned above, suggesting that the K-Pg extinction is likely unique in corresponding to these two types of geological catastrophe (Alvarez, 2003).

The K-Pg/Chicxulub/Deccan "coincidence" has led to speculation that Deccan volcanism might have been influenced by the Chicxulub impact (Rampino and Stothers, 1988; Richards et al., 2015), leaving open the possibility that only one or perhaps both of these potential causal mechanisms ultimately caused the extinction. A strictly "uniformitarian" view (same cause-effect relationships over time) of the geological record would suggest that the K-Pg extinction resulted primarily from Deccan volcanism since other major mass extinctions are associated with flood basalt volcanism and no major impacts. However, the micropaleontological record, in addition to records of fossil pollen on land, suggests an abrupt K-Pg extinction coincident with the Chicxulub impact (Schulte et al., 2010). This remarkable paradox has not yet been resolved.

Deccan magmatic activity plausibly attributed to the Reunion plume began at least several million (~5–10 Ma) years prior to K-Pg time (Mahoney et al. 2002, Pande et al., 2017b). Furthermore, the volumetrically dominant Western Ghats Deccan volcanism, commonly referred to as the "main phase" of eruption, started ~300–400 ka prior to the K-Pg boundary (Renne et al., 2015; Sprain et al., 2019; Schoene et al., 2015, 2019). Thus it is clear that the Deccan Traps did not result directly from the impact. Instead, Deccan volcanism is widely believed to mark the initial eruptive phase of the still-active Reunion hotspot track (see Fig. 1B), and to correspond to massive partial melting of the initial "head" of the Reunion mantle plume (Morgan, 1981; Richards et al., 1989; Campbell and Griffiths, 1990). A number of other flood basalt events are also thought to mark the initiation of mantle plumes (Richards et al., 1989). Consequently, the plume head model for flood basalt volcanism has become an established paradigm based upon well-understood dynamics associated with plume formation due to convective instability within the deep mantle (Richards et al., 1989; Farnetani and Richards, 1995; Burke 2011; Torsvik et al., 2014).

The resulting flood basalt events involve enormous volumes of mostly basaltic lava, often several million cubic kilometers in the continental setting (Coffin and Eldholm, 1994; Ernst et al., 2020). Several oceanic plateaus attributed to plume initiation, such as Ontong-Java, involve even larger volumes, potentially up to an order of magnitude greater than continental flood basalts (Farnetani et al., 1996; Ridley and Richards, 2010). Although the total duration of continental flood basalt events ranges from ~5 to 15 Ma, the largest lava volumes are usually erupted within just ~0.5–2 Ma (Courtillot and Renne, 2003; Kasbohm et al., 2020). In the case of the Deccan Traps, the main subaerial eruptions (Fig. 1A) concentrated in western India (Western Ghats–Central Deccan) generated of order ~1 million km^3 of basalt in a time period of order only ~1 million years (Vanderkluysen et al., 2011; Richards et al., 2015; Renne et al., 2015; Sprain et al., 2019; Schoene et al., 2015, 2019). However, Deccan-related

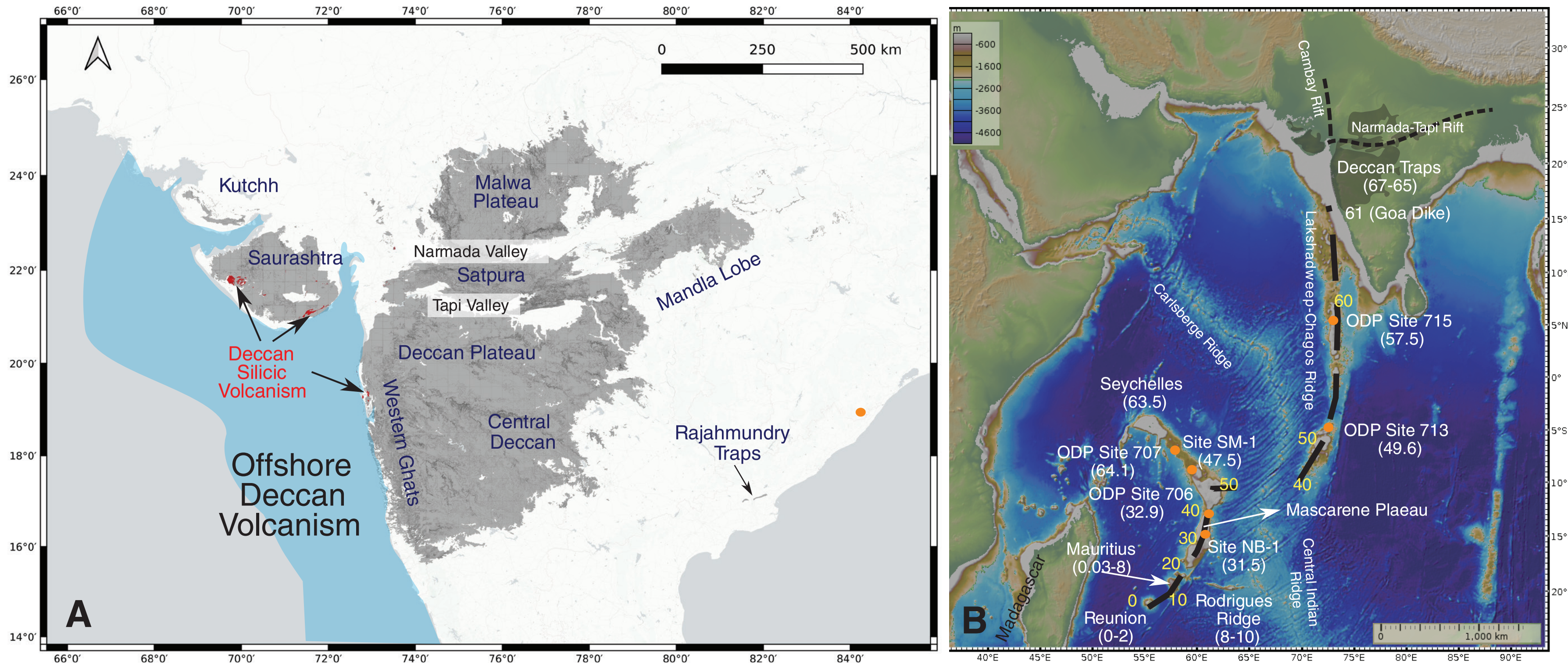

Figure 1. (A) Map of western India peninsula showing the distribution of main outcrops of Deccan Volcanic Province (DVP) and main sub-provinces (Deccan Plateau including the Western Ghats, the Central Deccan, and the Rajahmundry Traps), Satpura region, Mandla Lobe, Malwa Plateau, Kutchh-Saurashtra region, and the Offshore Deccan Volcanism. The red regions, primarily concentrated in the Saurashtra region, indicate small volume silicic volcanism associated with the DVP. (B) Bathymetric map of the Indian Ocean Basin with prominent structural-tectonic features (based on Mahoney et al., 2002; Sheth, 2005). The bathymetric base map is obtained from GeoMapApp (Haxby et al., 2010; Ryan et al., 2009). Ages (in Ma) are from the following references: 61 Ma Goa dikes (Widdowson et al., 2000). The modeled Reunion hotspot track is shown by the thick dashed line along with expected ages (yellow, in Ma). Other ages and references therein are from Mahoney et al. (2002); Sheth (2005); and Torsvik et al. (2013). ODP—Ocean Drilling Program.

activity to the north of the Western Ghats province (WG) began perhaps 5–10 million years earlier (Basu et al., 1993; Cucciniello et al., 2019; Mahoney et al., 2002; Parisio et al., 2016; Schöbel et al., 2014) and continued for at least a few million years after the Western Ghats eruptions in the Mumbai-Goa region (Pande et al., 2017a; Sheth et al., 2001; Widdowson et al., 2000).

Importantly, within the "main phase" Western Ghats eruptions, ^{40}Ar/^{39}Ar dates suggest that the onset of the largest flows with the most widespread areal coverage (Wai subgroup; see below) corresponds to Chicxulub/K-Pg time at 66.05 Ma (Renne et al., 2015; Sprain et al., 2019), and also to marked changes in the physical nature (e.g., flow lobe thickness) and geochemistry of Deccan flood basalt flows (Renne et al., 2015; Richards et al., 2015; Self et al., 2021) (See discussion re U-Pb dates below). Chicxulub probably generated an earthquake of magnitude M_w~11 (Day and Maslin, 2005; Richards et al., 2015; DePalma et al., 2019), creating worldwide ground motions far larger than even the largest tectonic earthquakes (e.g., the M_w 9.5 1960 Chilean earthquake, Kanamori 1978). Hence, it is reasonable to speculate that the Deccan Traps eruptions might have been influenced by seismic strong motion from the Chicxulub impact, referred to as the impact triggering hypothesis. Furthermore, it is possible that these seismically influenced Deccan eruptions may have contributed to the K-Pg mass extinction and/or prolonged the timescale of recovery from the extinction (Alvarez et al., 2019; Lyson et al., 2019; Richards et al., 2015; Sprain et al., 2018). However, whether these eruptions contributed enough volcanic gas to significantly alter the climate remains to be seen.

Another twist in this saga is that significant Deccan volcanism clearly occurred offshore western India as the Seychelles province was rifted away during the waning stages of the onshore eruptions (see Fig. 1B and Fig. 5, Devey and Stephens 1992; Fainstein et al., 2019, and discussion below). In fact, the offshore component may constitute as much as 2–3 times the volume of the Main Deccan Province (Western Ghats, Central Deccan) eruptions (Figs. 5–7). Unfortunately, we have only scant information on the volume, emplacement style, geochemistry, and whether these eruptions were subaerial or submarine. Importantly, the age of Deccan volcanism which is presently offshore constitutes a major gap in our understanding of the overall eruptive history of the Deccan Traps and the consequent environmental impacts. There are also several other significant Deccan-related volcanic provinces onshore (Satpura-Malwa Plateau, Mandla Lobe, Kutchh-Saurashtra; see Fig. 1A) whose geochemistry and emplacement ages are not fully constrained and which may have had originally significantly larger spatial extent than present day (Colleps et al., 2021; see discussion later). Although the volume of these outlying regions is likely not as significant as the Main Deccan Province or the offshore component (based on areal extent and section thickness), constraining their eruptive history is critical for understanding the overall Deccan Traps magmatic system and testing how "anomalous" the Wai sub-group lava may be.

In this paper, we review the results of recent geochronological, geochemical, and field-volcanological work, mainly from the Western Ghats province of western India, with an emphasis on the main-phase eruptions that corresponded closely in time with the K-Pg extinction. We then attempt to outline the work that we believe will provide critical additional constraints on Deccan-related events at K-Pg time, emphasizing the need for additional geochronological studies (high-precision and new techniques for finer resolution) as well as offshore exploration. This work is also pertinent for understanding the potential climatic impact of the Deccan Traps eruptions. Critical to assessing Deccan-associated climatic effects is understanding the timing and rates of volatile (CO_2, SO_2, Cl) degassing at a sub–1000 yr timescale (e.g., due to the years-decades atmospheric residence timescale for S, Schmidt et al. 2016). The magmatic volatile emissions are inherently tied to constraints on the timing and style of lava emplacement in the main Deccan Traps as well as the distal onshore and offshore provinces and structure of the underlying magmatic system(s).

The Deccan Traps are predominantly tholeiitic basalt (>95% of the exposed area) with small volumes of silicic, alkaline, and carbonatitic volcanism (Krishnamurthy, 2020). As shown in Figure 1A, most of the Deccan rhyolitic/silicic flows have present-day exposures either in the Saurashtra region (and adjoining parts of Narmada-Tapi rift zone), Barmer rift zone (silicic Deccan flows have been found in drill cores in the Raageshwari hydrocarbon field), or in the Mumbai region (Sheikh et al., 2020; Pandey et al., 2017; Dolson et al., 2015, and references therein). Given the predominance of visually similar basaltic lava flows across the Deccan Traps, lava geochemistry (especially trace elements and isotopes) has been used to stratigraphically correlate flows spatially. Since the thickest and most accessible onshore Deccan exposures (~3.5 km composite vertical section) are along the Western Ghats in northwestern India (Fig. 1A), these sections have become the basis for Deccan chemostratigraphic classification (Fig. 2) (e.g., Najafi et al., 1981; Sreenivasa Rao, et al., 1985; Mahoney et al., 1982; Cox and Hawkesworth, 1985; Beane et al., 1986). The Western Ghats section (and Central Deccan Traps subsequently) has been grouped into three subgroups (Wai, Lonavala, and Kalsubai, top to bottom) which are further subdivided into 12 geochemical formations (Beane et al., 1986; Mahoney et al., 1982; Cox and Hawkesworth, 1985; Basu et al., 2020; Devey and Lightfoot, 1986; Peng et al., 1994). The Kalsubai subgroup consists of the Jawhar, Igatpuri, Neral, Thakurvadi, and Bhimashanker formations and has a range of basaltic magma compositions ranging from picritic flows to evolved flows (Mg # <36, Beane et al. 1986). In addition, a number of the geochemical formation boundaries are demarcated by flows with a distinctive petrographic character—plagioclase-phyric megaporphyritic units known as giant plagioclase basalts (e.g., Shandilya et al., 2020, Sonu et al., 2021).

The next subgroup—Lonavala subgroup—consists of the Khandala and Bushe formations. The Bushe formation is particularly distinctive isotopically (Sr, Nd, and Hf isotopes) and contains significant geochemical (major, minor, and trace elements) evidence for crustal assimilation (Beane et al., 1986; Peng et al., 1994; Mahoney et al., 2000). The Wai subgroup comprises the

Poladpur, Ambenali, Mahabaleshwar, Panhala, and Desur formations and represents the most voluminous and aerially widespread subgroup (Figs. 2 and 3). The Wai subgroup lavas also have a distinct geochemical character compared to the underlying Lonavala subgroup lavas, especially the Bushe formation, with much lower crustal contamination based on strongly decreasing values of $^{87}Sr/^{86}Sr$ and higher values of ε_{Nd} and ε_{Hf} from the Poladpur-Ambenali-Mahabaleshwar flows (Peng et al., 1994; Basu et al., 2020). There are analogous changes in major (e.g., SiO_2), minor, and trace elements between the Wai and Lonavala subgroups. Finally, geochemical variation in Wai lava flows, especially the Ambenali formation, is significantly reduced compared to lower formations. Consequently, there was a significant change in the magmatic system co-incident with the Lonavala-Wai transition. Since the Ambenali Formation has the lowest $^{87}Sr/^{86}Sr$ and the highest ε_{Nd} values among the Western Ghats flows, it likely represents magma fractionally crystallized from the Reunion plume high-degree partial melt (Peng et al., 1994) with minimal crustal interaction. A noteworthy feature of the Western Ghats geochemical formations is that they show abrupt changes in $^{87}Sr/^{86}Sr$ ratios (and other isotope ratios indicative of contamination of plume melts by crustal and lithospheric components) through the stratigraphy (Kale et al., 2020) (with some examples mentioned above). These changes, sometimes across a single lava flow, suggest rapid changes in the magmatic source components for the erupted magmas. Thus, the Deccan Traps magmatic system appears to have a relatively short geochemical memory.

Over the past couple of decades, geochemical analyses of lava flow sections in the Indian Deccan Plateau have been used to extend the Western Ghats geochemical formations hundreds of km laterally into the Central Deccan (Peng et al., 1998; Jay and Widdowson, 2008), and the Rajamundry Traps (~1000 km

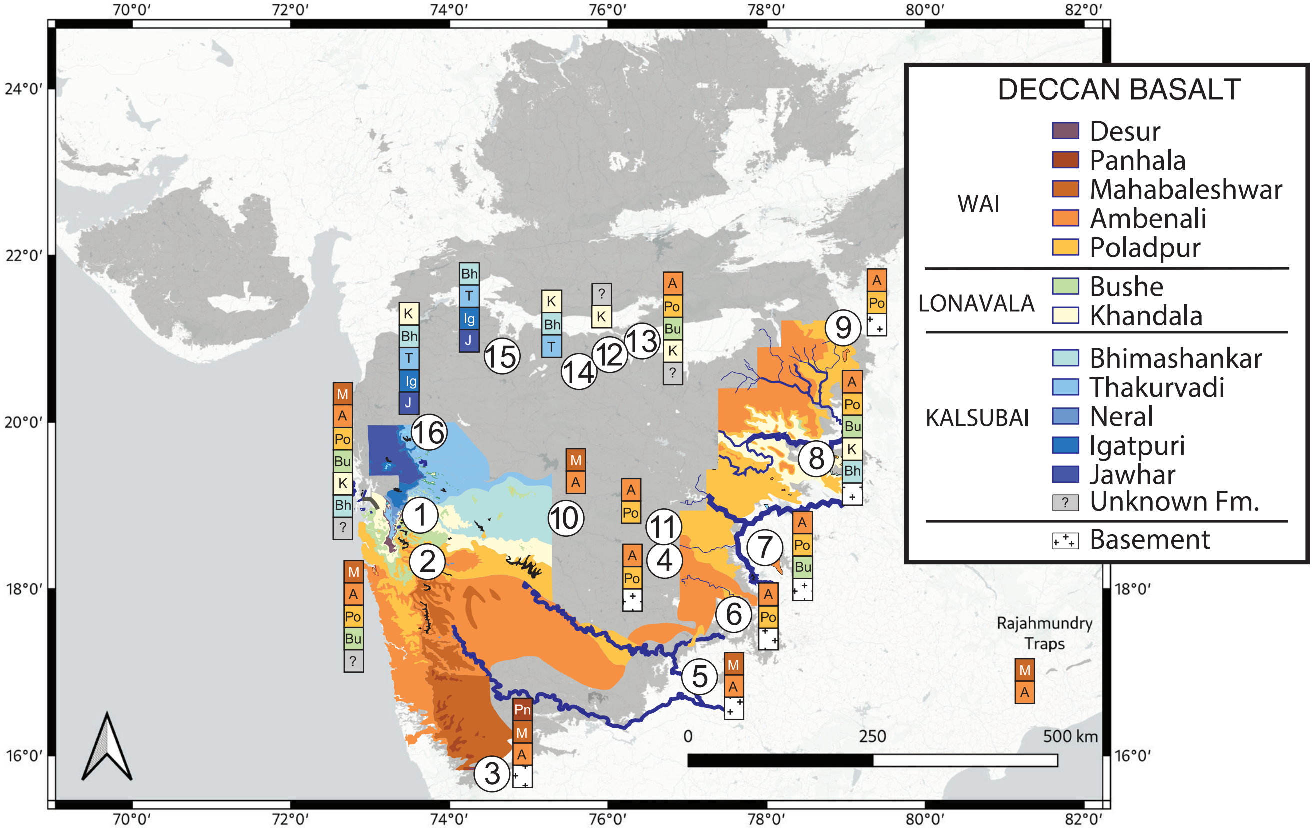

Figure 2. A spatial map for surface extent of various geochemical formations based on a compilation of the Western Ghats–Central Deccan geochemistry, using estimates from Subbarao et al. (2000). The numbered circles show locations of individual formation stratigraphic sections from Jay et al. (2009), Talusani (2010), Kumar et al. (2010), and Peng et al. (2014). For each section, we show our best estimate for which geochemical formation each flow corresponds to. The map clearly highlights the much larger spatial extent of the Wai subgroup flows compared to other subgroups as well as the data gaps in the Central Deccan region. We only show data from the Western Ghats–Central Deccan–Rajahmundry region since the chemostratigraphic correlations are most well developed in these regions, and it is not reasonable to extend the Western Ghats formations to other sub-provinces (see discussion in the text). Location names and references for section localities (circled numbers): 1: Pune–Purandhar; 2: Mahabaleshwar; 3: Belgaum; 4: Killari; 5: Gurmatkal; 6: Bidar; 7: Nizamabad; 8: Adilabad; 9: Nagpur; 10: Bhir; 11: Gangakhed–Ambajogai; 12: Ajanta-Mhaishmal, 13: Buldana; 14: Ellora–Outram; 15: Chandwad; 16: Kalsubai Peak. References: Devey and Lightfoot (1986); Subbarao et al. (1994); Mitchell and Widdowson (1991); Peng et al. (1998); Mahoney et al. (2000); Talusani (2010); Kumar et al. (2010); Peng et al. (2014).

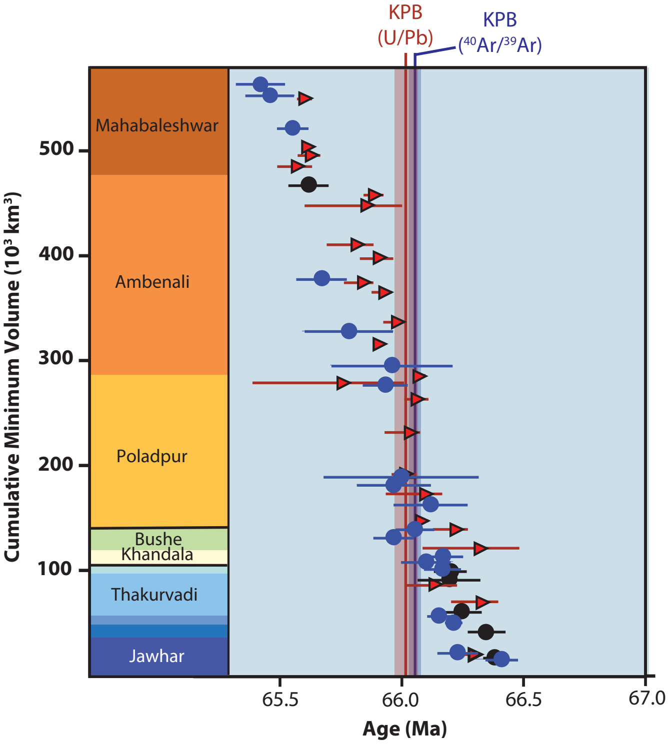

Figure 3. Composite cumulative volume versus age for chemical formations with the Deccan Traps lava group defined in the Western Ghats. Blue (black) circles are ^{40}Ar/^{39}Ar eruption ages determined in Sprain et al. (2019) and Renne et al. (2015). Ages are plotted with 2σ uncertainties. ^{40}Ar/^{39}Ar ages are reported using the calibration and decay constant of Renne et al. (2011). Red triangles are the U-Pb mean ages and 95% confidence intervals of deposition age (not including tracer uncertainty) reported in Schoene et al. (2019). Note: shown age uncertainties do not include systematic sources. These would add a few 10 ka to the uncertainty for each data point. The relative volumes per subgroup are from Richards et al. (2015). The ^{40}Ar/^{39}Ar K-Pg age is from Sprain et al. (2018) (66.052 ± 0.016 Ma, analytic uncertainty only) whereas the U-Pb K-Pg age is from Clyde et al. (2016) but modified in Schoene et al. (2019) (66.016 ± 0.050 Ma, internal uncertainty only). KPB—Cretaceous–Paleogene boundary.

from the Western Ghats (Self et al., 2008b; Fendley et al., 2020) (see sections and references in Figure 2 and its caption). These results suggest that individual Deccan Trap flows were hundreds of km long and had volumes on the order of thousands of km^3. Although there have been analogous efforts to extend the Western Ghats–Central Deccan geochemical stratigraphy to other sub-provinces (e.g., Malwa-Satpura Plateau, Mandla Lobe), the relative stratigraphic sequence and age of the flows is not the same as the Western Ghats section (Peng et al., 1998; Shrivastava et al., 2014; Sheth et al., 2018; Melluso et al., 2006; Sheth et al., 2013; Mahoney et al., 2000; see also discussion in the next section). Furthermore, the Pb isotopic composition of these flows is typically different from the Western Ghats flows despite similar major, minor, and trace element compositions (Peng et al., 1998, 2014; Shrivastava et al., 2014; Vanderkluysen et al., 2011; Sheth et al., 2018). Since the Indian crustal structure underlying the Deccan Traps varies for different Deccan sub-provinces, the likely explanation for these geochemical observations is that each sub-province has a distinct upper crustal magmatic plumbing system interacting with different crustal assimilants. The similarity of the major and minor element magma compositions between the Western Ghats geochemical formations and the other sub-provinces suggests that the same petrological processes (fractionation-recharge-assimilation) occurred for each of these magmatic systems (for each sub-province), but not necessarily at the same exact time as the Western Ghats.

HIGH-PRECISION GEOCHRONOLOGY OVERVIEW

It has long been appreciated that eruptions of the Deccan Traps encompassed the K-Pg boundary (e.g., Baksi, 1994; Pande, 2002; see references summarized by Richards et al., 2015). However, until recently there were major discrepancies between the various studies regarding the duration of volcanism, the nature of possible spatial-temporal trends, and placement of the K-Pg boundary within the lava sequence. Radioisotopic data published in 2015 and later are clarifying these issues considerably, although some new discrepancies have arisen.

The most numerous new data are ^{40}Ar/^{39}Ar dates from lavas in the Western Ghats (Renne et al., 2015; Sprain et al., 2019), which show a total duration of ~1 Ma for the volcanism, with a possible (but not statistically significant) 50% increase in volumetric eruption rate at the Cretaceous-Paleogene (K-Pg) boundary. For this data set, the most probable placement of the K-Pg boundary within the lava stratigraphy was shown to be near the transition between the Lonavala and Wai subgroups, specifically between the Bushe and Poladpur formations. Because this transition coincides with significant changes in geochemical and volcanological features (e.g., see Renne et al., 2015), these results are consistent with the impact triggering hypothesis of Richards et al. (2015), suggesting that the eruption of Wai subgroup flows may have been influenced by the Chicxulub impact. Placement of the K-Pg boundary at or near the Bushe-Poladpur formational contact is based on a Bayesian age model, although samples within the Khandala, Bushe, Poladpur, and Ambenali formations produced ages that overlap within the 95% confidence level of the age of the K-Pg boundary as determined by Sprain et al. (2018) (Fig. 3). Additionally, this placement has been established in only one stratigraphic section, which did not extend significantly below the top of the Bushe formation (Sprain et al., 2019); dating in other sections to determine whether this contact is isochronous everywhere would test the impact triggering hypothesis more rigorously. This raises the question of whether or not the contacts between geochemically defined (e.g., Beane et al., 1986) formations are isochronous; we return to this question below.

Another large new data set has been obtained by U-Pb dating of zircons separated from red bole horizons that occur intermittently between lava flows throughout the stratigraphy (Eddy et al., 2020; Schoene et al., 2019; Schoene et al., 2015). The term "red boles" in the Deccan Province is used to denote oxidized zones from a few cm to ~3 m thick, composed of various combinations of weathered flow-top and flow-bottom breccias, paleosols, and sediments (Duraiswami et al., 2020). The utility of dating zircons from these units rests upon the premise that in some cases a component of silicic tephra (including zircons) is included in them, which erupted during the formation of the red bole. An initial study that inferred eruption ages from youngest zircons for a limited number of red bole horizons yielded results (Schoene et al., 2015) that appeared to be consistent with subsequently published ^{40}Ar/^{39}Ar ages of Renne et al. (2015), but more extensive data sets for both U-Pb (now with eruption ages inferred from modeling of individual zircon age distributions; Schoene et al., 2019) and ^{40}Ar/^{39}Ar (Sprain et al., 2019), although dominantly in agreement (especially pre–K-Pg), revealed some significant discrepancies (Fig. 3). In brief, the U-Pb data were interpreted by Schoene et al. (2019) to indicate several distinct pulses of eruptions, whereas the ^{40}Ar/^{39}Ar data (Sprain et al., 2019) did not reveal any such pulses. Moreover, Schoene et al. (2019) inferred that the K-Pg boundary occurs later in the lava succession, within the eruption of the Poladpur or lower Ambenali formations. This placement, if correct, is inconsistent with the impact triggering hypothesis. Again, it is important to note that identification of eruption pulses and placement of the K-Pg boundary in Schoene et al. (2019) is still reliant on a Bayesian age model, albeit a different one than used in Sprain et al. (2019), as well as uncertainties attending stratigraphic correlations. A recent reassessment of the two data sets by Schoene et al. (2021), wherein they reinterpreted the ^{40}Ar/^{39}Ar data set using the Bayesian age model from Schoene et al. (2019), suggested that the ^{40}Ar/^{39}Ar data set is too imprecise to determine eruption tempo at the resolution inferred by Schoene et al. (2019). However, the reanalysis of Schoene et al. (2021) still shows an apparent discrepancy in the location of the K-Pg boundary between data sets, with the most likely position based on the U-Pb data set occurring near the top of the Poladpur Formation and the placement based on the ^{40}Ar/^{39}Ar data set occurring near the Bushe/Poladpur boundary. As noted by Renne (2020), all of the zircon age distributions of Schoene et al. (2019) in the Poladpur Formation overlap, leading to the possibility that they all represent reworking of a single population. This is also true in the Ambenali Formation, and unless it can be proven that the zircons are from primary ash fall deposits, we regard the implications for the location of the K-Pg boundary and the tempo of Deccan eruptions as tenuous. It is also noteworthy that the majority of the boles in Deccan are intra-formational rather than between geochemical or lithologic formations, especially for the Ambenali Formation (Jay and Widdowson, 2008; Self et al., 2021). Furthermore, there is no clear field evidence of a thick bole horizon at the Poladpur-Ambenali or Ambenali-Mahabaleshwar formations either in the Western Ghat sections or in the Koyna Drill cores which sample the Amenali/Poladpur boundary in detail and without any modern-day weathering biases (Jay and Widdowson, 2008; Self et al., 2021). Reconciliation of these discrepancies and the resulting implications for the impact triggering hypothesis, discussed further by Schoene et al. (2021) and Renne (2020), is still pending.

Whether or not the geochemically defined formations of the Western Ghats (shown in Fig. 2) are everywhere isochronous remains to be confirmed. If not, the eruptive histories of either Sprain et al. (2019) or Schoene et al. (2019), or both, may not apply even throughout the Western Ghats, let alone in the more distal sub-provinces (i.e., Mandla Lobe, Malwa Plateau, Gujarat). It's important to note that the similarity of ages between the U-Pb and ^{40}Ar/^{39}Ar data sets cannot be used as confirmation of isochroneity, as both parties often sampled the same sections. Eddy et al. (2020) used U-Pb dating on zircons in red boles to date horizons spanning ~50% of the lava sequence exposed in the Malwa plateau, and purported to find the same pulses of eruptions inferred by Schoene et al. (2019) in the Western Ghats. This conclusion is perplexing, as the distribution of Malwa dates reported by Eddy et al. (2020) appears to be smooth and continuous, the age span encompasses less than 40% of the duration of the Western Ghats, and no quantitative geochemical basis was provided for correlation between the two sub-provinces.

Kale et al. (2020) argue that the chemostratigraphic framework originally defined in the Western Ghats is regionally inconsistent, i.e., chemical types characteristic of the different formations appear in different stratigraphic order in different sub-provinces. Examples illustrating this point are evident, e.g., in the Satpura Range (Mahoney et al., 2000) and the Mandla Lobe (Shrivastava et al., 2014), where Shrivastava et al. (2015) presented ^{40}Ar/^{39}Ar dates which, if accurate, indicate much younger ages for lavas with geochemical counterparts (i.e., formational correlatives) in the Western Ghats.

Similarly, magnetostratigraphic analysis of lava flows in the Mandla lobe highlights a discrepancy if these flows are an extension of the Western Ghats lavas (Pathak et al., 2017). The paleomagnetic analysis suggests a normal-reverse-normal polarity sequence for the Mandla flows (albeit the analysis was far from straightforward due to potential tectonic complexities; Pathak et al., 2017). Based on the ages presented in Shrivastava et al. (2015), the authors attribute this polarity pattern to magnetic chrons C29n-C28r-C28n (Pathak et al., 2017), versus the C30n-C29r-C29n sequence observed in the Western Ghats (Chenet et al., 2009). Furthermore, the geochemistry of the Mandla flows is correlative with the Wai subgroup flows which fall within chrons C29r (Poladpur, Ambenali, and base of Mahabaleshwar) and C29n in the Western Ghats (Mahabaleshwar, Panhala, Desur) (Chenet et al., 2009; Jay and Widdowson, 2008). Thus, the observed normal-reverse-normal polarity sequence is not consistent with a correlation of these flows to the Wai subgroup. These observations are interpreted by Kale et al. (2020) to indicate the existence of multiple, widely separated eruptive centers fed by distinct magma bodies. This conclusion in some places is supported by isotopic geochemistry, where units that appear similar to Poladpur lavas have distinctly different Pb-isotopic compositions (Shrivastava et al., 2014). We conclude that the entrenched geochemically defined formation concept should not be used to connote chronostratigraphy, except in a very general sense.

An example where the long distance correlation does work is the Rajahmundry Traps on the Eastern Coast of Indian, some 800 km away from the Western Ghats. Geochemical, ^{40}Ar/^{39}Ar, and paleomagnetic data from the Rajahmundry Traps (Fendley et al., 2020) appear consistent with the chemical stratigraphy of Beane et al. (1986) and Western Ghats geochronology, which would follow from the conclusion of Self et al. (2008b) that the lavas at Rajahmundry flowed overland from vents in the Western Ghats.

With regard to eruption locations, a north-to-south progression of the Deccan volcanism has been inferred for years. This is based on three main lines of evidence: (1) A systematic southward overstepping of geochemically defined formations (Widdowson and Cox,1996); (2) the existence of older lavas and intrusions—presumably feeders for Deccan lavas—in the north (e.g., Basu et al., 1993; Courtillot et al., 2000; Cucciniello et al., 2019; Pande et al., 2017b; Parisio et al., 2016; Schöbel et al., 2014, Vanderkluysen et al., 2011); and (3) the existence of significant stratigraphic extent of normal paleomagnetic polarity below reversed polarity in lavas in the Satpura Range and Malwa Plateau (Schöbel et al., 2014; Eddy et al., 2020), presumed to be chron C30n under C29r. In the Western Ghats, the representation of the C30n chron is only suggested by transitional polarity in the lowermost exposed lavas in the Jawhar formation (Chenet et al., 2009). However, if the young ages (ca. 64 Ma) and C29n-C28r-C28n stratigraphy identified in the Mandla lobe (Shrivastava et al., 2015; Pathak et al., 2017) are correct, this suggests that young volcanism may have also occurred in the north. It should be noted that constraints on the duration of Deccan volcanism are limited by the fact that erosion has removed an unknown amount of the youngest lava pile.

In summary, there is good evidence that volcanism propagated generally from north to south in plate coordinates, consistent with northward motion (Pusok and Stegman, 2020) of the Indian plate during Late Cretaceous–Paleogene over a fixed melting region, i.e., a plume. However, despite this general pattern, it is still unclear specifically how relative motion between the Indian plate and Reunion plume affected the crustal magmatic architecture and eruption vent locations. Based on the spatial distribution of the mapped dikes (potentially feeding the lavas) in the Deccan Traps (Vanderkluysen et al., 2011; Mittal et al., 2021; GSI Bhukosh, 2020) as a proxy for crustal stress field, there is no clear southward progression mirroring this plume motion (Richards et al., 2015; Vanderkluysen et al., 2011). Additionally, the plate motion of the Indian plate over ~800,000 years of the Western Ghats flows (Sprain et al., 2019; Schoene et al., 2019), assuming an end-Cretaceous plate motion of 18 cm/yr (Cande and Stegman, 2011; Pusok and Stegman, 2020), is about ~150 km. We would note this is likely an upper limit since we are using the peak Indian plate velocity around the Cretaceous-Paleogene boundary and this plate velocity is much larger than average modern plate velocities (~5 cm/yr; Young et al., 2019). The ~150 km motion corresponds to approximately the distance between Surat (southern Saurashtra) and Nasik (~150 km NE of Mumbai), much shorter than the distance inferred by the overstepping model of Western Ghats flow emplacement (Widdowson and Cox, 1996; Chenet et al., 2008). Given the large spatial extent (potentially hundreds of km) of the mantle plume head, it is possible that the crustal magmatic system was much more spatially extended and had a different progression rate than the plume-plate motion. Additionally, the presence of upper crustal tectonic features, such as the Narmada-Tapi rift zone, likely played a significant role in the location of crustal dike transport and surface fissures (e.g., see Deccan dike swarm locations, Vanderkluysen et al., 2011; Mittal et al., 2021; GSI Bhukosh, 2020). Work in progress by the authors is expected to clarify the rate of this propagation and to further illuminate the chronology of volcanism in the Malwa-Satpura region and Mandla lobe and its relationship with mantle plume motion. It is also noteworthy that the extraordinarily fast northward rate of absolute motion of the Indian plate peaks, within seafloor magnetic isochron resolution, right at the K-Pg boundary (Cande and Stegman, 2011), which constitutes yet another enigma associated with other K-Pg boundary events.

An important component of Deccan volcanism that cannot currently be constrained by absolute geochronologic techniques is the tempo of Deccan eruption, at the sub-thousand-year resolution. Constraining the tempo of eruptions at this resolution is critical for assessing whether Deccan eruptions played a role in perturbing Late Cretaceous and early Paleogene environments. Many of the climate-modifying volatiles (especially sulfate aerosols) released by the Deccan magmatic system have short atmospheric residence times (decades to centuries) (Schmidt et al., 2016; Self et al., 2014). Thus, to understand if these volatiles have any role in generating short- or long-term effects on the environment, it is critical to understand the pacing of volatile release at similarly high temporal resolution. One method that has been used to constrain eruption frequency in flood basalts at the millennial to centennial timescale is paleomagnetic paleosecular variation analysis. Chenet et al. (2008, 2009) used this method in the Deccan and determined that Deccan eruptions were pulsed and that the total eruptive period in the Deccan is of order 1–7 ka. However, this method is non-unique, and the quasi-cyclic nature of paleo-secular variation may result in spurious correlations. Additionally, this method is non-quantitative and relies on basic assumptions about modern rates of secular variation to assess time. Therefore, new methods must be explored to test the eruptive model of Chenet et al. (2008, 2009) and to further assess the eruptive tempo of the Deccan Traps at this resolution.

MAGMATIC ARCHITECTURE ASSOCIATED WITH THE DECCAN TRAPS

The erupted volumes in individual Deccan eruptive episodes (~10^3–10^4 km^3, e.g., Shandilya et al., 2020; Fendley et al., 2020) are orders of magnitude greater than any modern basaltic volcanism (e.g., Kīlauea 2018 eruption, 0.9–1.4 km^3; Neal et al., 2019).

Additionally, the Western Ghats Deccan stratigraphy comprises more than 50 individual flows based on interflow geochemical variations and weathering horizons indicative of the time hiatuses between eruptions (Beane et al., 1986; Self et al., 2021). Thus, over the ~1 Ma duration of the main phase Deccan Traps eruptions (see above for geochronology discussion), the magmatic system erupted frequently with large volume eruptions.

However, on the scale of a single flow lobe, the Deccan lavas are remarkably similar morphologically to Hawaiian and Icelandic lavas (Self et al., 1998, 2021; Kale et al., 2020). Although the median flow lobe thickness for the Deccan lava lobes is a bit thicker (~10–15 m) than modern Hawaiian and Icelandic eruptions, it is comparable to the thickness of individual flow fields from the largest historical basaltic eruptions (e.g., Laki 1783; Self et al., 2021). It is noteworthy that the Deccan flow lob thickness is very comparable to measurements from other flood basalt provinces such as the Columbia River Basalts and the Siberian Traps (Self et al., 2021). Given the strong similarity in morphology, we conclude that, on average, the eruptions rates for Deccan flows may not have been very different from that of the Laki 1783 eruption (mean eruption rate ~2000–4000 m^3/s, Thordarson and Self, 1993; Guilbaud et al., 2005), but instead just lasted much longer (decades to hundreds of years based on analysis of Columbia River Basalt flows; Self et al., 1998; Vye-Brown et al., 2013b). Physically, this conclusion is not unexpected in the context of basaltic volcanism since there are some modern long-lived basaltic eruptions, e.g., the 35-year-long Pu‘u ‘Ō‘ō eruption in Kīlauea. Fendley et al., (2019) found similar estimates for eruption rates and durations for Deccan lavas using Hg chemostratigraphic analysis wherein sedimentary Hg concentration peaks are used as an eruption proxy. The two seemingly contrasting characteristics of Deccan lava flows (and continental flood basalt flows in general)—large eruptive volumes with eruption rates similar to historical ones—pose a key question: What is the crustal magmatic architecture of flood basalt provinces that produces these large, repeated, individual eruptive events?

The classical model for continental flood basalt eruptions, such as the Deccan, posits the existence of a large magma reservoir(s) spanning hundreds of km laterally and tens of km thick (see discussion in Mittal et al., 2021). In order to explain the lava geochemical characteristics, the erupted magma is hypothesized to undergo storage and fractional crystallization at a range of depths with a primary reservoir at Moho depth (Cox, 1980; Karlstrom and Richards, 2011; Black and Manga, 2017; Ernst et al., 2019) and some similarly large reservoirs in the middle-upper crust (e.g., multiple-km-thick upper-to-mid crustal sills: as in the 2060 Ma Bushveld and 2710 Ma Stillwater complexes; Ernst et al., 2019; Cashman et al., 2017; Marsh 2004). However, this type of magmatic system is inconsistent with the Deccan eruptive constraints, especially the lack of any multi–100 ka duration eruptive hiatuses between every eruption sequence, contrary to model predictions (Black and Manga, 2017; Mittal et al., 2021). There is clear evidence for some hiatuses between individual lava flows as indicated by the presence of red bole horizons (Chenet et al., 2008; Duraiswami et al., 2020). However, each red-bole cannot represent multiple 10s of ka of hiatus since many 10s of red boles exist throughout the stratigraphy (especially in the Wai-subgroup flows). Most likely, each red bole represents an eruption hiatus of a few ka given age constraints (Sprain et al., 2019; Schoene et al., 2019). Furthermore, Mittal and Richards (2021) used thermo-mechanical magma chamber models to show that large magma chambers erupt too quickly, with flood basalt eruptions lasting days to months rather than the observed timescale of decades to centuries.

Given these challenges with the classical model, Mittal and Richards (2021) proposed that individual Deccan eruptions were fed from a multiply connected network of smaller (~10^2–$10^{3.5}$ km^3) magma reservoirs present throughout the crust. The large and spatially extensive mantle melt flux (from the underlying plume "head" melting) enables the establishment of this trans-crustal Deccan magmatic system. Within this conceptual model framework, each eruption is not sourced from the same set of magma reservoirs. Instead, an eruption is initiated by the over-pressurization of a single magma body (likely due to magma recharge) and during the eruption, some secondary magma reservoirs/magma mushes can stochastically connect to this magma chamber depending upon the crustal stress state and thermo-poro-mechanical interactions between reservoirs (e.g., Mittal and Richards, 2019). The overall crustal structure of the magmatic systems is illustrated in Figure 4. The relative homogeneity of lavas erupted in the Wai subgroup, and their relatively uncontaminated nature, suggests that the Deccan magmatic system for these lavas was different from that feeding the previous eruptions. Either the disparate magma chambers from the pre-Wai time period underwent some degree of aggregation around the time of the Lonavala-Wai transition to be more homogenized, or the magma bodies were more geochemically buffered due to increased chemical plating of chamber walls by primitive basalt (Heinonen et al., 2019; Mittal and Richards, 2021). It is also important to note that the spatial location of the eruptive fissures and the corresponding magmatic system for Western Ghats lavas, within this model, changed over time with the initial flows likely fed by the Narmada-Tapi dike swarm and subsequent ones fed by the Coastal and Central Deccan dike swarm (also called the Nasik-Pune swarm) (Vanderkluysen et al., 2011; Mittal et al., 2021).

Our proposed model for the Deccan magmatic architecture (and for continental flood basalts in general) naturally explains the lack of large upper-crustal intrusive bodies in various geophysical data sets from the Deccan Traps (Mittal et al., 2021) and significant major and minor elements as well as isotopic changes between individual eruptive episodes. Presently, the main observational constraints for the model, especially eruptive tempo constraints, are based on work in the Western Ghats region (geochronology and paleomagnetism). Thus, we need additional high-precision geochronology and paleomagnetic data sets to test the validity of this magmatic architecture model for all the Deccan sub-provinces and to constrain the temporal evolution of

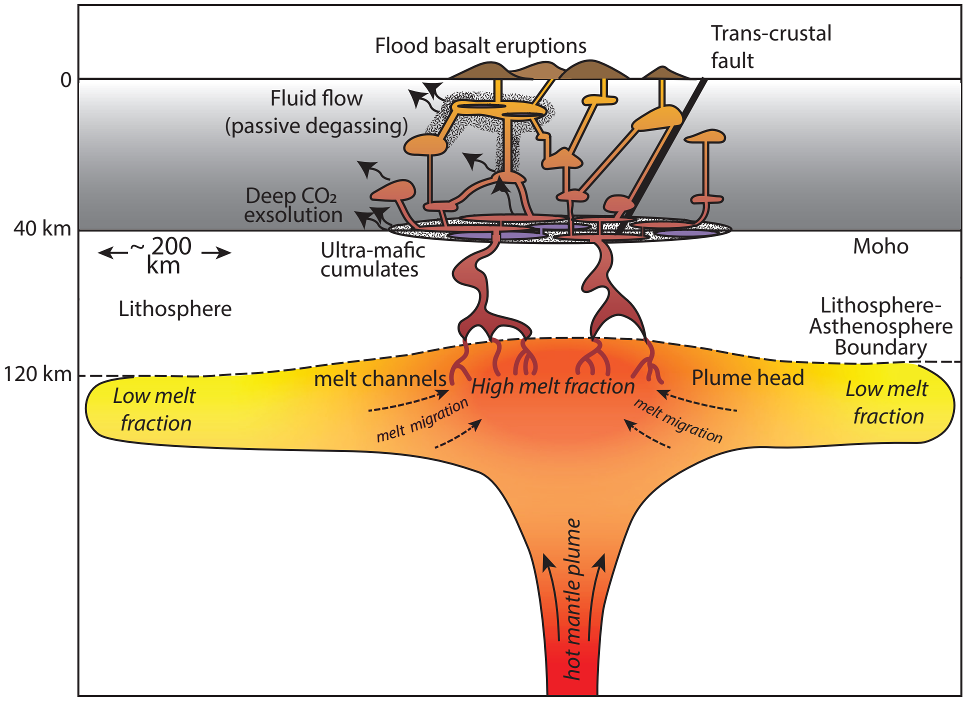

Figure 4. Cross-sectional diagram of the Deccan Traps magmatic system. The primary melt generation occurs from melting in the mantle plume head beneath the Indian subcontinent with subsequent transport through lithospheric and crustal magma reservoirs. The crustal magmatic system is envisioned as a trans-crustal magma mush architecture with numerous interconnected small to medium (~few hundred km^3) sized magma bodies. The darker colors in the plume head signify the degree of partial melting. In the crustal magmatic system, the shaded crustal grayscale colors represent the background geotherm (based on Richards et al., 2015; Mittal and Richards, 2021).

the magmatic system(s). Additionally, the direct incorporation of geochemistry in physical models for magma reservoir evolution will allow us to utilize thousands of geochemical analyses from the Deccan Traps for understanding this flood basalt province. Although there is a broad mixing pattern between different geochemical formations in the Western Ghats, especially with respect to Pb-Hf-Nd isotopic components, future work is required to test whether the proposed magmatic model can quantitatively explain the geochemical variations between formations, and within individual formations, and also incorporate the constraints on the spatial distribution of potential feeder dikes (see Mittal et al., 2021, for more discussion). Finally, it would be useful to have more observations of geochemical and isotopic variations along physically mapped flows to both assess the validity of detailed chemostratigraphic correlations and also the nature of the magmatic architecture (Vye-Brown et al., 2013a; Mittal et al., 2021). This type of sampling from historical long-lived basaltic eruptions (e.g., the 35-year-long Puʻu ʻŌʻō eruption in Kīlauea) have shown that there can be significant geochemical and isotopic changes during an ongoing eruption (Greene et al., 2013).

Our new model of continental flood basalt magmatic architecture likely has significant implications for the impact triggering hypothesis for the most voluminous Deccan eruptions (Richards et al., 2015), since the stability of a multiply connected magmatic system to seismic perturbations will be very different compared to a few large magma bodies. We posit that our proposed magmatic architecture is likely sensitive to seismic perturbations since eruptions are triggered mostly from magma recharge and seismic deformation can naturally lead to a significant change in permeability and melt transport (Richards et al., 2015; Sparks et al., 2019). In contrast, the previously hypothesized flood basalt architecture of a few large magma reservoirs (Black and Manga, 2017) has a low sensitivity to mantle flux variations (due to seismic perturbations) since a significant amount of time is still needed to accumulate buoyancy by bubbles and teleseismic waves can lead to enhanced crustal permeability leading to degassing without eruptions (Seropian et al., 2021).

OFFSHORE DECCAN-RELATED VOLCANISM (*continued below*)

In addition to the large subaerial extent, the Deccan Traps have a correspondingly large offshore volcanic component. Figure 1A shows the main presently subaerial provinces of the Deccan flood basalts, while Figure 1B illustrates the regional tectonic context offshore western India, including the beginnings of the post-Deccan Reunion hotspot track (Lakshadweep-Chagos Ridge) leading SSE-ward into the Indian Ocean Basin (using data from Mahoney et al., 2002; Sheth, 2005; Torsvik et al., 2013). Figures 5–7 show many details of the extensive Deccan-related volcanic sub-provinces that lie between the subaerial Deccan Traps formations and the Arabian Sea (adapted from Bhattacharya and Yatheesh, 2015; Corfield et al., 2010; Rao et al., 2018; Kumar and Chaubey, 2019; Todal and Edholm 1998). The larger of these provinces include the Saurashtra Volcanic Province and the Saurashtra and Kutchh Basins in the northeast; the Laxmi Ridge and the Laxmi and Mumbai basins at center; and the Kerala-Konkan Basin to the south (Figs. 5 and 6A). Additionally, the Cambay rift basin is a sediment-filled onshore basin with >2500-m-thick Deccan volcanics (presently the top

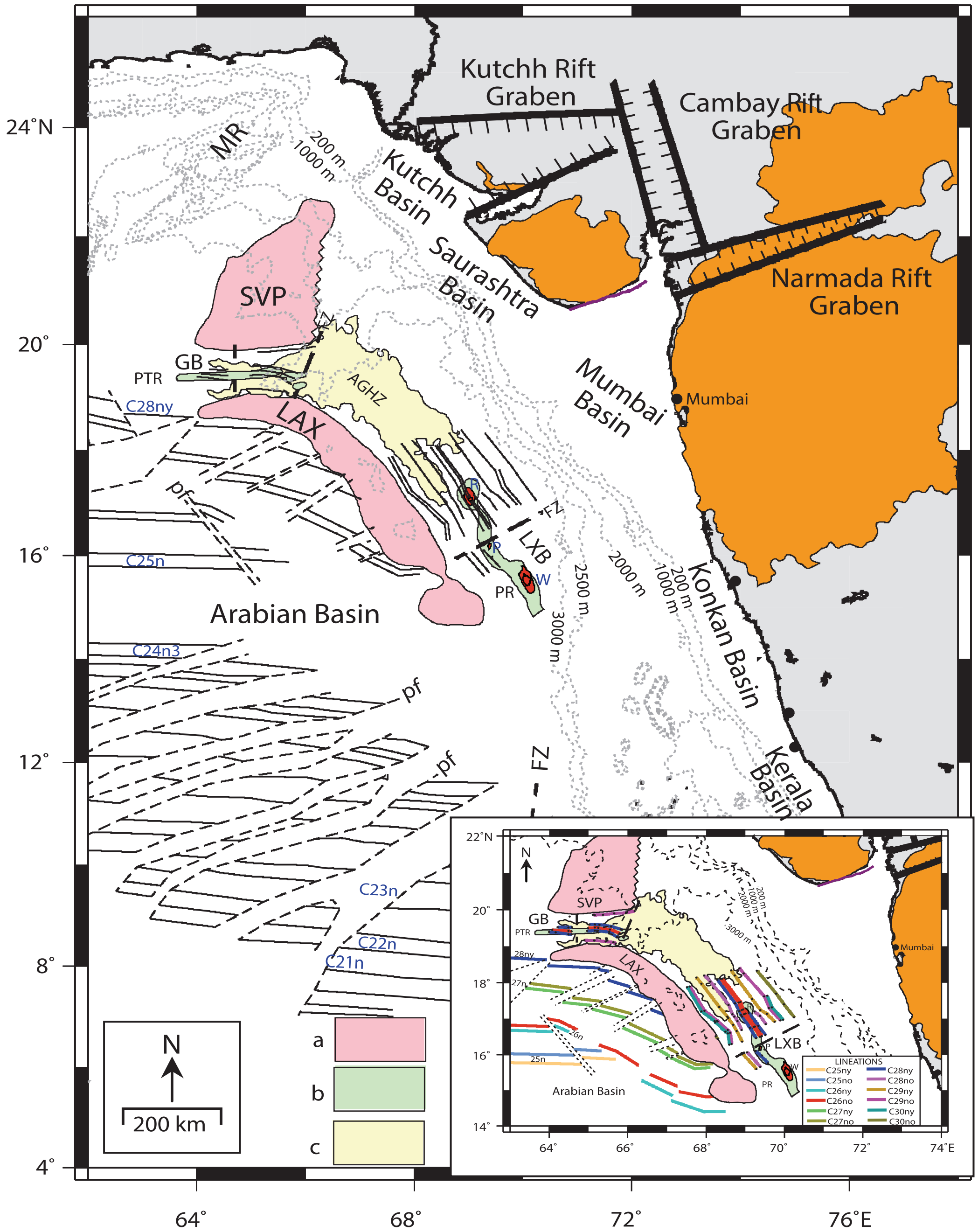

Figure 5. Simplified bathymetric map of offshore regions adjoining the western continental margin of India. The mapped seafloor spreading magnetic lineations are represented by solid black lines in the Laxmi Basin (after Bhattacharya et al., 1994; Yatheesh, 2007), in the Gop Basin (after Yatheesh et al., 2009), and in the Arabian Basin (after Chaubey et al., 2002). Various fracture zones (FZ) and pseudofaults (pf) are represented by the thin dotted lines. The on-land Deccan Traps are shown by the orange regions along with main tectonic features. The primary offshore tectonic components are (a) continental crust fragments (SVP—Saurashtra Volcanic Province, LAX—Laxmi Ridge); (b) axial basement high zone potentially corresponding with the extinct spreading axis of the Gop Basin (GB; PTR—Palitana Ridge) and the Laxmi Basin (LXB; PR—Pannikar Ridge); (c) regions of anomalous gravity high zone (AGHZ) potentially indicative of seafloor spreading regions. The seamounts in the Laxmi Basin are shown as red regions: R—Raman seamount, P—Panikkar seamount, and W—Wadia Guyot. Figure modified from Bhattacharya and Yatheesh (2015) with original data compiled from Biswas (1982); Bhattacharya et al. (1994); Chaubey et al. (2002); Srinivas (2004); Yatheesh (2007); Calvès et al. (2011); Yatheesh et al. (2013); Directorate General of Hydrocarbons (DGH) (2014); Ishwar-Kumar et al. (2013); and Ratheesh-Kumar et al. (2015). Inset shows the main tectonic features in offshore regions and the magnetic lineations—colored solid lines (modified from Bhattacharya and Yatheesh, 2015). In the figure, we use the C30n-C25r-C30n sequence assignment for Laxmi Basin magnetic lineations as preferred by Bhattacharya and Yatheesh (2015), with typical spreading rates of 2 cm/yr for the majority of the time. The large seamounts in Laxmi Basin all overlay oceanic crust equal to/younger than chron C28n.

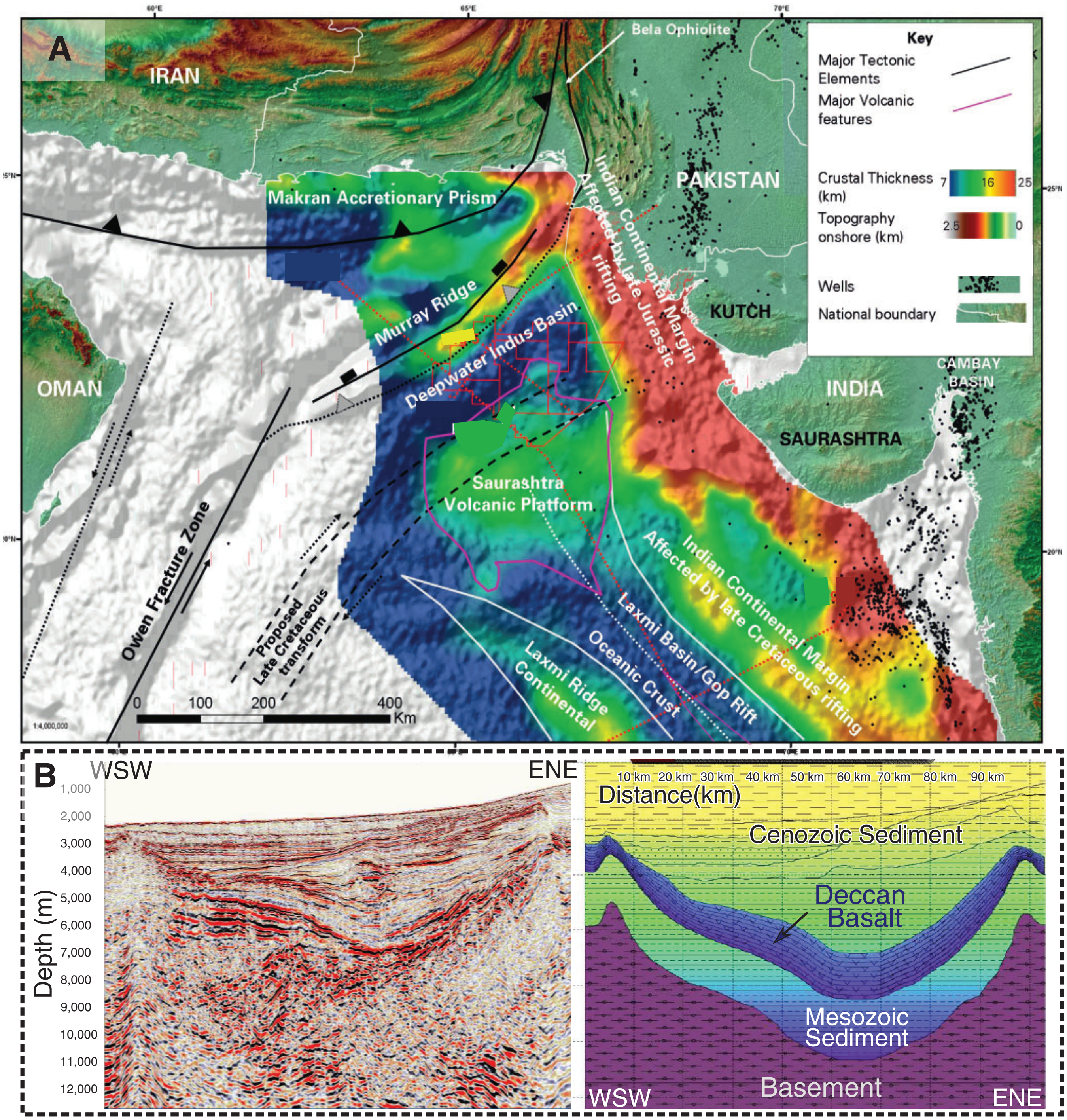

Figure 6. (A) Overview map showing the primary tectonic features of the Western Indian Continental Margin and the estimated offshore crustal thickness (using marine gravity anomaly, Corfield et al., 2010). The location of the multiple 2D seismic reflection lines and regional data is also shown on the figure. At these locations, the crustal thickness estimates have been independently validated (modified from Corfield et al., 2010). (B) Left—Seismic section synthesized by Kirchhoff Pre-stack Depth and Time Migration. This is a modern Kirchhoff method for obtaining maximal information from seismic reflection sections, especially when reflectors are of most interest. Basalt is represented by distinct bright and bold reflections. Sub-basalt dimmer amplitudes represent Mesozoic sediments. Right—A regional synthetic view of the Kerala-Konkan Basin, based on the interpretation of seismic and density data. (Figure courtesy of Dr. Roberto Fainstein, Schlumberger Limited.)

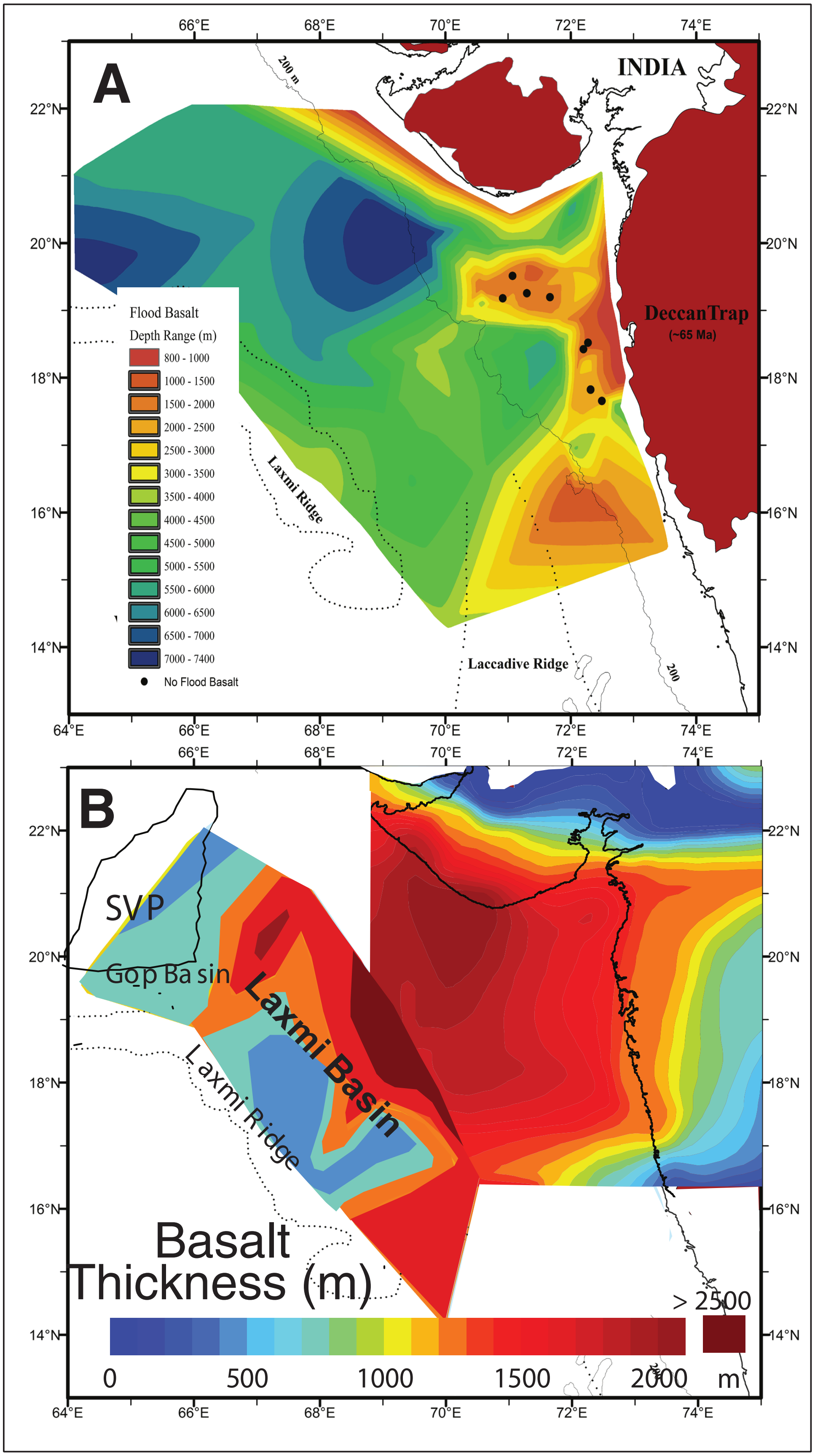

Figure 7. (A) Map showing depth of first occurrence of Deccan Traps flood basalt in the region offshore the Western Indian continental margin. The drill wells which reached the granitic basement without encountering any Deccan lavas are shown by black circles (typically in the isolated high features in Bombay High). This map is compiled from the following data sets: drill wells in western offshore (Mathur and Nair, 1993) and P-wave velocity based estimates using refraction station data (Rao, 1967, 1970; Naini and Talwani, 1983, modified from Kumar and Chaubey, 2019). (B) Deccan Trap lava flow thickness based on deep seismic sounding data (Kaila et al., 1990) in the onshore regions and information from offshore exploratory drill wells (Mathur and Nair, 1993; Dessai and Bertrand, 1995) and refraction station data (modified from Rao et al., 2018; Kumar and Chaubey, 2019).

Deccan surface is more than 2200 m below sea level, Fig. 1A) (Misra et al., 2019). It is important to bear in mind that much of the relatively shallow near-shore volcanics, as well as some of the seamounts, were actually erupted subaerially, and perhaps closely related both in space and time to the onshore Western Ghats and Saurashtra provinces (e.g., seamounts of a few thousand km^3 on the Saurashtra Platform and Laxmi Basin; Carmichael et al. 2009, Calvès, et al. 2011). In contrast, the lavas in the Laxmi Basin (and potentially other similar oceanic basins; Fig. 6A) were likely produced by deep water (greater than a few km) eruptions as evidenced by the absence of vesicles in International Ocean Discovery Program (IODP) Site U1457 basalts and the deep water distal sediment characteristics of the overlying mudstones (Pandey et al., 2015). However, additional work is required to constrain the water depth at which the lava erupted, especially using petrographic methods (e.g., vesicle fraction, shape, and size) since there can be a significant hiatus between the eruption and sediment deposition.

Because of potentially large petroleum reserves offshore western India, a variety of exploration geophysical data (seismics, magnetics, gravity), along with some public-domain borehole data, are available from these offshore regions. These data show extensive basalt formations of approximately Deccan age (based on biostratigraphy), which are often underlain by Mesozoic sedimentary rocks that include sub-basalt carbonates and sands (passive continental margin), and overlain by Paleogene sedimentary rocks that show evidence of marine transgressions and regressions (likely indicative of the post-Deccan collision of India and Asia) (Fainstein et al., 2019; Carmichael et al., 2009; Corfield et al., 2010) (e.g., Fig. 6B in the Kerala-Konkan Basin). Some of these offshore rift basins along continental India were formed by pre-Deccan rifting during the Cretaceous associated with the break-up of the Madagascar/Seychelles/Indo-Pakistan plate associated with the Marion Hotspot (Yatheesh, 2020). These include the Indus-Kutchh Basin in the north (Carmichael et al., 2009) and potentially Kerala-Konkan Basin in the south (Bhattacharya and Yatheesh, 2015; Yatheesh, 2020). In contrast, the formation of the Mumbai Basin, Laxmi Basin, and Gop Basin were closely associated temporally with Deccan Volcanism (Bhattacharya and Yatheesh, 2015). Some recent studies have suggested that some of the Southern Indian basins—e.g., the Kerala-Konkan Basin and the Mannar Basin near India Sri-Lanka, had an additional phase of K-Pg time period Deccan volcanism (Premarathne and Ranaweera, 2021). If this result is confirmed by future high-precision geochronology, it would significantly extend the spatial extent and volume of Deccan offshore volcanism.

Seismically derived cross sections indicate the presence of seaward-dipping reflectors within the basinal basalts, consistent with extension associated with rifting of the Seychelles and Laxmi Ridge from the Indian subcontinent at approximately Deccan time (Bhattacharya and Yatheesh, 2015). These structures are similar to structures observed, for example, in the North Atlantic Tertiary province at the (plume-head) initiation of the Iceland hotspot and rifting associated between Greenland and Europe (White et al., 1987; White and McKenzie, 1989). A review of the emplacement and tectonics associated with these vast near-Deccan-age volcanics offshore western India is beyond the scope of this paper (See Carmichael et al., 2009; Calvès et al., 2011, Bhattacharya and Yatheesh, 2015; Yatheesh, 2020). However, a rough estimate of the volume of these lavas as revealed mainly through seismic stratigraphy (and associated intrusions within the Mesozoic sediments) is ~1.2–1.6 million km^3, or of order 1–3 times that of the exposed Western Ghats province onshore (Fainstein et al., 2019, Calvès et al., 2011). The large offshore Deccan volumes are illustrated by Figure 7B which shows estimates of Deccan basalt thickness using deep seismic sounding data (Kaila et al., 1990) in the onshore regions, information from offshore exploratory drill wells (Mathur and Nair, 1993; Dessai and Bertrand, 1995), and refraction station data (using representative P-wave velocity, modified from Rao et al. [2018] and Kumar and Chaubey [2019]). Even these estimates represent a lower bound, given that seismic exploration profiles remain limited in areal coverage (focused on potential petroleum-producing areas) of the vast offshore region of interest with variable resolution.

The challenge of accessing the offshore Deccan Traps is illustrated by Figure 7A, where the depth of the top of the flood basalt is plotted. Especially in the oceanic offshore components (e.g., Kutch-Saurashtra Basins and Laxmi Basin), it is necessary to drill through very thick Indus delta sediments before reaching the basalt. Interestingly, some drill wells in the Mumbai Basin region (typically Bombay High) reached the granitic basement without encountering any Deccan lavas (black circles in Fig. 7A) illustrating the presence of significant local topography during lava flow emplacement (Kumar and Chaubey, 2019). However, it is presently unknown to what degree the offshore basalts are temporally correlated with the onshore Deccan basalts, as no radioisotopic dating has, to our knowledge, been published in the public domain, and relatively few paleontological constraints exist from boreholes that penetrate to or through the basalts. Multiple magnetic lineations have been reported from the Laxmi and Gop basins suggesting that these were paleo spreading centers formed due to Reunion plume associated continental rifting. Although there are multiple interpretations of what magnetic isochrons the magnetic lineations correspond to, a highly likely interpretation is the C30n-C29r-C30n sequence assignment for Laxmi Basin (see Bhattacharya and Yatheesh, 2015, with typical spreading rates of 2 cm/yr for the majority of the time; Fig. 5). Thus, the offshore component may have been active for a long duration across the K-Pg boundary. However, this conclusion needs to be confirmed by radioisotopic ages.

The lack of precise age information from the offshore Deccan-related basalts is currently one of the largest gaps in our ability to understand a possible relationship between Deccan flood volcanism and the K-Pg mass extinction. In turn, this paucity of constraints, if not addressed, will continue to pose a source of uncertainty in trying to correlate Deccan-related outgassing with climate events before, during, and after the K-Pg extinction. An important caveat, of course, is that we do not know what gaseous species from flood volcanism cause the main climate/extinction effects. If CO_2 is the main culprit (Bond and Wignall, 2014), then submarine volcanic outgassing will be just as important as subaerial eruptions. On the other hand, if the launching of other species such as SO_2, Cl, and F into the atmosphere is the main cause of mass extinction (Self et al., 2008; Sobolev et al., 2011; Black et al., 2012, 2014a, 2014b; Callegaro et al., 2014; Schmidt et al., 2016), then submarine volcanism may not be as relevant, since these non-CO_2 species likely must be transported high into the atmosphere (typically stratosphere) to cause severe climate and ecosystem perturbations. This transport is much harder to do if the eruptions are underwater compared to when they are on land due to the rapid cooling of the plume and the dissolution of SO_2 by the seawater. The notion that non-CO_2 species are critical for mass extinctions is potentially supported by the lack of an extinction event associated with the enormous ~50 million km^3 magmatic event that created the Ontong Java at 120 Ma, which likely did have a significant environmental impact but no major extinctions (e.g., Ocean anoxia events; see Clapham and Renne, 2019, and references therein). In the Deccan case, the relationship between volcanic outgassing, environmental change, and extinction is of course also predicated upon understanding what percentage of offshore lavas may have erupted subaerially even if they are presently submarine.

POSSIBLE INFLUENCE OF THE CHICXULUB IMPACT UPON DECCAN VOLCANISM

Richards et al. (2015) suggested the possibility that Deccan volcanism might have been affected by strong ground motion from the Chicxulub impact (e.g., the impact triggering hypothesis), which we emphasize is quite different from suggesting that the impact "caused" the volcanism (mantle partial melting) (e.g., Rampino and Stothers, 1988; Boslough et al., 1996). Chicxulub clearly did not cause the melting that led to Deccan Traps volcanism, as Deccan-related magmatism began well before the Chicxulub impact (Venkatasan et al., 1993; Renne et al., 2013; Sprain et al., 2018; Schoene et al., 2014, 2019). Moreover, the region of the Deccan Traps was not, as suggested by others long ago, located at the antipode of the impact where seismic waves might have been focused, and even if it had been, the amount of shear dissipation energy would have been inadequate to pervasively melt the mantle (Ivanov and Melosh, 2003). On the other hand, the historical record shows clearly that eruptions from existing volcanoes can be triggered by earthquakes (Brodsky et al., 1998; Manga and Brodsky, 2006; Sawi and Manga, 2018; Seropian et al., 2021), though the magnitude of the forcing as well as the magmatic system for the Chicxulub-Deccan case are very different.

The impact triggering hypothesis was based upon observations suggesting that a significant change in Western Ghats volcanism occurred at the onset of Wai-subgroup (Poladpur, Ambenali, Mahabaleshwar Formations; see Fig. 3)—lava flows became much more aerially extensive and became more simple and sheet-like in character, with an increase in flow lobe thickness (Jay and Widdowson, 2008; Self et al., 2021). At the time of our 2015 paper (Richards et al., 2015), it therefore appeared that there might have been a significant increase in the overall lava eruption rate within the Wai sub-group. (Now, we see a possible 50% increase in eruptions rate which is not statistically significant.) These changes were accompanied by a shift in the isotope and trace element geochemistry of the lava flows toward more mantle-like (less crustally contaminated) signatures (Beane et al., 1986; Vanderkluysen et al., 2011). Likewise, major and minor element chemistry signaled a shift toward magmas derived more directly from deep-mantle melting, with less crustal interaction (Renne et al., 2015; Richards et al., 2015). Finally, the mapped dikes feeding the Wai sub-group flows were of relatively random orientation, perhaps an effect of increased magma overpressure in the crust, compared with dikes feeding flows in the underlying Lonavala and overlying Kalsubai sub-groups, whose orientations were more aligned with regional tectonic stresses (Vanderkluysen et al., 2011; Mittal et al., 2021, find a similar conclusion with a much larger and complete Deccan dike data set). Furthermore, the onset of Wai sub-group magmatism appeared to occur, within existing geochronological and paleomagnetic constraints, around Chicxulub/K-Pg time (e.g., Duncan and Pyle, 1988; Chenet et al., 2007, 2008, 2009).

This was, admittedly, not an easy hypothesis to test, but the most immediately obvious test relied upon improved geochronology. When we made the impact triggering hypothesis, the onset of Wai sub-group volcanism (lowermost Poladpur formation) was only known geochronologically to within ~500,000 years precision (Courtillot et al., 1986, 1988a, 1988b; Pande, 2002; see also summary figure 1 of Richards et al., 2015). Since "correlation is not causation," as the saying goes, such a test could, sensu strictu, only be negative in nature—that is, could it be shown that the Lonavala-Wai sub-group transition (Bushe-Poladpur formation transition) did not correspond to Chicxulub/K-Pg time?

As discussed above, results from recent $^{40}Ar/^{30}Ar$ dating show that the lowermost Poladpur formation is very close to K-Pg age, and based on the Bayesian models presented in Sprain et al. (2019) and Schoene et al. (2021), the most likely position of the K-Pg boundary based on the $^{40}Ar/^{30}Ar$ data set is near the Bushe/Poladpur boundary. In other words, the onset of Wai sub-group volcanism is not currently distinguishable in time from Chicxulub/K-Pg time (Sprain et al., 2019). However, it is important to note that the most likely position for the K-Pg from the age model derived from the U-Pb data set is near the top of Poladpur which does not support the impact triggering hypothesis (Schoene et al., 2019), Despite this, it should not a priori be assumed based on precision that the placement of the K-Pg from the U-Pb data set is more accurate than that from the $^{40}Ar/^{30}Ar$ data. As outlined above, and elaborated further in Schoene et al. (2021), Renne (2020), and Sprain (2020), this topic is complex and discrepancies in the placement of the K-Pg boundary between the techniques are still being assessed. Although this is not "confirmation" of the hypothesis outlined above, the new geochronological data (with the uncertainties as discussed above) does not contradict the hypothesis. It was by no means obvious when the hypothesis was made that this prediction would survive initial geochronological testing, so in this sense, the hypothesis remains intact, if not thoroughly tested. (We do note, however, as discussed above, that the case for a markedly increased eruption rate with Wai sub-group volcanism is unclear.)

A more direct "positive" test of the idea that Deccan volcanism could have been influenced by the Chicxulub impact was recently suggested via a study finding an abrupt increase in crustal production at fast spreading ridges at K-Pg time (Byrnes and Karlstrom, 2018). These authors found concentrated free-air gravity and topographic anomalies at fast ridges, indicative of excess volumes of magmatism in the range of 10^5–10^6 km^3, constrained by seafloor magnetics to have corresponded roughly in time to the K-Pg boundary. This result is potentially important, because mid-ocean ridge magmatism is driven by mantle melting, and therefore relevant to the melting of a mantle plume head beneath the lithosphere, in contrast to volcanism from shallow crustal magma chambers (see discussion below). Although this result has not been corroborated by other independent studies, we note that excitation of other mantle magmatic systems by the Chicxulub impact is a direct prediction of the impact triggering hypothesis, so that the Byrnes and Karlstrom (2018) results, if they hold up, would qualify as direct supporting evidence, and other such evidence might be expected to exist in the geological record.

Beyond the aforementioned data, the impact-triggering hypothesis has yet to find strong support from considerations of how, physically, the nature of Deccan flood volcanism might have been affected by the Chicxulub impact. Most of the literature on triggering of volcanic eruptions by earthquakes focuses upon mechanisms that apply mainly in the shallow crust and to individual volcanic edifices (noticed as early as per Darwin, 1840), e.g., bubble nucleation/magma chamber overpressure; magma chamber resonance, sloshing, or roof collapse; hydrothermal system activity; near-field static stress changes, etc. (Watt et al., 2009; Bonali et al., 2013; see also Seropian et al., 2021, for a recent review). On the other hand, strong seismic motions could transiently increase the effective permeability of a partially molten sub-lithospheric mantle via several processes. Richards et al. (2015) attempted some generic modeling of the timescale over which such a permeability change might occur and dissipate, concluding that timescales of order 10s to 100s of thousand years were plausible, the latter corresponding to the approximate duration of the aerially vast and immediately post K-Pg time Poladpur, Ambenali, and Mahabaleshwar lava formations within the Wai sub-group (Renne et al., 2015). However, this remains a rather ill-defined realm of physics that has little relevant experimental basis at sub-lithospheric pressures, and thus it remains largely a subject of speculation.

On the other hand, the case for very strong ground motion from the Chicxulub impact has strengthened since our 2015 paper. Based on our work since that study, we now believe that the moment magnitude of the earthquake due to the Chicxulub impact was of order M_w ~11 (10.5–11.5), or as much as two magnitude levels above those of the largest historical earthquakes from subduction zones. The most recent evidence for this comes from a remarkable and unlikely source—the K-Pg seiche deposit recently discovered in southwestern North Dakota ("Tanis"), on the boundary of the late-Cretaceous Western Interior Seaway atop the famous dinosaur-fossil–bearing Hell Creek Formation (DePalma et al., 2019). The associated surge was a minimum of 10 m in amplitude at a teleseismic distance of more than 3000 km from Chicxulub and is not a direct tsunami deposit associated with the impact. To put this amplitude in context, we can compare the observed amplitudes of seismic seiches recorded at teleseismic distances from the great 1964 M_w ~9.2 Alaska earthquake. The largest seiche amplitudes recorded in North America did not exceed ~1.2 m in terms of near-shore run-up (McGarr and Vorhis, 1968). Scaling to the >10 m amplitude surge observed at Tanis, Chicxulub must have caused at least a M_w ~11 earthquake (DePalma et al., 2019), consistent with previous conclusions reached on the basis of teleseismically generated slope collapse features around the Atlantic basin that also occurred at Chicxulub/K-Pg time (Bralower et al., 1998; Day and Maslin, 2005). The Tanis surge deposit might also have been caused by a "local" earthquake or landslide triggered by seismic strong ground motion from the impact, and this is a subject under active study.

To put this latter conclusion into perspective, long-period ground motions due to Chicxulub were likely of order tens of meters (as scaled from synthetic seismograms by Meschede et al., 2011) and it is not difficult to imagine that the deep magmatic plumbing of the Deccan plume head, pancaked beneath the Indian continental lithosphere, might have been affected (e.g., a transient permeability increase) in ways that go far beyond our experience with historical seismic/volcanic coupling events.

POSSIBLE CLIMATIC IMPACTS OF DECCAN VOLCANISM

Part and parcel of the discussion related to Deccan's role in the K-Pg mass extinction and recovery interval is the underlying assumption that the Deccan Traps perturbed global climate, and that this global climate perturbation negatively affected life. Observations from oxygen isotope records, leaf margin analysis, and clumped isotope paleothermometry (e.g., Barnet et al., 2018; Hull et al., 2020; Wilf et al., 2003; Tobin et al., 2014) show evidence for a global warming event (Late Maastrichtian Warming Event; LMWE), followed by a global cooling event, that began in the Late Cretaceous and ended at the K-Pg boundary. The onset of this climatic event coincides in general with the onset of the main phase Deccan volcanism recorded in the Western Ghats, around the C30n/C29r reversal, and further appears coincident with records of increasing ecological stress in mammal and amphibian populations (Sprain et al., 2018; Figs. 3 and 8). This coincidence has led to the hypothesis that Deccan may have weakened some Late Cretaceous ecosystems making them more susceptible to the effects of the Chicxulub impact (Arens et al., 2014). Additionally, it is observed that both terrestrial and marine fauna had long recovery intervals (~1 Ma) following the extinction event, suggesting that recovery may have been influenced by the continual eruption of the Deccan Traps after the mass extinction (Alvarez et al., 2019; Lyson et al., 2019).

However, we can now observe based on recent high-precision geochronology (Renne et al., 2015; Sprain et al., 2019; Schoene et al., 2015, 2019) that that Late Cretaceous climate change (~3–4 °C warming followed by cooling; Fig. 8) was only associated with the eruption of 25%–50% of the Deccan volume recorded in the Western Ghats (depending on lower or upper Poladpur K-Pg placement). In contrast, post–K-Pg, when 50%–75% of the Western Ghats volume was emplaced, a much smaller global climate perturbation is recorded (besides short-term variations attributed to the Chicxulub impact e.g., immediate months to millennial scale cooling interval of 2–4 °C (Vellekoop et al., 2014) followed by a possible short ~100 ka warming period (~5 °C) (MacLeod et al., 2018)). Specifically, there is ~2 °C gradual global warming post–K-Pg through the end of C29r (Barnet et al., 2018; Fig. 8) which is consistent with the magnitude expected from CO_2 emissions associated with the Wai subgroup flows (Hull et al., 2020). These observations of warming events pre– and post–K-Pg boundary, as well as the geochronologic constraints, are in contrast to previously held assumptions, which stated that the amount of climate-modifying volatiles released should directly correspond to lava volume. This conclusion is independent of whichever geochronologic method is used for dating Western Ghat Deccan flows (Sprain et al., 2019; Schoene et al., 2019).

One potential explanation for this mismatch is that the Western Ghats eruption chronology is not representative of the entire picture of Deccan eruptive history. As discussed earlier, we lack clear constraints on the timing of the emplacement of offshore Deccan lavas. It remains possible that some offshore lavas could have been emplaced around the time of the Kalsubai and Lonavala subgroups, contributing to the observed Late Cretaceous climate change (especially the LMWE). It is further possible that differences in eruptive tempo between pre–K-Pg and post–K-Pg lavas could lead to different climate responses (the stronger pre–K-Pg cooling despite large Wai eruption post boundary). In this scenario, pre–K-Pg eruptions could have had short recurrence times (order 100 years), allowing for the buildup of climate-modifying volatiles (particularly SO_2) in the atmosphere, whereas post–K-Pg

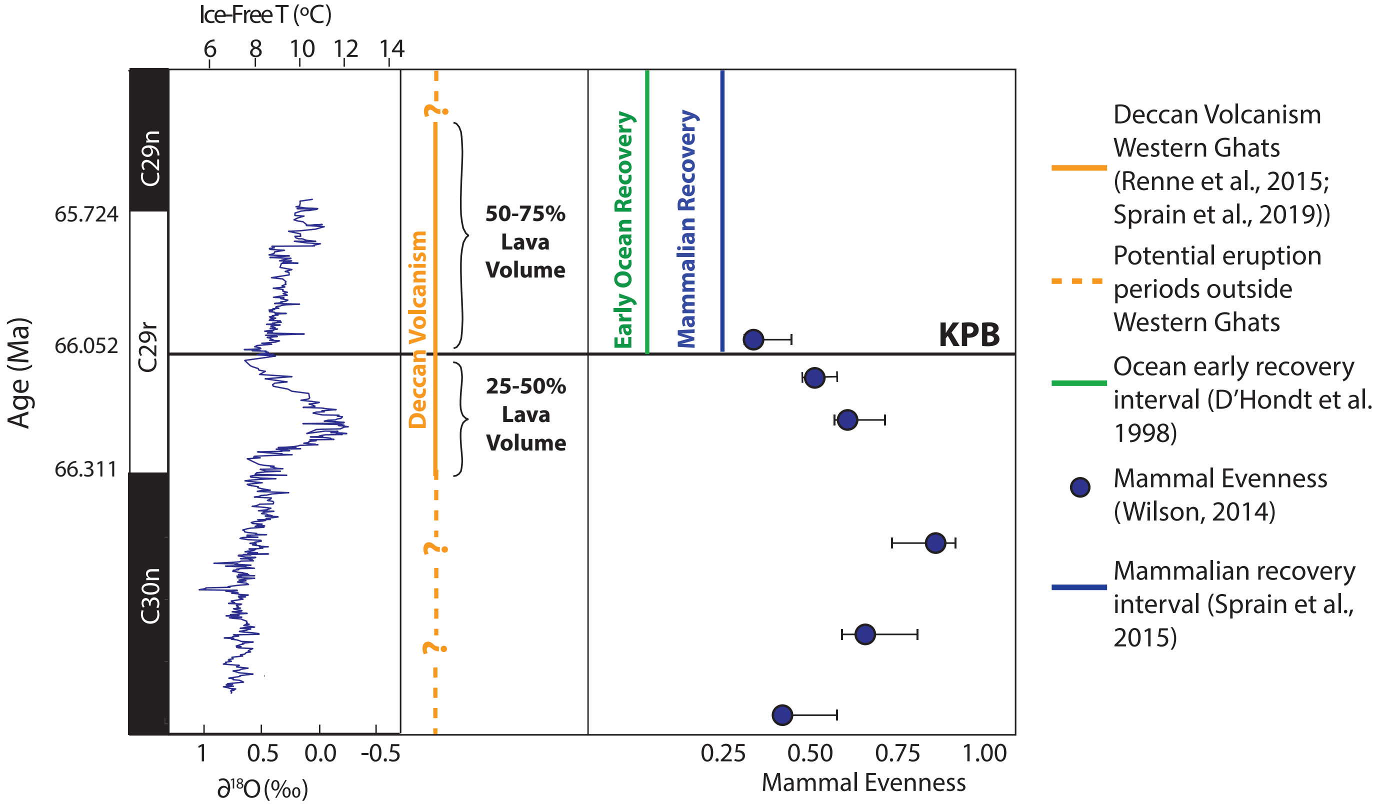

Figure 8. Circum–K-Pg boundary environmental changes. Figure plots different environmental and ecological changes along with the timing of Deccan volcanism around C29r. Temperature and mammal evenness, which is a measure of ecological stress with smaller numbers indicating higher stress (mammal richness does not significantly change until the last 10 m of the Hell Creek Formation, where there is a loss of 75% of all species) are from Barnet et al. (2018) and Wilson (2014), respectively; mammalian recovery is after Sprain et al. (2015); Deccan volcanism is after Sprain et al. (2019); and ocean recovery interval is after D'Hondt et al. (1998). Figure is after Tobin et al. (2014) and Sprain et al. (2018). Error bars on mammal evenness represent 95% confidence intervals (see Wilson, 2014, for more details).

eruptions could have long eruptive hiatuses, allowing more time for volatiles to be removed from the atmosphere before the next eruption. Additionally, the pre–K-Pg and post–K-Pg lava flows may have different volatile content or different degassing rates due to different levels of crustal contamination and magmatic storage (Beane et al., 1986; Hernandez Nava et al., 2021). Finally, Hull et al. (2020) suggest that observed smaller climate perturbations post–K-Pg could simply be due to the large carbon cycle perturbation associated with the mass extinction event and buffering by a strongly perturbed post–K-Pg ocean carbon reservoir.

However, none of these potential explanations (potentially barring the offshore component) really help explain the LMWE warming very well since the observed warming requires eruption of ~1 million km^3 of Deccan basalt over ~150 k.y. (Hull et al., 2020), comparable to the voluminous Wai subgroup eruptions but at a factor of 2–3 faster eruption rates. Furthermore, if the eruptions occur too quickly, the volcanic SO_2 will lead to cooling contrary to observations (or requiring even larger erupted CO_2 volumes). Since there is no evidence of such a large, fast eruption rate in the Deccan province, we must consider alternative sources of Deccan-associated CO_2. In particular, we must seriously question the assumption that the eruption of lavas is the sole control on the release of volatiles—whether of magmatic or crustal ultimate origin—to the atmosphere. A highly likely possibility is that pre–K-Pg volatile release in the Deccan was decoupled from individual eruptions, and instead, magmatic volatiles were passively released from crustal magma bodies, through preexisting faults and surface hydrological systems (Sprain et al., 2019; Hernandez Nava et al., 2021; Mittal and Richards, 2021). This “cryptic” or “passive” degassing would primarily alter global climate through CO_2 emissions, as SO_2 (oxidized to sulfate aerosols) must reach the stratosphere to cause global cooling, whereas noneruptive SO_2 emissions very rarely leave the troposphere (Günther et al., 2018; Carn et al., 2017) especially without a thermal effect of a large lava flow field or a continuous fissure eruption (Glaze et al., 2017; Kaminski et al., 2011) .

Numerous studies have invoked a similar type of degassing from subvolcanic intrusions as a major source of volatiles, primarily CO_2 for other flood basalt provinces (e.g., Siberian Traps; Svensen et al., 2009). Besides magmatic volatiles, other sources of volatiles include devolatilization of crustal materials such as coals through interaction with magma bodies. For Deccan specifically, we posit that crustal C sources (especially organic carbon) are unlikely to be a dominant volatile source because, unlike the Siberian case, there are not known voluminous sources of C- or S-rich sedimentary rocks in the sub-Deccan crust. Although the paleo-rift basins such as the Narmada-Tapi rift basin have Mesozoic sediments with coals, the presently available geophysical and field data does not show evidence for a large sill complex heating the sediments (Patro and Sarma, 2016), unlike those associated with Siberian Traps, North Atlantic Magmatic Province, Karoo flood basalt, and the Central Atlantic Magmatic Province (Svensen et al., 2018 and references therein). Additionally, we do not observe a large change in carbon isotope composition in records synchronous with the LMWE (Hull et al., 2020). This is in contrast to other large igneous provinces where sill emplacement is expected to have played a large role in producing climate modifying volatiles, e.g., the Siberian Traps, which did correlate with significant excursions in carbon isotope records (Jones et al., 2016). In conclusion, while noneruptive degassing associated with organic-rich sediments is a reasonable initial hypothesis, there are compelling reasons to doubt that this carbon source played a major role in Deccan-associated emissions, particularly during the LMWE. In the future, reanalysis or new geophysical data, along with direct analysis of sediment/lava interactions in the Deccan in active Deccan co-located coal mining regions in India may help constrain this process further.

We consequently conclude that the source of the CO_2 associated with LMWE is presumably either from carbonates or is mantle-derived (plume melts or lithospheric, e.g., Black and Gibson 2019; Hernandez Nava et al., 2021). In particular, magmatic volatile degassing associated with intrusive Deccan components (intrusive to extrusive ratio of greater than 10:1 based on available geophysical data; Mittal et al. 2021) is sufficient to explain the LMWE warming (Hull et al., 2020; Hernandez Nava et al., 2021). Additionally, from a magmatic system perspective, high initial volatile degassing is expected as the magmatic system is being set up, since the crust is initially colder and has high permeability (Mittal and Richards 2019, 2021) and the first magmas have high volatile content (since they are lower degree partial melts; Hernandez Nava et al., 2021). Thus, from a magmatic process perspective, it is not entirely surprising to have significant CO_2 non-eruptive emissions preceding large-volume surface eruptions (Wai subgroup).

Overall, there are many outstanding questions related to the timing and tempo of volatile release in the Deccan which directly affect our understanding of Deccan’s role in perturbing Late Cretaceous or early Paleogene environments. Assessing the timing and style of emplacement of distal onshore and offshore records, constraining the eruptive tempo of pre–K-Pg and post–K-Pg eruptions at the sub–1000 yr timescale, and further constraints on the timing and magnitude of passive degassed volatiles, would greatly improve our understanding of Deccan’s role in the K-Pg mass extinction and recovery. There is already a large amount of work on globally distributed stratigraphic sections (e.g., foram assemblages, carbon and oxygen isotopes, mercury) coeval with the Deccan Traps and the K-Pg boundary to help assess how Deccan volcanism affected the ecosystems (Hull et al., 2020; Birch et al., 2016; Witts et al., 2018; Scasso et al., 2020; Robinson et al., 2009; Woelders et al., 2017; Font et al., 2016; Sial et al., 2016; Punekar et al., 2016; Li and Keller 1998; Fendley et al., 2019; Tobin et al., 2012; Alvarez et al., 2019; Sinnesael et al., 2019; Keller et al., 1996).

CHALLENGES AND OPPORTUNITIES

In this section, we briefly highlight a few areas where important progress can be made in future studies. This is not an exhaustive list, but rather a summary of some of the main points indicated in the sections above.

Geochronology and Eruptive Tempo Onshore

To better constrain eruptive tempo onshore, more high-precision dates need to be obtained from new sections in the Western Ghats, in addition to distal provinces, to (1) assess the placement of K-Pg boundary and resolve discrepancies between chronologies based on U-Pb versus ^{40}Ar/^{39}Ar data, (2) determine the fidelity of the geochemically based stratigraphic framework within the Deccan, (3) robustly determine eruptive volumes versus time across the entire Deccan province, and (4) assess changes in eruption style/lava flow morphology and geochemistry for different sub-provinces across the K-Pg boundary. In addition, a significant research focus is needed to understand what the red boles in Deccan (and similar features in other North Atlantic Igneous Province and the Columbia River Basalts) represent (Duraiswami et al., 2020). This is partially motivated by the fact that the red boles are the primary source of zircons dated by the U-Pb method in Deccan and hence it is critical to understand their provenance. In addition, if the red boles indeed represent explosive Deccan volcanism, this would have significant implications in terms of the tempo of volcanism and the potential environmental effects.

Geochemistry of Lava Flows and Dike Swarms

Continued work on the geochemistry (especially isotopes and volatile contents) and petrology of the Deccan Traps is required to ascertain geochemical variations temporally across the K-Pg boundary, spatially within a single flow, as well as differences across the sub-provinces. These data sets would be critical for understanding how Deccan petrogenesis and magmatic architecture changes over time and the relationship between the mafic, silicic, and alkaline components in the Deccan. This work would also, in addition to geochronology, help the continued assessment of the validity of the geochemical stratigraphic framework for the Western Ghats–Central Deccan and the development of a similar stratigraphic framework for other sub-provinces. Finally, the majority of the present work in the Deccan Traps has focused on the lava flows rather than the dike swarms potentially feeding the eruptions. High-precision geochronology and geochemistry would be invaluable in constraining where Deccan lavas erupted from and how far they flowed. In addition, analysis of the Deccan swarm will help constrain the duration of Deccan intrusive magmatism and hence the duration of intrusive volatile release.

Geochronology and Stratigraphic Relations Offshore

So far, no definitive age determinations, either from radioisotopic or paleontological methods, have been published that constrain the precise timing (onset and cessation) of the vast basalt formations offshore western India. This remains a major hole in our ability to place K-Pg events in the full context of Deccan volcanism. There are, in fact, a few commercial exploration drill holes that have penetrated sub-Cenozoic sediments into (and through, in one case) the underlying Deccan-related basalt, but so far access has not been granted (or facilitated) to borehole samples that would allow for precise age-dating. We remain hopeful that such access can, in time, be obtained, as just a few precise age determinations could fill major gaps in our knowledge, not only of Deccan volcanism, but also potentially of the relation between regional tectonics and Deccan/plume-head dynamics and magmatism. The alternative of IODP drilling would be enormously expensive, but is perhaps the last resort.

Triggering from Chicxulub?

The triggering hypothesis, so far, cannot be ruled out by geochronology within the classic Western Ghats formations—based on the ^{40}Ar/^{39}Ar geochronological data, the Lonavala-Wai transition overlaps with the K-Pg boundary. However, the placement of the K-Pg in the Deccan based on U-Pb data does not support the impact triggering hypothesis and future work to resolve the discrepancies between the ^{40}Ar/^{39}Ar and U-Pb data sets will further test the triggering hypothesis. The only evidence so far that could be considered a positive test, the fast-ridge crustal production anomalies noted by Byrnes and Karlstrom (2018) is not firmly established or corroborated, and additional evidence is for anomalous mantle magmatism due to the Chicxulub impact is needed. Furthermore, the physics of how such triggering might work is wholly lacking, though not implausible given analogs with modern day earthquake-volcano interactions and seismic liquefaction. In particular, it is unclear how a large M_w 11 earthquake would impact the crustal/lithospheric magmatic system quantitatively. Questions that need to be answered in future work include: What is the time delay between the impact and the eruptions, and how does it depend on the assumptions of magmatic architecture? Are the geochemical changes in the erupted flows consistent with the observed geochemical signature seen in the Wai subgroup lavas? Is the net effect of seismic waves on the magmatic system the same in the mid-upper crust as in lower crust/lithosphere—i.e., do seismic perturbations always lead to enhanced eruptions, or can they lead to enhanced shallow crustal CO_2 degassing due to transient crustal permeability increase (e.g., Seropian et al., 2021; Mittal and Richards, 2019)? Physical models of these processes would thus be extremely helpful in providing quantitative predictions to compare against observations. Moreover, the correspondence of other Phanerozoic mass extinction events to flood volcanism, along with the unique K-Pg/Chicxulub/Deccan coincidence remains perplexing, and the possible role of Deccan volcanism in the K-Pg extinction also remains unclear.

Outgassing History of Deccan Flood Volcanism

Obtaining a better assessment of eruptive volume versus time from both understudied onshore and offshore sections would greatly aid in testing hypotheses related to volatile release and climatic impact of the Deccan. It is also critical to constrain the eruptive tempo of Deccan volcanism on a sub–1000 yr level in order to assess whether Deccan played a role in perturbing Late Cretaceous and early Paleogene environments. Many important volcanic volatile species have short residence times in the atmosphere (e.g., years-decades for S; Schmidt et al., 2016), and thus to better model their potential short and long-term environmental effects, we need to constrain eruption tempo as well as the volatile concentrations. The required resolution is currently unobtainable by high-precision geochronologic techniques (^{40}Ar/^{39}Ar or U-Pb), and new methods must be explored in the future (e.g., mercury and paleomagnetic secular variation).

SUMMARY

Over the past 5–10 years, great progress has been made in understanding the timing of events surrounding the K-Pg boundary and the eruption history of the Deccan Traps (and other mass extinctions and flood basalt events), as well as new constraints on the eruption "tempo" of Deccan volcanism. Advances in the near future can be expected in constraining the outgassing history of Deccan volcanism, as well as temporal variations in the geochemical signatures of the lavas, with implications for the magma plumbing system. Although current data do not contradict the impact triggering hypothesis (between impact and Deccan volcanism), the potential causal pathways have not been clearly elucidated. In our view, the biggest "missing piece," regarding both the potential K-Pg influences and the overall picture of Deccan volcanism, is our scant knowledge of the potentially huge volumes of Deccan lavas that lie offshore western India—we do not have reliable volume estimates, much less precise geochronological or geochemical constraints. Much work also remains to be done as well in understanding the history of onshore Deccan volcanism outside of the classical Western Ghats formations—Mandla, Malwa, and Saurashtra provinces. Therefore, analysis of new and existing samples from offshore drilling, as well as increasingly thorough and precise dating of the onshore Deccan provinces are needed to advance our understanding of the enigmatic relation between Deccan volcanism and the K-Pg extinction.

ACKNOWLEDGMENTS

The authors are pleased to be able to contribute to this volume honoring the remarkable career of Walter Alvarez. Almost every geologist in the world today can probably remember when they first learned of the discovery of the Chicxulub impact and its correspondence in time with the K-Pg mass extinction event. This singular discovery regarding the disappearance of the dinosaurs led to a transformed (non-uniformitarian) view of Earth history and has greatly informed our understanding of our place as human beings in this strange Universe. This paradigm shift has, famously, given rise to great controversy, and not always of a collegial nature. However, Walter Alvarez's influence has remained that of reasoned curiosity, an infectious sense of adventure, and, above all, goodwill and fairness toward colleagues who have both agreed and disagreed with him. We are personally indebted to Walter for his friendship and mentorship over the years, and hope that our contribution helps to sustain his spirit of discovery in the ancient science of geology, and an openness to being surprised and in awe of the puzzles posed by the natural world.

We are grateful to many colleagues for their various contributions to our grasp of the topics we've addressed in this paper, although they may not share all of our conclusions. Among myriad of these, several stand out in addition to Walter: Michael Manga, Isabel Fendley, Ben Black, Raymond Duraiswami, Sally Gibson, Jan Smit, Vivek Kale, Andrea Marzoli, Kanchan Pande, Steve Self, Hetu Sheth, and Löyc Vanderkluysen. We also gratefully acknowledge support from National Science Foundation grants EAR1615003, EAR161520, EAR1736737, the Esper S. Larsen fund of the University of California at Berkeley, the Ann and Gordon Getty Foundation, and the Crosby Postdoctoral Fellowship. We sincerely thank the editor and the two anonymous reviewers for their comments that helped improve the clarity of the manuscript.

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