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Widespread silicic and alkaline magmatism synchronous with the Deccan Traps flood basalts, India

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ABSTRACT

Deccan Traps (DT) volcanism and the Chicxulub bolide impact have been suggested as potential triggers of the Cretaceous–Paleogene boundary (KPB) mass extinction. Recently published geochronology has established a timeline for the main basaltic sequence of the DT, showing that the majority of eruptions occurred within 700–800 kyr spanning the KPB. Silicic to alkaline magmatism linked to the DT, spatially associated with the Narmada lineament in central India, has been long known but not as well studied. Previous geochronology of some of the felsic magmatic centers has yielded dates that span many millions of years, making their temporal relationship with DT volcanism uncertain. We present zircon U-Pb ages from the Alech, Barda, Girnar, Rajula and Phenai Mata silicic–alkaline complexes, in addition to a series of trachytes on the coastal plain near Mumbai. While the trachytes are ~64 Ma and mark the continental breakup of India ~1.5 Myr after the main phase of DT eruptions, the silicic-alkaline complexes were all emplaced coevally with the main phase of DT volcanism ca. 66.2-65.7 Ma. Initial ε_{Hf} in zircons (+10 to -20), whole-rock $^{87}Sr/^{86}Sr$ (0.702439-0.760932) and ε_{Nd} (+1.11 to -35.7) for all five intrusive complexes suggest a hybrid origin involving juvenile sources as well as significant assimilation of older continental crust. Recognition that the silicic-alkaline complexes are coeval with basaltic magmatism and associated with a significant thermal imprint on the crust in and near the Narmada rift sedimentary strata supports the hypothesis that outgassing of organic-rich sediments may have contributed to the end-Maastrichtian warming and biologic crisis.

1. Introduction

The Deccan Traps (DT) continental flood basalt province in the Indian Peninsula has been proposed as a potential driver for the ca. 66 Ma Cretaceous-Paleogene boundary (KPB) mass extinction (Courtillot et al. 1988 and Courtillot and Renne 2003), in addition to the Chicxulub bolide impact in the Yucatan peninsula (Alvarez et al., 1980). More than 30 years ago, it was already clear that the DT erupted over a short period spanning the KPB (Courtillot et al., 1988; Duncan and Pyle, 1988; Basu et al., 1993). Recent high-precision U-Pb ages of volcanic zircons within weathering surfaces ('redboles') found in between the tholeiitic flows (Schoene et al., 2015, 2019; Eddy et al., 2020) as well as Ar–Ar dating of plagioclase phenocrysts from the tholeiites themselves (Renne et al., 2015; Sprain et al., 2019) have confirmed that the vast majority of basaltic volcanism of the DT occurred within ~700 kyr spanning the KPB, and has resolved relatively small differences in timing between the impact, the K-Pg extinction and major eruptive pulses.

Although the DT dominantly comprise tholeiitic flood basalts and basaltic andesites, there are well-documented examples of rhyolite, trachyte, basanite and carbonatites (Lightfoot et al. 1987; Basu et al. 1993, 2020; Sethna 1999; Sheth et al. 2011, amongst others) found throughout the DT but concentrated in western and northern India (Fig. 1). Previous studies on these units have focused mostly on the petrogenesis of the trachytic and rhyolitic rocks within the DT and their geochemical relationship to DT mafic magmas. However, their temporal relationship with respect to DT basaltic volcanism remains poorly constrained. This study provides new U-Pb geochronology and Hf, Nd and Sr isotopic character-

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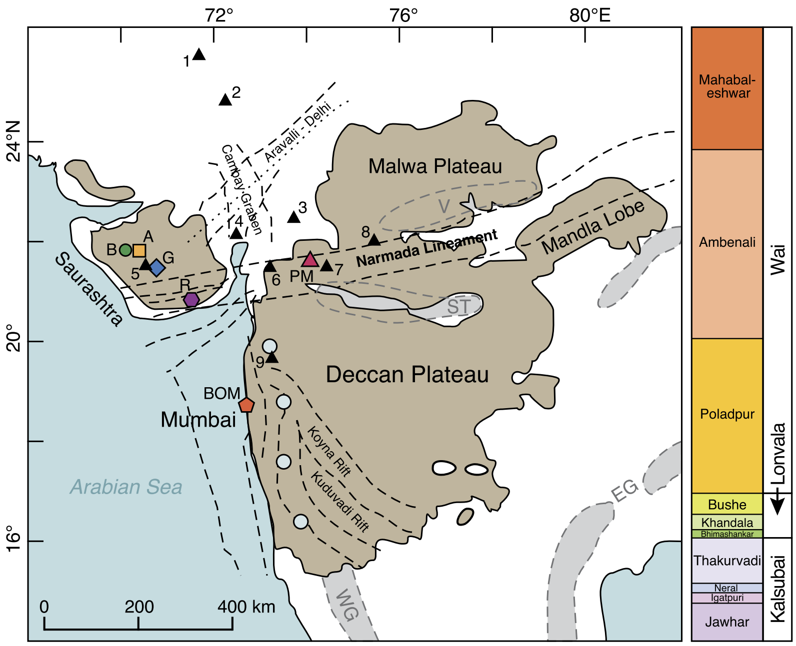

Fig. 1. Map of the western Indian Peninsula showing approximate locations of multiple discrete silicic/alkalic igneous complexes associated with the Deccan Traps (DT) and their major structural tectonic framework. Colored symbols represent igneous centers studied here (*A* Alech, *B* Barda, *G* Girnar, *R* Rajula, *PM* Phenai Mata, *BOM* Mumbai trachytes); black triangles are other associated silicic and alkalic-carbonatitic complexes (1. Sarnu-Dandali, Barmer District, Rajasthan; 2. Mundwara, Sirohi District, Rajasthan; 3. Pavagadh Hills; 4. Kadi, Gujarat; 5. Osham, Gujarat; 6. Netrang, Gujarat; 7. Amba Dongar, Gujarat; 8. Barwaha, Madhya Pradesh; 9. Jawhar nepheline syenite dike). Also shown are major cratonic uplifts (ST Satpura, V Vindhyan, WG Western Ghats, EG Eastern Ghats) and structural features. Locations in the Western Ghats exposing the thickest continuous stratigraphic sections of basalt and associated redbole horizons are shown as gray circles. The major formations of the DT grouped into Kalsubai, Lonvala, and Wai subgroups, are represented in the right-hand column with the box heights corresponding to cumulative erupted volume (Richards et al., 2015). Map modified after Basu et al. (1993), Beane et al. (1986) and Raval and Veeraswamy (2000).

istics of select silicic/alkalic magmatic centers within the DT occurring as discrete, isolated complexes, and sometimes associated with non-tholeiitic, alkalic-carbonatitic lithologies that appear to be genetically linked to the DT. With the exception of two alkalic intrusive bodies (labeled 1 and 2 in Fig. 1), the vast majority of these complexes occur within known exposures of DT flood basalts. The relationship between these centers and the major E-W trending Narmada-Tapti lineament as well as some of the cratonic uplifts is noteworthy, suggesting a structural control on their occurrence. Our new geochronologic and isotopic-geochemical results from the silicic magmatic complexes indicate these are coeval with the DT basaltic eruptions (Renne et al., 2015; Schoene et al., 2015, 2019; Sprain et al., 2019; Eddy et al., 2020). Their wide occurrence and ample evidence for interaction with crustal lithologies suggests that the effect of evolved magmatism should be considered, in conjunction with flood basalt eruptions, in models evaluating the environmental impact of Deccan magmatism.

2. Felsic magmatic centers along the Narmada-Tapti Lineament and their relevance

For this first high-precision zircon geochronology study of felsic rocks within the Deccan, we selected five magmatic centers featuring zircon-bearing granophyres. Four of them (Alech, Barda, Girnar, Rajula) are located in Saurashtra Peninsula, near the NW limit of present DT exposures and along the western extension of the Narmada–Tapti Lineament; the fifth, Phenai Mata, is located ca. 500 km to the east along the lineament (Fig. 1). In addition, we analyzed samples of coastal trachytic dikes from the Mumbai area to evaluate their temporal relationship with the DT and the timing of the Indian continental breakup. Below we provide a brief summary of key geologic features of these complexes, results from previous investigations, and samples selected for this study.

2.1. Alech–Barda

Along the westernmost end of the Narmada-Tapti lineament, Alech and Barda (A, B in Fig. 1) are the largest felsic intrusive complexes of the entire DT province. Cucciniello et al. (2019) obtained whole rock Ar-Ar ages of three granophyres from these complexes that range from 70.2 to 69.2 Ma (recalculated to Fish Canyon sanidine, FCs, age of 28.294; Renne et al. 2010, 2011), predating the entire Deccan Traps by 3–4 Ma; such early silicic magmatism, if accurately dated, is a result of considerable interest. Cucciniello et al. (2019) concluded that these complexes formed by extensive closed-system fractional crystallization of basaltic magmas. In order to test this model, we studied 6 samples of granophyres, basalt, and rhyolite from Alech Hills, and 5 samples of granophyres and basalt from Barda Hills (see Fig. S5a for sample locations). Four granophyres (A7, B2, B5, B6) yielded zircon for U-Pb geochronology.

2.2. Girnar Hills

The Girnar Complex, with a maximum elevation of 1050 m above sea level and a roughly circular outline, occupies an area of 174 km^2 SE of Barda–Alech (G in Fig. 1; detailed in Fig. S5b). It is considered part of the western extension of the Narmada-Tapti rift system/lineament (Chandrasekhar et al., 2002). In a detailed geological and petrological study of the Girnar Hills, Mathur et al. (1926) considered this magmatic body as a laccolith emplaced within a thick layer of late Cretaceous basalt in the Saurashtra peninsula, and estimated its volume to ca. 23 km^3. This intrusive magma body consists of a diverse association of olivine gabbro, diorite, monzonite, syenites, nepheline syenites and granophyres (Fig. S5b). The association of both silica undersaturated (nepheline syenite) and saturated rocks in the Girnar hills is a unique feature of this complex (Mathur et al., 1926; Sahoo et al., 2020), that is investigated here using Nd, Sr and Hf isotopic analyses from

8 samples. Three of these samples (G1, G8 and G9) come from a granophyre that constitutes a marginal dike in the form of a ring (Fig. S5b), and yielded zircons for U-Pb geochronology and Hf isotopic determinations.

2.3. Rajula

The Rajula Complex (R in Fig. 1) consists of rhyolites, trachytes and granophyres associated with basaltic flows, as well as felsic dikes (Fig. S5c), according to Chatterjee and Bhattacharji (2001). These authors, on the basis of geochemistry and geochronology, considered melting of upper crust in response to rifting in this area to produce some of these lithologies. They carried out K-Ar geochronology on a set of mafic to felsic dikes and one basaltic flow, giving ages that range from 63.0±1.0 to 65.8±0.9 Ma (excluding one date of ca. 73 Ma; all dates quoted with 2-sigma uncertainties). We analyzed one sample each of a basalt, rhyolite and a trachyte from this area as shown in the geological map of Fig. S5c. Only the trachyte yielded zircon for U-Pb geochronology.

2.4. Phenai Mata

The Phenai Mata Igneous Complex (PM in Fig. 1, and Fig. S5d) is part of the larger Chota Udaipur carbonatitic-alkalic district (Ray and Ramesh, 1999), 40 km northwest of the Amba Dongar Complex. Both complexes lie along the Narmada-Tapti lineament, approximately 550 km east of the Alech–Barda Hills. The Amba Dongar Complex contains a prominent Ca-Mg-Fe carbonatite ring complex along with nephelinite and trachyte associations. These complexes cover an area of 1200 km^2 (Viladkar, 1996), and are intimately linked with layered tholeiitic gabbro-granophyre intrusions. In this area, Precambrian metamorphic rocks are overlain by late Cretaceous marine sedimentary rocks, including the diagnostic fossil-bearing Bagh Beds which are in turn overlain by the DT basalts. Phenai Mata is a composite plug of gabbros, basalts, granophyres, nepheline syenites and trachytes (Sukeshwala and Sethna, 1973). Two biotites from an alkali gabbro of the Phenai Mata Complex were dated by Basu et al. (1993) using Ar-Ar, resulting in a weighted mean age of 66.0 ± 0.1 Ma (recalculated to FCs age of 28.294 Ma; Renne et al. 2010, 2011). In that study, olivines and pyroxenes from an olivine gabbro yielded $^3He/^4He$ (R/Ra) ratios that are 3.4 and 3.1 times the atmospheric ratio, respectively, indicative of significant crustal contamination of the magma source. Recently, Parisio et al. (2016) reported Ar-Ar ages of mineral separates from tholeiites and alkalic rocks from the area (also relative to FCs age of 28.294 Ma), ranging in age from 66.60 ± 0.35 to 65.25 ± 0.29 Ma for Phenai Mata and Dongargaon, and 66.40 ± 2.80 to 64.90 ± 0.80 Ma for Mount Pavagadh (Fig. S1). One sample of microgranite from Phenai Mata (4-24) yielded zircon for U-Pb geochronology.

2.5. Mumbai trachytes, Salsette Island

Near Manori in the Salsette Island (Fig. S5e) a series of trachytes are found in the lowlands, almost at sea level where most of the greater Mumbai city is situated (Sethna, 1999). These lowland volcanics are in sharp contrast with the > 2.5 km thick sequence of the Deccan lavas in the Western Ghats. The timing of this volcanism is important as the trachytes are situated on the Panvel flexure zone along the western Indian rifted continental margin, and they are thought to mark post-DT crustal extension and continental breakup (Lightfoot et al., 1987). Rb-Sr (Lightfoot et al., 1987) and more recently Ar-Ar (Pande et al., 2017) geochronological data are available on rocks from this area, the latter yielding plateau ages ranging from 62.4 ± 0.2 to 63.4±0.3 Ma (relative to FCs at 28.294; Renne et al. 2010, 2011). In this study, we provide high-precision U-Pb ages from a set of trachytic dikes associated with rifting that follows the main phase of DT volcanism.

3. Analytical methods

Major element compositions of bulk samples were determined by inductively coupled plasma – optical emission spectrometry (ICP-OES) at Boston University. Strontium and Neodymium were separated from bulk samples at University of Texas at Arlington and analyzed by thermal ionization mass spectrometry (TIMS) at Boston University for Sr isotopes, and multicollector – inductively coupled plasma – mass spectrometry (MC-ICP-MS) at Trent University for Nd isotopes. Moderate-precision U-Pb and Lu-Hf isotopic analyses of zircon were conducted by laser ablation (LA)-ICP-MS at the Arizona Laserchron Center (ALC), following the methods described in Pullen et al. (2018) and Ibañez-Mejia et al. (2015). High-precision U–Pb zircon analyses by chemical abrasion (CA)-ID-TIMS were conducted at Princeton University and the Massachusetts Institute of Technology (MIT), on zircons extracted from the epoxy mounts, using the methods summarized by Schoene et al. (2019). Hafnium isotopic analyses from chemically purified zircon were conducted by solution-MC-ICP-MS using a Thermo Neptune (Princeton University) and a Nu Plasma II (MIT) following methods similar to those described in Eddy et al. (2017). Detailed descriptions of all analytical methods are available in the Supplemental Material. All U-Pb dates shown are $^{206}Pb/^{238}U$ dates and are reported at the 2-sigma level without systematic uncertainties unless otherwise noted.

4. Results

4.1. Major and trace element geochemistry

We analyzed the major element compositions of 37 whole rock samples from the five acidic-alkalic complexes studied here. Lithological-geological maps, some more detailed than others, are available in the Supplemental Material (Figs. S5a-e). The major oxides were analyzed by ICP-OES (Table ST2) indicating high silica (rhyolites- granophyres) to lower silica (alkali basalt-nepheline syenite) compositions. We also analyzed all samples using standard petrologic-mineralogical methods, that were consistent with their chemical analyses (Table ST2) and CIPW normative mineralogy. Our results also include a few samples from the Pavagadh and Osham complexes that lie on the Narmada-Tapti trend (Fig. 1), for which no new U-Pb ages are reported but that have published Ar-Ar ages within the range of DT volcanism (Parisio et al., 2016; Sheth et al., 2012). Some of the analyzed rocks in Table ST2 are coarse grained nepheline syenites with visible nepheline crystals in hand specimens, but which due to possible "nugget effects" do not show high enough alkalis and lower silica to accurately reflect their mineralogy in bulk rock chemistry.

4.2. U–Pb zircon geochronology

A subset of zircons separated from 10 of the samples were initially surveyed using laser ablation ICPMS U–Pb dating. Although the majority of the dates were found to overlap the DT basalt eruption timeline (Fig. S3), the results also indicate a common occurrence of xenocrystic cores, mostly of Neoproterozoic age (Table ST1a). A subset of these crystals were removed from the grain mounts and analyzed by CA-ID-TIMS, yielding a coherent grouping of U–Pb dates around 66 Ma as well as a range of discordant analyses likely representing mixtures of ~66 Ma rims and Precambrian xenocrystic cores (Fig. 2, Table ST1b). These mixed analyses,

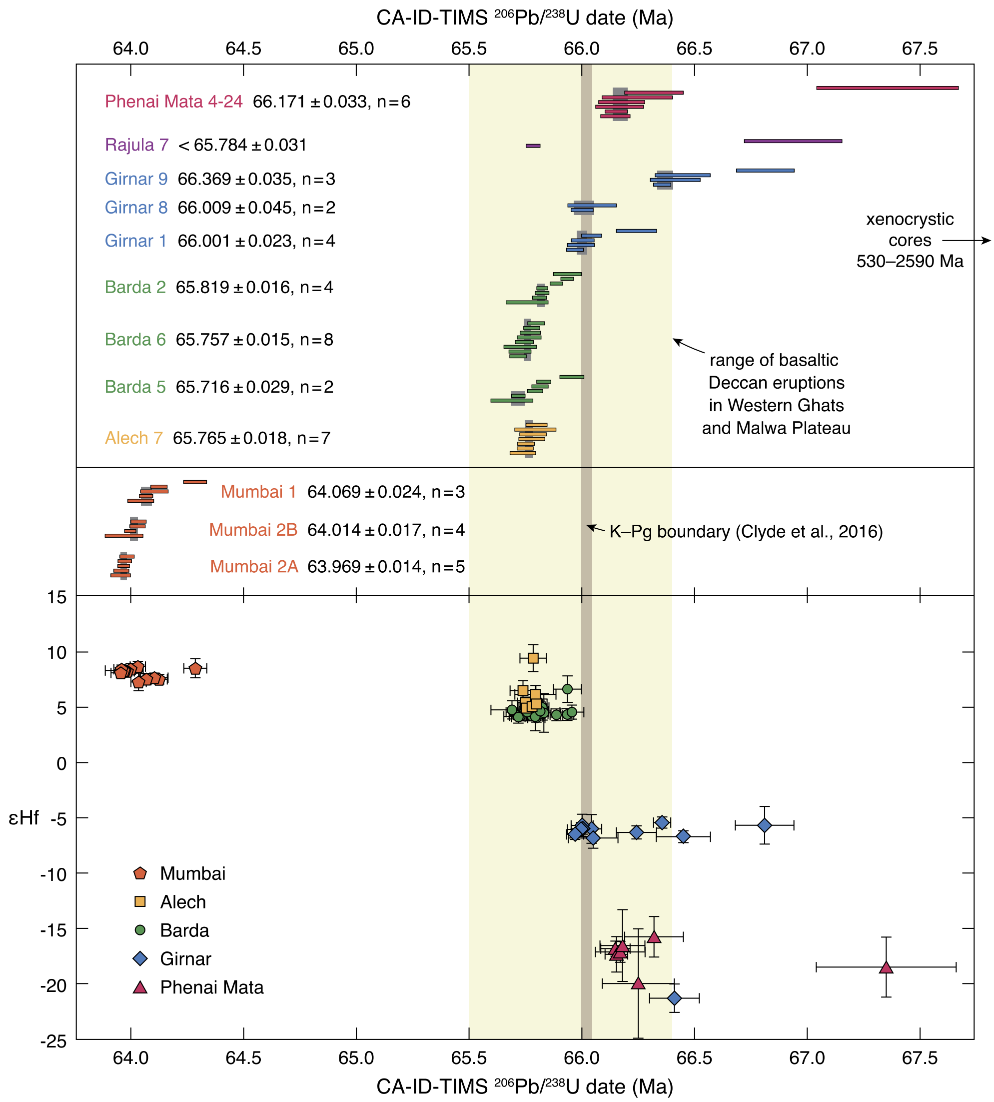

Fig. 2. U–Pb dates and Hf isotopic compositions of zircon from selected felsic igneous complexes in the Saurashtra Peninsula (Alech, Barda, Girnar, Rajula), the Narmada–Tapti rift (Phenai Mata), and the Salsette Island (Mumbai). (A) Rank-order plot of concordant CA-ID-TIMS $^{206}Pb/^{238}U$ dates of single zircon crystals shown in relation to the timeline of Deccan Traps basalt eruptions of Schoene et al. (2019) and Eddy et al. (2020), and the U–Pb age of the K–Pg boundary (Clyde et al., 2016). Emplacement ages are estimated using the weighted mean approach; dates included in the weighted means are underlain by gray bars. All data are reported with 2-sigma internal uncertainties (see Table ST1b for propagated systematic uncertainties in tracer calibration and U decay constant). For Rajula 7, only a maximum emplacement age based on the youngest zircon is provided. (B) Whole-crystal, age-corrected εHf for the same zircon crystals analyzed by solution MC-ICPMS.

found almost exclusively in the Girnar Hills samples, return upper intercepts in concordia space that point toward cores of late Proterozoic age, with a dominant population at 530–750 Ma (Table ST1e). This result places constraints on the age of sub-Deccan Traps basement in the Saurashtra Peninsula, which appears distinctly younger than the nearby Aravalli–Delhi Belt (e.g., McKenzie et al. 2013), instead bearing similarity to peak metamorphic ages from Madagascar (e.g., Collins and Pisarevsky 2005).

Fig. 2 summarizes the $^{206}Pb/^{238}U$ dates for all concordant single zircon analyses performed in this study. Due to sample consumption during LA-ICP-MS analyses and the common occurrence of xenocrystic cores, the yield of young concordant grains was low; in the extreme case of Rajula 7, we only found two such crystals. We interpret all obtained concordant U–Pb dates (Fig. 2, Fig. S4) to represent crystallization ages of zircon growing within the individual magmatic systems. The age dispersion found amongst zircon in single samples ranges from unresolvable (e.g., Alech 7) to as much as a million years (Phenai Mata); this might be due to either continuous crystallization or scavenging of zircon 'antecrysts' and their reincorporation into younger magmas within the same magmatic complex. As all dated samples in this study represent dikes or very shallow intrusive lithologies (mostly granophyres) typically characterized by high cooling rates, the U–Pb data can be used to estimate their emplacement/solidification ages. We employed two approaches for interpreting emplacement ages: i) using the youngest zircon for each sample, and ii) using a low-MSWD weighted mean calculation (Table ST1b). This treatment could be applied to all samples but one, Rajula 7, which only yielded two concordant zircons and therefore only provides a maximum emplacement age (Fig. 2A). Both interpretations return estimates that overlap within uncertainty for all samples, and thus we favor the weighted mean age of the youngest coherent group of dates as it is less sensitive to analytical outliers, or potential Pb loss. Regardless of the chosen emplacement age interpretation, our data clearly show that the Alech–Barda, Girnar and Rajula complexes in Saurashtra, and Phenai Mata in the east, were active over the time frame of DT basaltic volcanism (Fig. 2). Felsic magmatism may have been active since as early as 67 Ma (i.e., antecrysts of this age were found in samples from Phenai Mata, Rajula and Girnar), and continued at least until 65.7 Ma at Alech–Barda in the west. Ages of

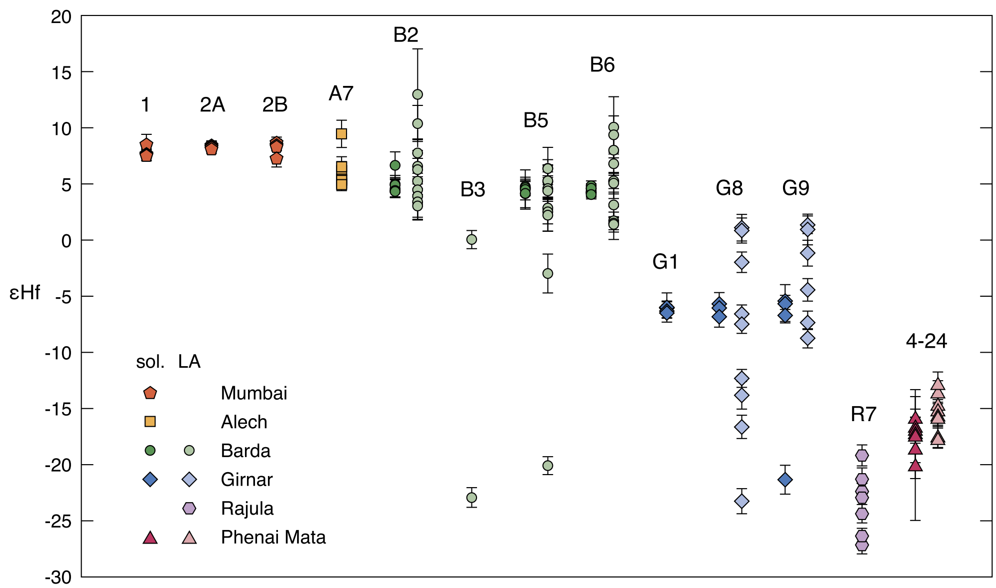

Fig. 3. Hf isotopic compositions of zircon determined in solution on crystals dated by CA-ID-TIMS (Fig. 2) and by spatially resolved (i.e., LA-MC-ICPMS) methods. Note that LA data may include old xenocrystic cores. Uncertainties are shown at 2-sigma level (see Tables ST1c, ST1d, ST1e for details).

the three Mumbai trachytes (BOM 1, 2A-B) cluster around 64 Ma, distinctly younger than DT volcanism.

4.3. Hf isotope geochemistry of zircon

We analyzed zircon crystals for Hf isotopic compositions in two complementary ways: i) by spatially-resolved LA-MC-ICPMS using epoxy-mounted zircons previously analyzed for U-Pb isotopes by LA-ICP-MS (Fig. 3 and Table ST1c); and ii) by bulk-crystal solution-MC-ICPMS using matrix fractions remaining from U–Pb separation of zircons dated by CA-ID-TIMS (Figs. 2B, 3 and Table ST1d). Both datasets reveal a large variability in age-corrected εHf, from mantle-like values of up to +9, to extremely negative values down to <-25 characteristic of old crustal sources. Importantly, because the U-Pb and Lu-Hf laser ablation data (Fig. 3) were obtained from separate ablation pits, some analyses may represent inadvertent mixtures between young overgrowths and xenocrystic zircon components. In contrast, the solution Hf data were obtained from the exact same zircon volume dissolved to determine U–Pb ages by CA-ID-TIMS. Therefore, the bulk zircon data allow for a more effective recognition of mixed compositions and accurate assignment of Hf isotopic values for the same volume of zircon representing young, ~66 Ma magmatic growth (Fig. 2B). Consistent with U–Pb results, samples with clear age inheritance also have varying numbers of low, negative εHf values in addition to the tightly clustered young magmatic Hf (e.g. G8, Fig. 3). This suggests that, in most samples, outliers to low values in laser ablation data may represent mixed analyses with old xenocrystic zircon domains. The age-controlled solution εHf (Fig. 2B) is in most cases invariable both within individual samples and between samples from the same magmatic complex; only G9 had a single outlying zircon at εHf =-21, suggesting either isotopic heterogeneity of Girnar Hills magmas or a small xenocrystic core component. The clustered solution data, interpreted to represent Hf isotopic compositions of the host magmas, indicate varying amounts of reworked crustal material in the source of the melts. This crustal contribution appears to decrease with time from the early, strongly negative εHf $\leq$ -15 at Phenai Mata, to the late, distinctly more mantle-like signatures (εHf $\geq$ +5) at the younger Alech–Barda complex. The 64 Ma Mumbai trachytes display the most primitive εHf, consistent with their origin in a rifting setting.

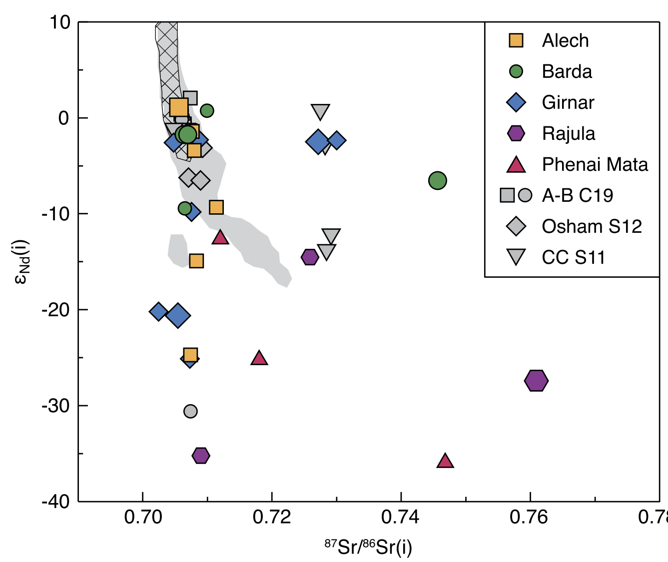

Fig. 4. Initial Nd and Sr isotopic compositions of whole-rock samples from five intrusive complexes within the Deccan Traps, compared to the entire range of Nd–Sr isotopes of DT basaltic volcanism (in gray; data from Peng et al. 1994, other recent data of the DT basaltic volcanism fall mostly within the gray field). The cross-hatched area represents the compositional range of the Poladpur, Ambenali and Mahabaleshwar formations of the DT. Grey symbols represent literature data for Alech–Barda (A-B, Cucciniello et al., 2019 (C19)) and other potentially coeval silicic magmatic centers, Chogat–Chamardi (CC) and Osham (Sheth et al., 2011, 2012 (S11, S12)). Large symbols represent samples with corresponding U–Pb geochronology.

4.4. Whole-rock Sr and Nd isotopes

Initial ε_{Nd} and $^{87}Sr/^{86}Sr$ isotopes of silicic and mafic rocks from the five intrusive complexes (Fig. 4; Table ST3) display extreme variability, with initial ε_{Nd} values between +1.1 and -35.7, and $^{87}Sr/^{86}Sr$ between 0.702439 and 0.760932. Individual magmatic complexes are strongly heterogeneous in their isotopic composition; however, we observed no relationship between the degree of magmatic evolution and radiogenic isotope ratios. The spread of Sr–Nd isotope data presented here is well in excess of values found in Deccan Trap basalts (Cox and Hawkesworth, 1985; Peng et al., 1994; Vanderkluysen et al., 2011), clearly indicating that many of the analyzed silicic lithologies are not simple closed-system differentiates of DT basalts as previously suggested (e.g., Cucciniello et al., 2019). The negative ε_{Nd} and elevated $^{87}Sr/^{86}Sr$ indicate that the origin of these magmas included, perhaps in addition to relatively unevolved mantle melts, a variable component of reworked ancient continental crust. The presence of reworked ancient continental crust is also supported by Proterozoic cores to some of the zircons (Fig. 2, Table ST1b). In extreme cases, e.g., at Rajula or Phenai Mata (Fig. 4), the crustal component appears dominant in the isotopic mass balance, implying that some (relatively minor) volumes of the felsic Deccan magmas might be close to pure crustal melts.

5. Discussion

5.1. Synchronicity of felsic complexes with flood basalt volcanism

Our new geochronology comprises the first U-Pb dates for felsic complexes associated with the Deccan Traps magmatic province. Recently published high-precision U-Pb and Ar-Ar geochronology for the main sequence of the Deccan Traps in the Western Ghats (Schoene et al., 2019; Sprain et al., 2019) and from lower parts of the stratigraphy found in the Malwa Plateau (Eddy et al., 2020) show that the vast majority of basaltic volcanism occurred between ca. 66.4 and 65.5 Ma. Although zircons from any given sample in this study range over a time period of between 1 Myr and several tens of kyr, the youngest zircon –or youngest group– from each shallow intrusion give an estimate for when that sample intruded and rapidly crystallized. This interpretation is supported by the observation that some of these samples are fine grained shallow level granophyres with miarolitic cavities and therefore cooled quickly after emplacement (De and Bhattacharyya, 1971). Given that interpretation, and that this dataset is not comprehensive of all the northern Deccan felsic intrusive complexes, it is notable that each of the five studied intrusions fall within the window of basaltic DT volcanism (Fig. 2). In other words, our data show that mafic and felsic volcanism of the DT were coeval and therefore most likely genetically linked to the Reunion mantle plume. Additionally, the apparent relationship between the intrusive complexes studied here, the major E-W trending Narmada-Tapti lineament, and some of the cratonic uplifts such as the Malwa plateau (Fig. 1), may suggest a structural control on their emplacement.

A close comparison between the DT basalt eruption ages and the results obtained here suggests that the emplacement of some of the felsic complexes we studied took place during a period in which Schoene et al. (2019) documented a lull in basaltic volcanism in the Western Ghats, some 500 km to the southeast. Two samples from the Girnar complex (G1 and G8) give dates that coincide with, or shortly postdate, the eruption of the Poladpur Fm. and the KPB date of 66.016 ±0.050 Ma re-interpreted by Schoene et al. (2019) using the results of Clyde et al. (2016). The Alech and Barda complexes were emplaced ca. 65.7 Ma, near the end of the Deccan Trap sequence, between the Ambenali and Mahabaleshwar formations (Schoene et al., 2019). We note that the Ar-Ar data from this same interval does not show a hiatus (Sprain et al., 2019), perhaps indicating there is a local hiatus identified by the U-Pb data; however, given the larger uncertainties in the Ar-Ar dataset, those data are unlikely to identify a hiatus even if one was present (Schoene et al., 2020). Our U-Pb ages of the Alech and Barda complexes indicate that even if the hypothesized lulls in basaltic eruptions are confirmed regionally, there was not a complete cessation of DT magmatism altogether. Whether or not mafic magmatism continued through these periods of repose proposed in the Western Ghats, either as intrusive or extrusive magmatism, remains to be seen through additional work.

In some cases, the ages from this study can be compared to published Ar-Ar data from the same complexes. Nine out of ten K-Ar dates from the Rajula complex from Chatterjee and Bhattacharji (2001) range from 63.0 ± 1.0 to 65.8 ± 0.9 Ma. This is the most poorly dated of our samples (Rajula 7, Fig. 2), yielding only two non-inherited zircon grains, the younger of which is 65.784±0.031 Ma, which can be taken as a maximum age for this sample. More U-Pb data from this complex will be necessary to make a robust comparison. We provide robust U-Pb ages for four samples from the Alech-Barda complexes, each falling in a tight cluster around ca. 65.7 Ma (Fig. 2). In contrast, recent Ar-Ar geochronology from whole-rock granophyre samples yielded plateau ages for the same complexes of 70.2-69.2 Ma (Cucciniello et al., 2019), >3 Ma older than our dates and also much older than the main phase of basaltic volcanism in the DT. Although we did not date the same samples used in that study, it is possible that the whole rock samples dated by Ar-Ar were subject to excess ^{40}Ar or ^{39}Ar recoil, resulting in spuriously old dates (Renne et al., 2015). It seems unlikely, however, given the consistency of our results from four separate samples, that the age offset between the two methods is due to residual Pb-loss. We thus argue that our U-Pb results ca. 65.7 Ma more accurately date the emplacement of the Alech and Barda magmatic complexes than previous Ar-Ar whole-rock data. Finally, a recent study on the Phenai Mata complex (Parisio et al., 2016) presented biotite Ar-Ar step-heating plateau ages on three samples ranging from 66.24 ± 0.37 to 66.47 ± 0.34 Ma, in good agreement with our U-Pb date of 66.171 ± 0.033 Ma (Fig. 2). In summary, our U-Pb dates from each complex agree well with published Ar-Ar data carried out on mineral separates and less well compared to Ar-Ar dates on whole rock samples. The latter Ar-Ar geochronology tends to yield older dates and dates that span over several million years compared to single mineral Ar-Ar geochronology and U-Pb geochronology. This observation has been made previously (e.g., Renne et al., 2015; Kasbohm and Schoene, 2018), and opens up the possibility that the age span of 4-5 million years for the DT determined by a range of Ar-Ar techniques should be revisited by single mineral Ar-Ar and U-Pb geochronology.

5.2. Silicic centers as volcanic sources for zircons within basalts

In order to apply U-Pb zircon geochronology to establish a timeline for flood basalt volcanism in the DT, Schoene et al. (2015, 2019) and Eddy et al. (2020) recovered zircon from weathering horizons (so called "redboles") between basalt flows in the Western Ghats and the Malwa Plateau, respectively. While some of the sampled horizons are clearly volcaniclastic, most of them do not obviously contain ashfall at the outcrop scale. The pristine, euhedral nature of these zircons, in addition to the stratigraphic coherence of the resulting ages, led them to conclude that the zircons were derived from volcanic airfall during times of quiescence between basaltic eruptions. Because zircon is exceedingly rare in basaltic magmas, they further speculated that the zircons were likely derived from yet unidentified, but proximal silicic volcanic sources. Our ages from five silicic complexes in the northern Deccan magmatic province overlap in timing with basaltic volcanism (Fig. 5) and are thus candidates as sources for zircons within the Western Ghats, some 500 km away. Because the samples studied here are all from shallowly emplaced intrusions, this hypothesis requires that there was an explosive eruptive component associated with the studied complexes. Regardless, as noted above, three out of five of the studied complexes have intrusion ages that fall within apparent flood-volcanism hiatuses in the Western Ghats, and therefore are not exact matches for sources of ashfall within the basaltic interbeds. Alternatively, plotting the distribution of all zircons recovered from the redboles, including those that were interpreted to have grown long before the eruptions represented by the ash beds, shows there was continuous zircon growth in sili-

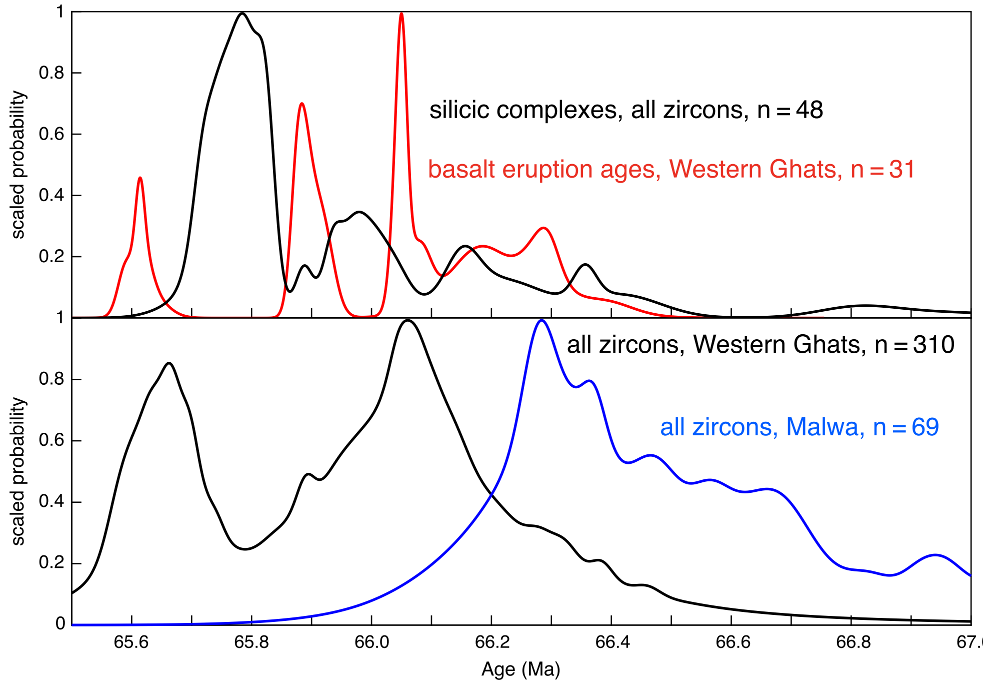

Fig. 5. Comparison of probability density functions compiling all non-inherited U–Pb zircon ages and uncertainties from this study ('silicic complexes'), all zircons found in redbole horizons in the Western Ghats (Schoene et al., 2019) and in the Malwa Plateau (Eddy et al., 2020), and the modeled timeline of Deccan Traps basalt eruptions in the Western Ghats using U/Pb geochronology ('basalt eruption ages'; Schoene et al., 2019).

cic centers throughout the entirety of mafic volcanism. Fig. 5 also substantiates the observation of Schoene et al. (2019) of continued zircon crystallization through apparent lulls in basaltic magmatism in the Western Ghats and offers an explanation to their presence during periods of interpreted basaltic-volcanism quiescence as inferred from the existing U-Pb data. Altogether, these results indicate that magmatism in the Deccan magmatic province was continuous in some form since as early as 67 Ma until after 65.6 Ma.

In summary, although direct matching of individual zircon crystals from redbole horizons with the intrusives we analyzed here as potential sources is not yet plausible, the overlap in duration of zircon crystallization documented within the redbole horizons and the silicic complexes shows there is a possibility that as the geochronologic database for these silicic complexes expands, a connection with particular zircon sources should be further explored. For example, thick successions of rhyolitic ashfall and flows have been described recently at Mt. Pavagadh (Fig. 1; Sheikh et al. 2020), though these have not yet been dated. Thus, further work and additional geochemical 'fingerprinting' of zircon using trace element and/or Hf isotopic compositions, may shed further insights into this issue.

5.3. Sources of Deccan felsic magmas

Strontium–Nd isotopic compositions of bulk samples, supplemented by Hf isotopic compositions of zircon interpreted to represent original magmatic values, show large variations exceeding the isotopic range found in DT flood basalts (Fig. 4). This observation clearly indicates that variable amounts of ancient crustal material were involved in their origin in addition to mantle-derived melts. Extreme degrees of isotopic heterogeneity found among adjacent samples from individual magmatic complexes (e.g., Girnar), as well as the co-occurrence of silica-saturated and undersaturated rocks (e.g., Mathur et al., 1926), suggest variable pathways of magma–crust interaction that may depend on crustal architecture and lithology, depth and length of crustal magma storage or final emplacement, or its physical parameters. In some cases, for example at Barda–Alech, or Osham (Sheth et al., 2012), the isotopic compositions require little to no crustal addition in comparison to the DT magmas, suggesting that evolved magmas may have been formed as near-closed-system differentiates of DT basalts (e.g., Cucciniello et al., 2019). In others, particularly at Phenai Mata and Rajula, Hf–Sr–Nd isotope ratios indicate a nearly pure crustal origin of at least some of the lithologies (Fig. 4; Chatterjee and Bhattacharji, 2001). Our limited dataset of five magmatic complexes dated at ∼66 Ma describes a rough geographic and temporal trend along the Narmada–Tapti lineament, whereby the crustal character of magmas decreases from the early (ca. 66.3–66.1 Ma), extremely evolved compositions at Phenai Mata in the east (εHf of -20), towards the more mantle-like Barda–Alech magmas in the west at 66–65.7 Ma (Figs. 1, 2). The strong association of the studied silicic complexes with the Narmada–Tapti lineament (Fig. 1) suggests a key role of this structure in facilitating the interaction between mantle plume-derived melts and the crust, perhaps by providing the right combination of available lithologies and crustal architecture for the plume-derived magmas to stall and interact with the crust sufficiently long to generate evolved, silicic melts. An alternative explanation may be that many Deccan basaltic magmas interacted with the crust, causing wide-ranging variability in radiogenic isotope compositions, but the reason why silicic magmatism is less commonly seen over most of the Deccan Province may be because viscous crustal melt could not get shallowly emplaced before being re-assimilated by younger batches of basaltic magma. Perhaps the reason we see silicic components most commonly along the lineament is because it provided stress conditions that allowed silicic melts to migrate to shallow levels (and possibly erupt). While the geographic coverage of our data is not broad enough to fully evaluate this relationship, we expect further isotopic and geochronologic studies to be able to refine these observations.

5.4. Implications for environmental impact of the Deccan magmatic province

A major portion of the E-W trending Narmada-Tapti-Son lineament zone (or, the Narmada lineament; Fig. 1) comprises a variety of rock types ranging in age from the Archean to Recent (Jain et al., 1995; Abdul Azeez et al., 2017). Parallel to this lineament is a ~50-60 km wide basin that has been active since Gondwanan times, and contains fluvial, lacustrine, and marine sediments with an aggregate thickness of 6–8 km that were deposited from the early Permian to early Cretaceous (Jain et al., 1995). These sediments include coalfields and marine Cretaceous deposits of the Bagh Beds. Geophysical studies extending a stretch of 500 km along the Narmada-Tapti river have imaged these Gondwana sediments beneath Deccan basalts, persisting from at least as far east as the Mandla Lobe to as far west as the Saurashtra peninsula (Fig. 1; Kaila, 1988; Verma and Banerjee, 1992; Abdul Azeez et al., 2017). Abundant diabase dikes, most simple and some composite, are found close to the Narmada-Tapti river (Jain et al., 1995; Vanderkluysen et al., 2011). Inliers in the Tapti valley contain silicic and basic rocks, such as granophyre and diabase carrying numerous xenoliths of quartzose tuffs; these inliers also contain multiple rhyolite and dacite dikes thought to be of DT age (Jain et al., 1995), similar to those observed in western Saurashtra.

Volatile release from the thermal metamorphism of sedimentary units within this rift basin/lineament, caused by DT magma injections near the Malwa Plateau- Mandla Lobe (Fig. 1), could be important for better understanding the potential role that magma interaction with overlying sediments, including coal, had in the KPB environmental crisis. While some of the dike swarms cross cutting the Narmada rift sediments have been correlated geochemically with surface flows (Vanderkluysen et al., 2011), the volume of potential sills and their timing across the rift basin remains unknown. Eddy et al. (2020) reported U-Pb geochronology from zircons interstratified within Deccan basalts near the Narmada river on the southern end of the Malwa Plateau which support the idea (Devey and Lightfoot, 1986; Mitchell and Widdowson, 1991) that the majority of lavas in the northern Deccan correlate to early volcanism ca. 66.4-66.2 Ma. Based partly on this observation, Eddy et al. (2020) speculate that this early phase, because it was focused near the Narmada rift sediments, may have had a disproportionate effect on climate due to sediment outgassing. Augmenting these observations, our geochronological data demonstrates that coeval silicic-alkalic-carbonatitic volcanism was also active near and in the Narmada rift and the Saurashtra peninsula throughout the entire lifespan of the mafic magmatism (Fig. 5). Some of these intrusions were emplaced directly into the rift sediments though the importance of contact metamorphism and volatile release has not been studied in detail. Additionally, the Nd, Sr, and Hf isotopic data from this study indicate a substantial role of crustal assimilation in generating the silicic magmas. The thermal footprint of Deccan magmatism in the crust in and around the Narmada-Tapti rift was therefore substantial and a better understanding of volatile release from deep crustal metamorphism and shallower surface outgassing of organic rich sediments could provide greater insights into the causes of the environmental impact of the DT through time. This process is increasingly invoked in other flood basalt provinces that coincide with environmental crises (Svensen et al., 2009; Burgess et al., 2017; Davies et al., 2017), but has perhaps been underappreciated for the Deccan Traps.

5.5. The trachytes of Salsette Island (Mumbai) and their significance

The basic lavas of the Mumbai area (Fig. S5e), belonging to the Salsette subgroup (Sethna, 1999), are associated with rhyolites and contemporaneous trachytic flows showing characteristic western dips of 10°-20°, west of the Panvel flexure along the western Indian continental margin (Auden, 1949; Sethna, 1999). This flexuring seems to have formed by continental crust subsidence due to thinning and extension following the main sequence Deccan Traps lava eruptions, continental break-up and opening of the Indian Ocean (e.g. Desai and Bertrand, 1995; Hooper et al., 2010).

The three trachyte dike samples we studied yielded consistent U-Pb ages ca. 64.0 Ma (Fig. 2). This age has important implications for the rift-to-drift transition of the Seychelles Islands and Laxmi Ridge continental sliver (off Mumbai coast in the Arabian Sea)- India breakup. Published bulk-rock Ar-Ar ages of basalts, trachytes and rhyolites in this area (Pande et al., 2017) suggested their emplacement to have taken place at 63.0±0.1 Ma, and the trachytes were also dated by Sheth et al. (2001) at 61.0±0.6 Ma (later corrected by Pande et al., 2017 to 61.4±0.6 Ma; all recalculated here relative to FCs of Renne et al., 2010, 2011). Both of these results are at odds with our high-precision U-Pb age of 64.0 Ma. It should be noted that these lavas are from the Panvel flexure zone along the Western Indian continental margin, and the ages are clearly much younger than the main sequence DT flood basalts of the Western Ghats (Fig. 2). This age difference has implications for understanding the separation of Seychelles from the Indian Plate, as the east-west extension along the west coast of India is known to have begun during the final phases of the Deccan Traps basalt eruption (Hooper et al., 2010). Hooper et al. (2010) also concluded that the structures associated with the Panvel flexure were established by 64-65 Ma and that the Mumbai volcanics of the Salsette subgroup of Sethna (1999, Fig. S5e), comprised of trachytes and rhyolites, were erupted between 64-62 Ma and reflect lithospheric thinning leading to the separation of Seychelles from the Indian Plate. The Ar-Ar ages reported by Hooper et al. (2010) were likely more reliable than Pande et al. (2017) as they were obtained from plagioclase mineral separates rather than whole rock aliquots as analyzed by Pande et al. (2017). We thus conclude that the more precise and reliable U-Pb ages of zircons reported in this study for the three Mumbai trachytes should be a clear indicator of the timing of the separation of the Seychelles from the Indian Plate.

Regarding the petrogenesis of the Manori trachytes, a Rb-Sr whole rock isochron age of 61.5±1.9 Ma with an initial $^{87}Sr/^{86}Sr$ of 0.7085±18 for the silicic eruptions was interpreted by Lightfoot et al. (1987) as reflecting partial melting of underlying DT basaltic rocks during crustal extension. In this context, it is noteworthy that the initial Sr-isotopic compositions of the lower Deccan Formations, such as Khandala and below (e.g., Basu et al., 2020) are in agreement with the Manori trachytes' Sr-isotope signature. Additionally, the initial Hf isotopic compositions of zircon from the trachytes reported here (Fig. 3) are similar to the Lower Deccan lavas (Basu et al., 2020), suggesting their possible origin by partial melting and/or assimilation of already erupted and deeply buried Lower Deccan lavas.

6. Conclusions

At least five silicic magmatic complexes, 550 km apart from one another and comprising diverse lithologies, formed within the Deccan flood basalt province, and are coeval with DT basaltic volcanism. High precision CA-ID-TIMS U–Pb zircon dates from the two northwesternmost felsic complexes in Saurashtra, Alech and Barda, suggest their emplacement took place during the hypothesized lull in DT eruptions near the transition between the Ambenali and Mahabaleshwar Fms. in the Western Ghats. Three other intrusive complexes to the east and along the Narmada-Tapti lineament yield slightly older ages, covering the entire age span of the Deccan as determined by redbole zircon and Ar-Ar geochronology (Schoene et al., 2019; Sprain et al., 2019; Eddy et al., 2020). These geochronologic data indicate that felsic complexes within the Deccan provide a feasible origin for the zircon found within redbole horizons 500 km to the south. Furthermore, our high precision U-Pb ages of trachytes from the Salsette Islands west of the Panvel flexure provide a 64.0 Ma date for the cessation of flood basalt volcanism and breakup of the Indian continent.

Whole-rock Nd and Sr isotopic compositions and age-corrected zircon Hf isotopic compositions indicate that these five magmatic complexes formed by extensive reworking of Proterozoic basement, likely through plume-induced crustal melting and/or assimilation. Our results show that high-magmatic flux events in the Deccan resulted in significant crustal melting, and potentially outgassing of organic rich sediments within the Narmada-Tapti rift which may have released additional CO_2 throughout the duration of the DT. The temporal relationship between DT basaltic and silicic/alkalic volcanism, as well as the widespread crustal signatures of the latter, may be of fundamental importance to better understand potential mechanisms leading to the KPB environmental crisis and mass extinctions during emplacement of large igneous provinces in continental regions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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