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^{40}Ar/^{39}Ar dating of the Mumbai tholeiites and Panvel flexure: intense 62.5 Ma onshore–offshore Deccan magmatism during India-Laxmi Ridge–Seychelles breakup

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SUMMARY

Mumbai, located on the western Indian continental margin, exposes Danian-age Deccan magmatic units of diverse compositions, dipping seaward due to the Panvel flexure. The Ghatkopar-Powai tholeiitic sequence contains seaward-dipping (thus pre-flexure) flows and subvertical (thus post-flexure) dykes. We present new ^{40}Ar/^{39}Ar ages of 62.4 ± 0.7 and 62.4 ± 0.3 Ma (2σ) on two flows, and 62.2 ± 0.3, 62.8 ± 0.3 and 61.8 ± 0.2 Ma on three dykes, showing that this sequence is much younger than the main 66–65 Ma Deccan sequence in the Western Ghats escarpment. The mutually indistinguishable ages of the Ghatkopar-Powai tholeiites overlap with available ^{40}Ar/^{39}Ar ages of 62.6 ± 0.6 and 62.9 ± 0.2 Ma for the seaward-dipping Dongri rhyolite flow and 62.2 ± 0.6 Ma for the Saki Naka trachyte intrusion, both from the uppermost Mumbai stratigraphy. The weighted mean of these eight ^{40}Ar/^{39}Ar ages is 62.4 ± 0.1 Ma (2 SEM), relative to an MMhb-1 monitor age of 523.1 ± 2.6 Ma (2σ), and indicates essentially contemporaneous volcanism, intrusion and tectonic flexure. This age also coincides with the rift-to-drift transition of the Seychelles and Laxmi Ridge-India breakup and the emplacement of the Raman-Panikkar-Wadia seamount chain in the axial part of the Laxmi Basin. Pre-rift magmatism is seen in the 64.55 Ma Jogeshwari basalt in Mumbai and 63.5–63.0 Ma intrusions in the Seychelles. Post-rift magmatism is seen in the 60.8–60.9 Ma Manori trachyte and Gilbert Hill basalt intrusions in Mumbai and 60–61 Ma syenitic intrusions in the Seychelles. The Mumbai area thus preserves the pre-, syn- and post-rift onshore tectonomagmatic record of the breakup between the Seychelles and the Laxmi Ridge-India. Voluminous submarine volcanism forming the Raman, Panikkar and Wadia seamounts in the Laxmi Basin represents the offshore syn-rift magmatism.

Key words: Continental margins: divergent; Continental tectonics: extensional; Dynamics of lithosphere and mantle; Large igneous provinces; Effusive volcanism.

1 INTRODUCTION

The major tectonic events that formed the western continental margin of India and its adjoining deep offshore basins are the breakup and separation of India, Seychelles and Madagascar in the Late Cretaceous and Palaeocene time (Bhattacharya & Yatheesh 2015, Fig. 1). The oldest among these events is the separation of India and the Seychelles from Madagascar, which was initiated at ∼88 Ma (e.g. Storey *et al.* 1995; Pande *et al.* 2001; Bhattacharya & Yatheesh 2015), and created the Mascarene Basin (Figs 1a and b). This breakup event was immediately preceded by flood basalt volcanism on Madagascar and in India (e.g. Valsangkar *et al.* 1981; Storey *et al.* 1995; Torsvik *et al.* 2000; Pande *et al.* 2001; Melluso *et al.* 2009; Ram Mohan *et al.* 2016; Sheth *et al.* 2017). At ∼68.5 Ma, India broke up from the welded Seychelles and Laxmi Ridge (referred to as Greater Seychelles), resulting in the formation of the Laxmi Basin between India and the Laxmi Ridge, and the Gop Basin between the Laxmi Ridge and the Saurashtra Volcanic Platform (Fig. 1c). This was in turn followed by the breakup of the Seychelles from the conjoined Laxmi Ridge-India, initiated shortly before chron C28ny (Chaubey *et al.* 2002; Royer *et al.* 2002; Yatheesh 2007; Collier *et al.* 2008; Ganerød *et al.* 2011; Bhattacharya & Yatheesh 2015), i.e. shortly before ∼62.5 Ma according to the geomagnetic polarity timescale of Cande & Kent (1995). This separation created the conjugate Arabian and Eastern Somali basins, on the Laxmi Ridge and Seychelles sides, respectively (Fig. 1d), and was preceded by the formation of the Deccan Traps flood basalt province (Fig. 1d) during 66–65 Ma, continuing up to ∼62–60 Ma in both western India and the Seychelles (Sheth *et al.* 2001a,b; Ganerød *et al.* 2011; Owen-Smith *et al.* 2013; Sheth & Pande 2014; Shellnutt *et al.* 2017).

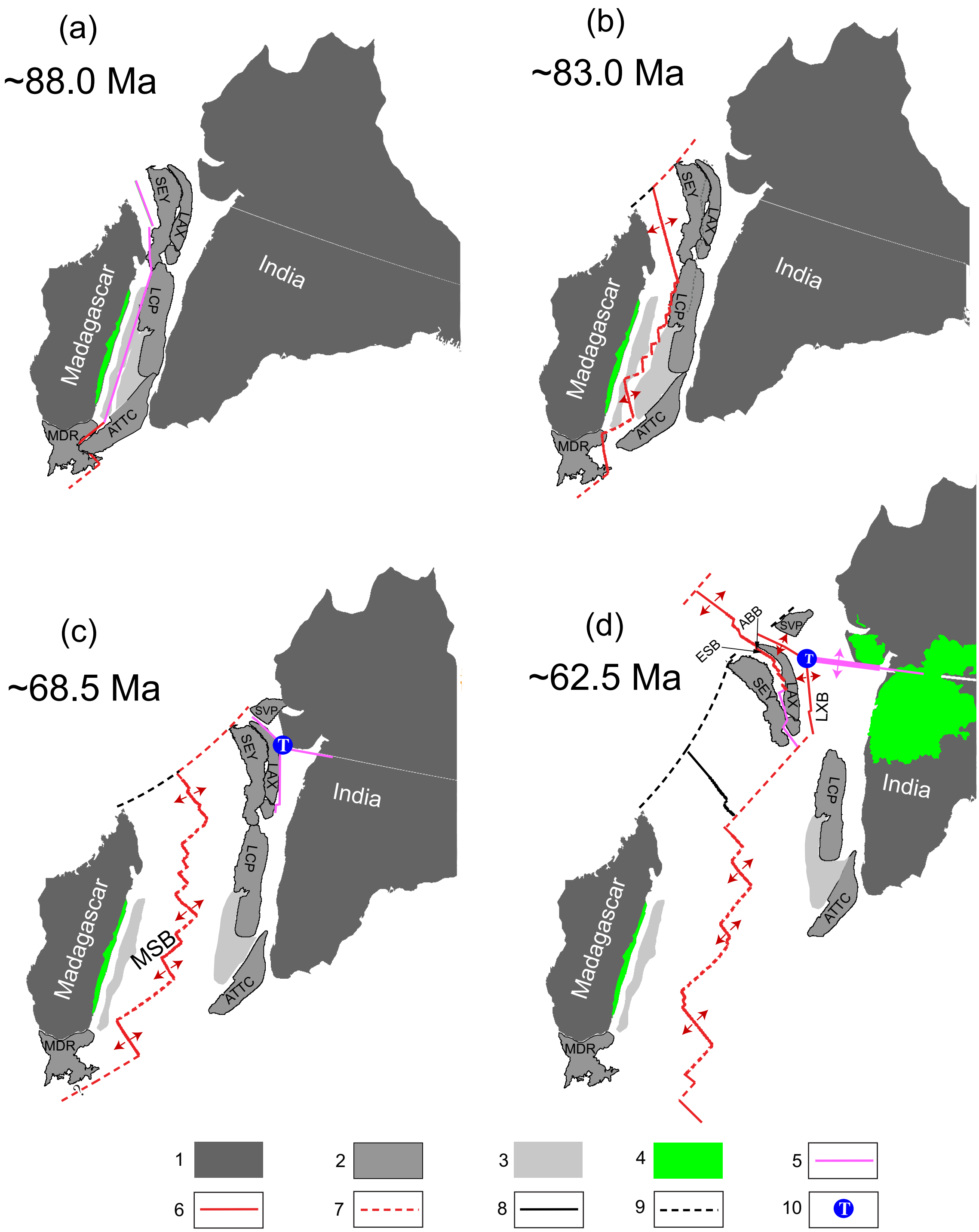

Figure 1. Schematic diagrams (based on Bhattacharya & Yatheesh 2015) depicting the major stages of India-Seychelles-Madagascar breakup and the early opening history of the Arabian Sea. (a) ~88 Ma; (b) ~83.0 Ma; (c) ~68.5 Ma and (d) ~62.5 Ma. Explanations to the legend are as follows: (1) Major continental blocks, (2) Microcontinents, (3) Ultra-thinned continental crust, (4) Volcanics, (5) Rift axis, (6) Ridge axis, (7) Transform fault, (8) Extinct spreading centre, (9) Palaeo-transform fault, (10) The Gop-Narmada-Laxmi fossil Triple Junction off the Saurashtra peninsula. Red and pink coloured arrows represent the directions of spreading and rifting, respectively. The names of geographical domains or topographical features (after Bhattacharya & Chaubey 2001) are abbreviated as follows: ABB, Arabian Basin; ATTC, Alleppey-Trivandrum Terrace Complex; ESB, Eastern Somali Basin; LAX, Laxmi Ridge continental sliver; LCP, Laccadive Plateau; LXB, Laxmi Basin; MDR, Madagascar Ridge; MSB, Mascarene Basin; SEY, Seychelles Plateau and SVP, Saurashtra Volcanic Platform.

Mumbai City (Figs 2a and b) is situated in the structurally complex Panvel flexure zone (Samant *et al.* 2017, and references therein) on the western continental margin of India, in which the magmatic units show prominent dips towards the Arabian Sea. These magmatic units are of Danian age (post-Cretaceous/Palaeogene boundary), and show diverse compositions and emplacement styles (e.g. Sukheswala & Poldervaart 1958; Sethna & Battiwala 1977; Sheth *et al.* 2001a,b; Cripps *et al.* 2005; Sheth & Pande 2014). Sethna

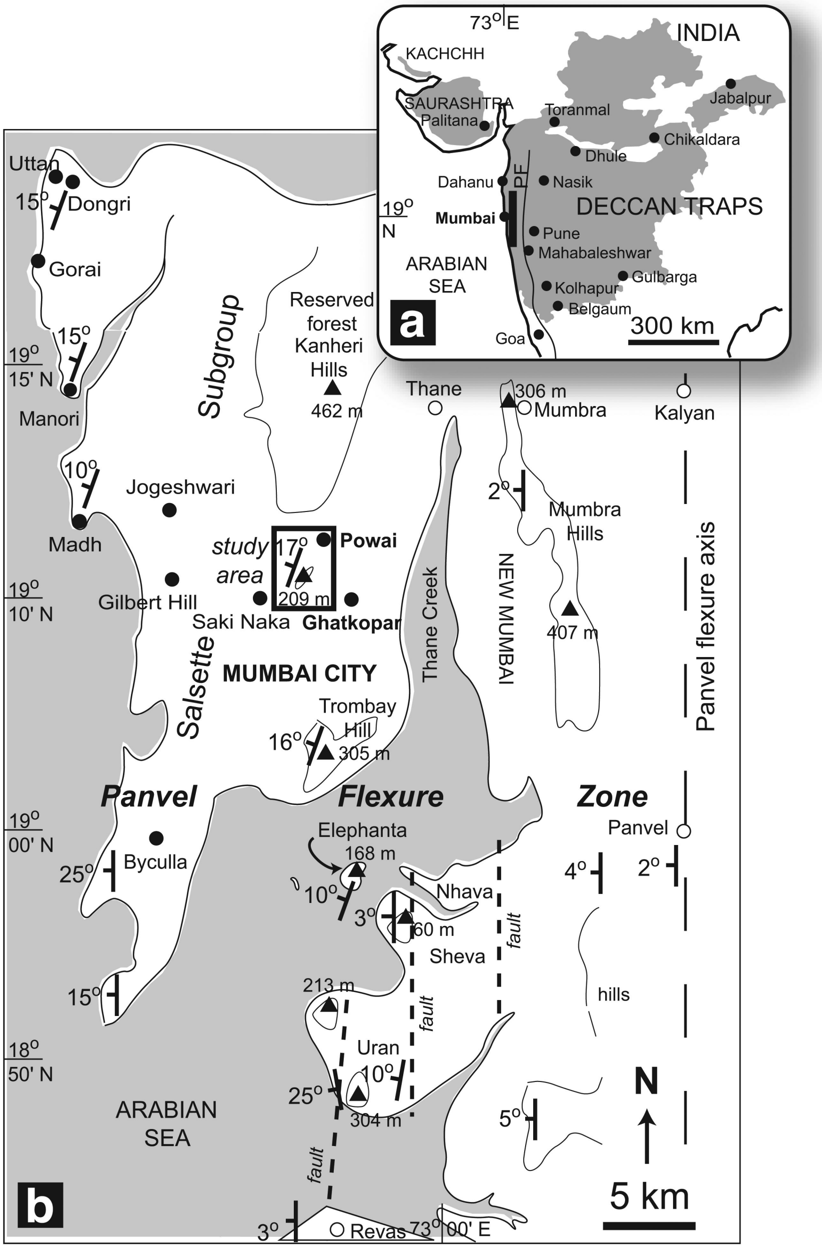

Figure 2. (a) Map of the Deccan Traps (shaded area) with important features and localities marked. WGE is the Western Ghats escarpment, and PF (short heavy line) is the Panvel flexure. (b) Map of Mumbai City and nearby areas of the western Indian rifted margin, showing the major topographic, geological and structural features, and localities mentioned in the text. Hilly areas are shown by grey outlines, and elevations (in metres above sea level) by black triangles. Box with thick black boundary shows the area of this study. The Panvel flexure zone is indicated, as are some of the identified constituent faults and structural dips of the Deccan lava flows. Based on Samant *et al*. (2017).

(1999) named the Mumbai sequence the Salsette Subgroup. He divided it into the Mumbai Island Formation (comprising subaqueous units including spilitic pillow basalts, tuffs and shales), followed upwards by the Madh-Uttan Formation (made up of rhyolite lava flows), in turn followed by the Manori Formation (comprising trachyte intrusions). The volcanic units dip prominently westward, towards the Arabian Sea, due to the Panvel flexure. Sheth *et al.* (2014) presented field, petrographic, major and trace element and Sr–Nd isotopic data on a tholeiitic flow-dyke sequence, exposed in the Ghatkopar-Powai area of northeastern Mumbai (Fig. 2b). They considered it possibly emplaced from a nearby, unknown eruptive centre, as it was geochemically unrelated to the main Deccan tholeiitic sequence in the Western Ghats escarpment to the east (Fig. 2a) which is 66–65 Ma in age (Baksi 2014; Renne *et al.* 2015). Sheth *et al.* (2014) considered the seaward-dipping flows as pre-Panvel flexure, and the subvertical dykes (i.e. which did not experience tilting) as post-Panvel flexure, as schematically explained in Fig. 3. They also observed that the dominant ~N–S orientation of the numerous dykes implied a strongly E–W extensional stress field, probably as the Seychelles was about to be rifted from western India, but they had no age data to confirm this scenario. Because absolute age data on the Ghatkopar-Powai tholeiitic flows and dykes would be very helpful to elucidate the interplay of multiple magmatic and tectonic events (Fig. 3), we have obtained accurate and precise

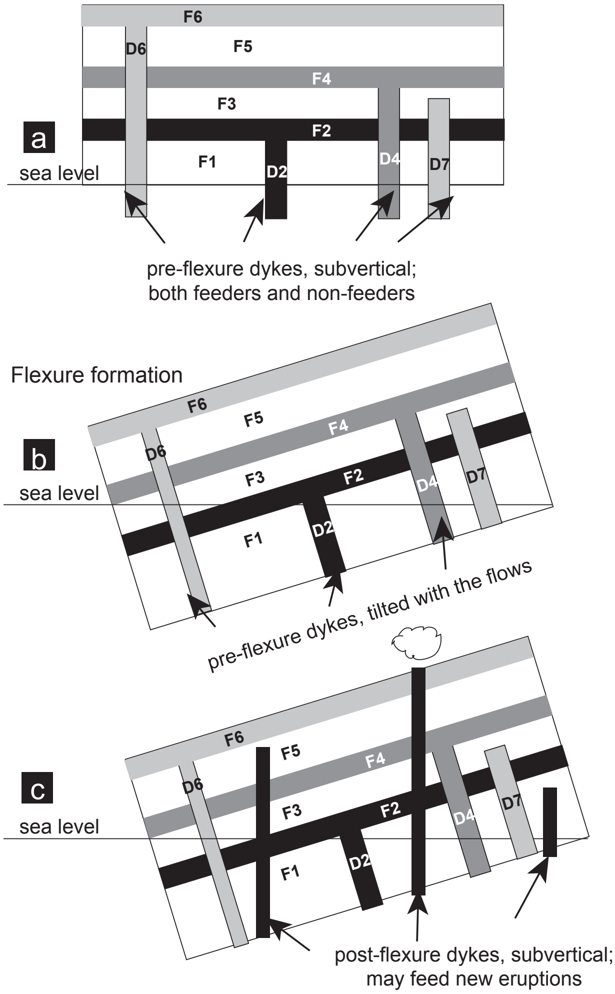

Figure 3. Schematic cartoon indicating how the timing of flexure formation can be deciphered by dating rifted margin dykes. (a) Horizontal lava pile containing feeder and non-feeder dykes that are emplaced vertically or nearly so. Different colours indicate different lava flows and their feeder dykes: dyke D2 feeds flow F2 (black), dyke D4 feeds flow F4 (dark grey) and dyke D6 feeds flow F6 (light grey). Flows F1, F3 and F5 (all white) came from feeder dykes located elsewhere. Dyke D7 is a non-feeder, simply terminating within the lava pile. (b) Flexure forms, tilting the flows F1–F6 and the dykes D2, D4, D6 and D7 towards the newly formed ocean basin. (c) After flexure formation, new dykes continue to be emplaced, in a subvertical orientation, and may be feeders or non-feeders (black dykes without numbers; the central dyke feeds an eruption). The lowermost panel shows the situation observed today. The timing of Panvel flexure formation can be determined by dating the tilted (thus pre-flexure) flows and dykes and the subvertical and non-tilted (thus post-flexure) dykes; the ages obtained must be consistent with field relationships. This is the idea and the objective of this study.

$^{40}Ar/^{39}Ar$ ages on several of these units. The ages indicate rapid and essentially synchronous volcanism, intrusion and deformation in the onshore and adjacent deep offshore areas, with broader plate tectonic implications for the evolution of the western continental margin of India, specifically the Seychelles and Laxmi Ridge-India breakup event.

2 GEOLOGY AND PETROGRAPHY

All localities mentioned in this paper are shown in Fig. 2(b). The Ghatkopar-Powai tholeiitic flows dip 17°–18° west, and their feeder dykes are not exposed. The flows are cut by numerous subvertical dykes with a strong preferred orientation (N–S, NNW–SSE and NNE–SSW). These dykes may have fed lavas at higher stratigraphic levels now lost due to erosion. The flows and dykes are subalkalic basalts and basaltic andesites, with a flow of ankaramite (Sheth *et al.* 2014; Chatterjee & Sheth 2015). The flows are generally highly weathered, with much secondary zeolitization and silicification and values of LOI (loss on ignition) reaching 7.77 wt.%. However, the two flow samples dated in this study (MMF4 and MMF7 from the base and top, respectively, of the IIT Hill in Powai; see fig. 2 of Sheth *et al.* 2014) are relatively fresh, with moderate LOI values (2.33 and 2.39 wt.%, respectively). The dykes, fine- to medium-grained, are much fresher and contain much less olivine than the flows. Many dykes are aphyric, and the porphyritic dykes have plagioclase as the main phenocryst phase, rarely with small clinopyroxene and olivine microphenocrysts. Of the three dykes dated in this study (N40°-striking MMD1, N20°-striking MMD13 and N40°-striking MMD15), the first two have LOI values of 1.03 and 1.37 wt.%, respectively, whereas the third has not been geochemically analysed.

Flow MMF4, a subalkalic basalt, shows a fine-grained groundmass of plagioclase and clinopyroxene with fairly abundant, small ($\leq$1 mm), rounded, fractured and moderately altered olivine phenocrysts (Fig. 4a). Flow MMF7 is an ankaramite with beautiful rounded clusters, up to 5 mm in size, of twinned and radially arranged clinopyroxene phenocrysts, as well as smaller phenocrysts of olivine, in a fine-grained basaltic groundmass (Fig. 4b). Dyke MMD1, a basaltic andesite, is aphyric, with a fine-grained groundmass consisting essentially of plagioclase and clinopyroxene with accessory iron oxides (Fig. 4c). Dyke MMD13, a three-phenocryst subalkalic basalt, shows glomerocrystic aggregations of large numbers of relatively big (1 mm) lath-shaped plagioclase grains with rounded microphenocrysts of olivine and clinopyroxene, in a very fine-grained groundmass (Fig. 4d). Dyke MMD15 is a fine-grained basalt essentially made up of plagioclase and clinopyroxene, with sparse microphenocrysts of plagioclase (Fig. 4e).

3 $^{40}Ar/^{39}Ar$ DATING

3.1 Methods

Fresh rock chips (∼20–25 g) were crushed, cleaned in deionized water in an ultrasonic bath, and sieved. About 0.02 g of each was packed in aluminium capsules. The Minnesota hornblende reference material (MMhb-1) of age 523.1 ± 2.6 Ma (Renne *et al.* 1998) and high-purity CaF_2 and K_2SO_4 salts were used as monitor samples. High-purity nickel wires were placed in both sample and monitor capsules to monitor the neutron fluence variation, which was typically ∼5 per cent. The aluminium capsules were kept in a 0.5 mm thick cadmium cylinder and irradiated in the heavy-water-moderated DHRUVA reactor at the Bhabha Atomic Research Centre (BARC), Mumbai, for ∼100 hr. The irradiated samples were repacked in aluminium foil and loaded on the extraction unit of a Thermo Fisher Scientific noble gas preparation system. Argon was extracted in a series of steps up to 1400 °C in an electrically heated ultrahigh vacuum furnace. After purification using Ti–Zr getters, the argon released in each step was measured with a Thermo Fisher ARGUS VI mass spectrometer (equipped with five Faraday cups fitted with 10^{11} Ω resistors) located at the National Facility for $^{40}Ar/^{39}Ar$ Geo-thermochronology in the Department of Earth Sciences, IIT Bombay, India.

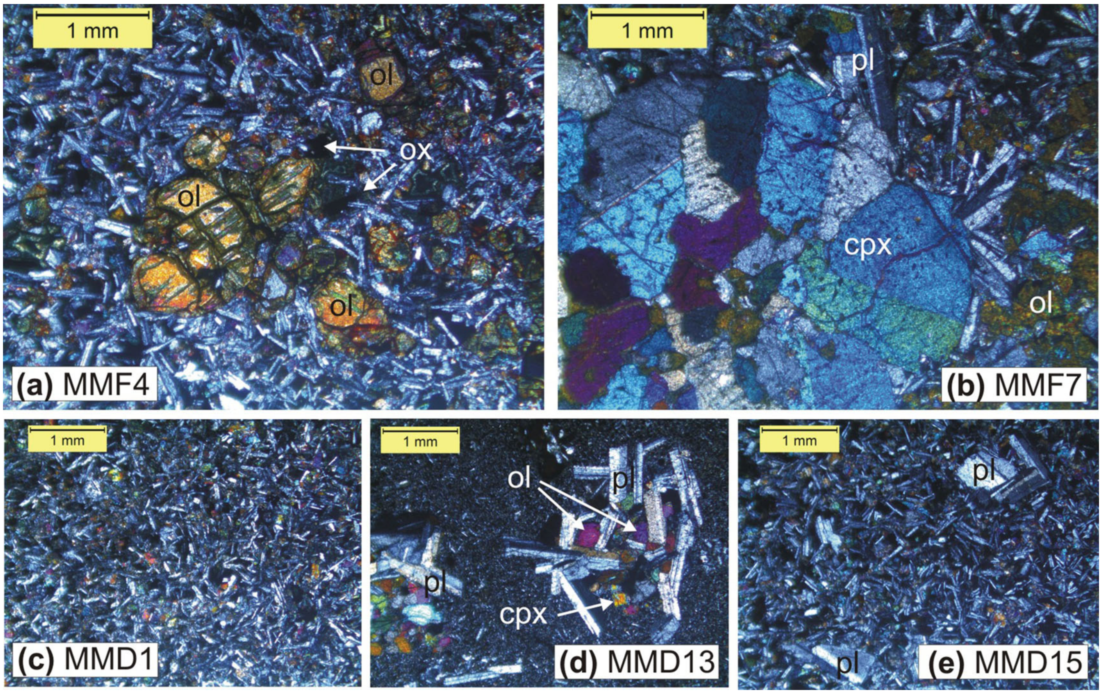

Figure 4. Photomicrographs of the five dated samples, all taken between crossed nicols. (a) Flow MMF4. (b) Ankaramite MMF7, with a large rounded aggregate of individual twinned clinopyroxene grains. (c) Dyke MMD1. (d) Dyke MMD13. (e) Dyke MMD15. Abbreviations used are: ol (olivine), cpx (clinopyroxene), pl (plagioclase) and ox (Fe-Ti oxide).

Table 1. Summary of $^{40}Ar/^{39}Ar$ dating results for the Ghatkopar-Powai tholeiite flows and dykes.

	Plateau					Isochron				Inverse isochron			
Sample	Steps	^{39}Ar (%)	Age (Ma)	MSWD	*p*	Age (Ma)	Trap	MSWD	*p*	Age (Ma)	Trap	MSWD	*p*
MMF4, flow	13	71.2	62.4 ± 0.7	0.08	1.00	62.2 ± 1.2	295.9 ± 3.3	0.02	1.00	62.2 ± 0.8	296.1 ± 2.7	0.05	1.00
MMF7, flow	12	77.9	62.4 ± 0.3	0.53	0.88	62.4 ± 0.7	295.6 ± 6.1	0.06	1.00	62.4 ± 0.4	295.0 ± 4.0	0.47	0.91
MMD1, dyke	13	72.6	62.2 ± 0.3	0.94	0.50	62.2 ± 0.5	295.8 ± 1.8	0.23	0.99	62.1 ± 0.3	296.1 ± 1.4	0.69	0.75
MMD13, dyke	10	74.1	62.8 ± 0.3	0.26	0.98	62.8 ± 0.7	295.5 ± 6.2	0.04	1.00	62.8 ± 0.4	295.6 ± 3.6	0.23	0.99
MMD15, dyke	13	74.5	61.8 ± 0.2	0.22	1.00	61.9 ± 0.5	295.2 ± 4.1	0.04	1.00	61.9 ± 0.3	295.0 ± 2.6	0.15	1.00

Notes: Trap is initial $^{40}Ar/^{36}Ar$ ratio (trapped component), MSWD is mean square weighted deviate and *p* is the corresponding probability. Errors are reported at the 2σ confidence level and monitor mineral is MMhb-1 (523.1 ± 2.6 Ma, Renne *et al.* 1998). Decay constants used are those of Steiger & Jager (1977). All samples are whole-rock samples. Their locations are as follows: MMF4 and MMF7 (19°08′25″ N, 72°55′10″ E), MMD1 (19°07′00″ N, 72°55′10″ E) and MMD13, MMD15 (19°06′30″ N, 72°54′35″ E).

Interference correction factors for Ca- and K-produced Ar isotopes based on analysis of CaF_2 and K_2SO_4 salts were $(^{36}Ar/^{37}Ar)_{Ca}$, $(^{39}Ar/^{37}Ar)_{Ca}$ and $(^{40}Ar/^{39}Ar)_K$ = 0.000334, 0.000762 and 0.000808, respectively, for samples MMF4, MMF7 and MMD13. For samples MMD1 and MMD15, irradiated in another batch, the same correction factors were 0.000344, 0.001062 and 0.000647, respectively. ^{40}Ar blank contributions were 1–2 per cent or less for all temperature steps.

Following the procedure described in Dalrymple *et al.* (1981), Venkatesan *et al.* (1993) and McDougall & Harrison (1999), the neutron fluence variation during the irradiation was determined using ^{58}Co γ-activity of the irradiated nickel wires kept with the monitor as well as the individual samples. Values of the irradiation parameter J for the samples were determined by normalizing the variations in the ^{58}Co γ-activity in the nickel wires kept with the samples to the activity associated with the nickel wire kept with the monitor. Fluence-corrected values of J for the samples are as follows: MMF4 (0.002663 ± 0.000010), MMF7 (0.002407 ± 0.000009), MMD1 (0.002229 ± 0.000009), MMD13 (0.002324 ± 0.000009) and MMD15 (0.002113 ± 0.000008). The plateau ages reported comprise a minimum of 60 per cent of the total ^{39}Ar released and four or more successive degassing steps whose mean ages overlap at the 2σ level excluding the error contribution (0.5 per cent) from the J value. The data were plotted using the program Isoplot/Ex v. 3.75 (Ludwig 2012).

3.2 Results

Table 1 gives the summary of the $^{40}Ar/^{39}Ar$ results (plateau, isochron and inverse isochron ages with 2σ uncertainties) for the five samples. Plateau spectra along with Ca/K ratios and isochron plots for the five samples are shown in Figs 5 and 6. The stepwise analytical data are given in the online data set (Table S1, Supporting Information). All $^{40}Ar/^{39}Ar$ ages mentioned in this paper are reported with 2σ uncertainties.

The subalkalic basalt flow MMF4 yielded a 13-step plateau constituting 71.2 per cent of the ^{39}Ar release and an age of 62.4 ± 0.7 Ma (Fig. 5a). The ankaramite flow MMF7 yielded a 12-step plateau constituting 77.9 per cent of the ^{39}Ar release and an age of 62.4 ± 0.3 Ma (Fig. 5b). Each sample yielded isochron and inverse isochron

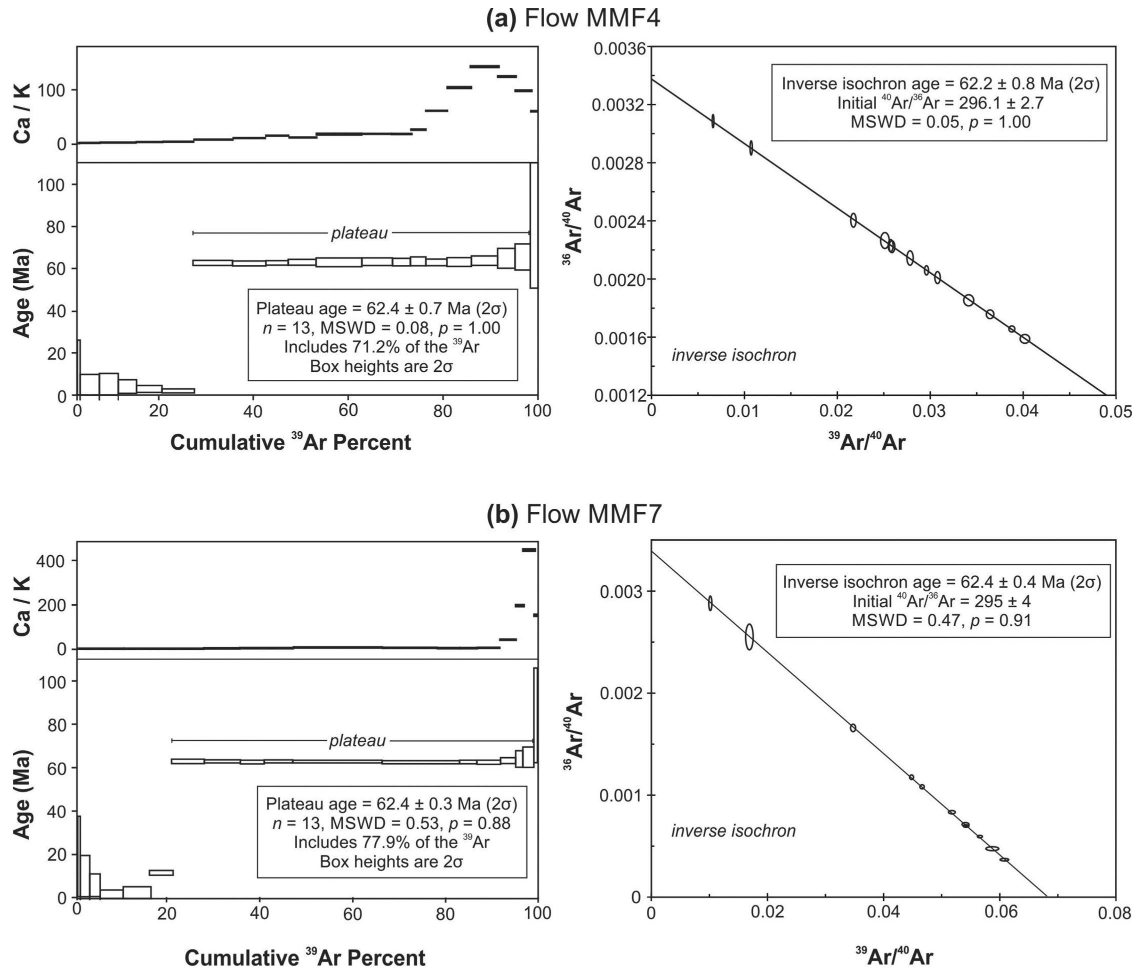

Figure 5. $^{40}Ar/^{39}Ar$ plateau spectra, Ca/K ratios and inverse isochrons for Ghatkopar-Powai tholeiitic flows (a) MMF4 and (b) MMF7. Also shown are values of the MSWD (mean square weighted deviate) and probability (p).

ages statistically indistinguishable from the plateau ages (Figs 5a and b, and Table 1). The dyke MMD1 yielded a 13-step plateau constituting 72.6 per cent of the ^{39}Ar release and an age of 62.2 ± 0.3 Ma (Fig. 6a). Dyke MMD13 yielded a 10-step plateau constituting 74.1 per cent of the ^{39}Ar release and an age of 62.8 ± 0.3 Ma (Fig. 6b). Dyke MMD15 yielded a 13-step plateau constituting 74.5 per cent of the ^{39}Ar release and an age of 61.8 ± 0.2 Ma (Fig. 6c). All three samples yielded isochron and inverse isochron ages statistically indistinguishable from their plateau ages (Figs 6a–c and Table 1).

All five samples yielded well-developed plateau spectra with large amounts of ^{39}Ar release (71.2–77.9 per cent), and their isochrons and inverse isochrons have acceptable mean square weighted deviate values and atmospheric $^{40}Ar/^{36}Ar$ ratios (295.5) of the trapped argon as given by their intercepts. The Ca/K ratios corresponding to the plateau steps for each sample show little variation (Figs 5a and b and 6a–c). Even the low-temperature steps in the age spectra which show younger $^{40}Ar/^{39}Ar$ apparent ages (because of low-temperature alteration) have Ca/K ratios closely similar to those corresponding to the plateau steps. Only for the high-temperature steps, highly variable Ca/K ratios are observed in every sample, probably reflecting the presence of fluid inclusions. All these characteristics, combined with the moderate LOI values of the samples and the petrographic observations, indicate that these ages are primary crystallization ages. For the lava flow samples, these reflect the eruption ages, whereas for the dyke samples, they reflect the age of intrusion. The ages are also consistent with the geological field relationships. Samples MMF4 (subalkalic basalt) and MMF7 (ankaramite) come from the lowest and uppermost flows exposed in the IIT hill in the Powai area, and show no time gap within analytical uncertainties. In fact, dykes MMD1 and MMD13 have intrusion ages that are indistinguishable from the eruption ages of the flows, and dyke MMD15 has an intrusion age which is ∼0.5 Myr younger, or essentially identical, within analytical uncertainties.

4 DISCUSSION

An important issue in studies of volcanic rifted margins is the timing of flexure formation relative to flood volcanism and continental breakup (Sheth & Pande 2014). Understanding this requires, besides careful field work, accurate and precise radio-isotopic dating of fresh, alteration-free volcanic units from key stratigraphic positions. Because all these conditions rarely obtain together, critical age data on key eruptive units in flexure zones are often scarce (Sheth & Pande 2014). We have provided $^{40}Ar/^{39}Ar$ ages for the Ghatkopar-Powai tholeiites here that are consistent with existing work and which indicate the timing of magmatism relative to tectonic deformation. The new $^{40}Ar/^{39}Ar$ ages show that tholeiitic

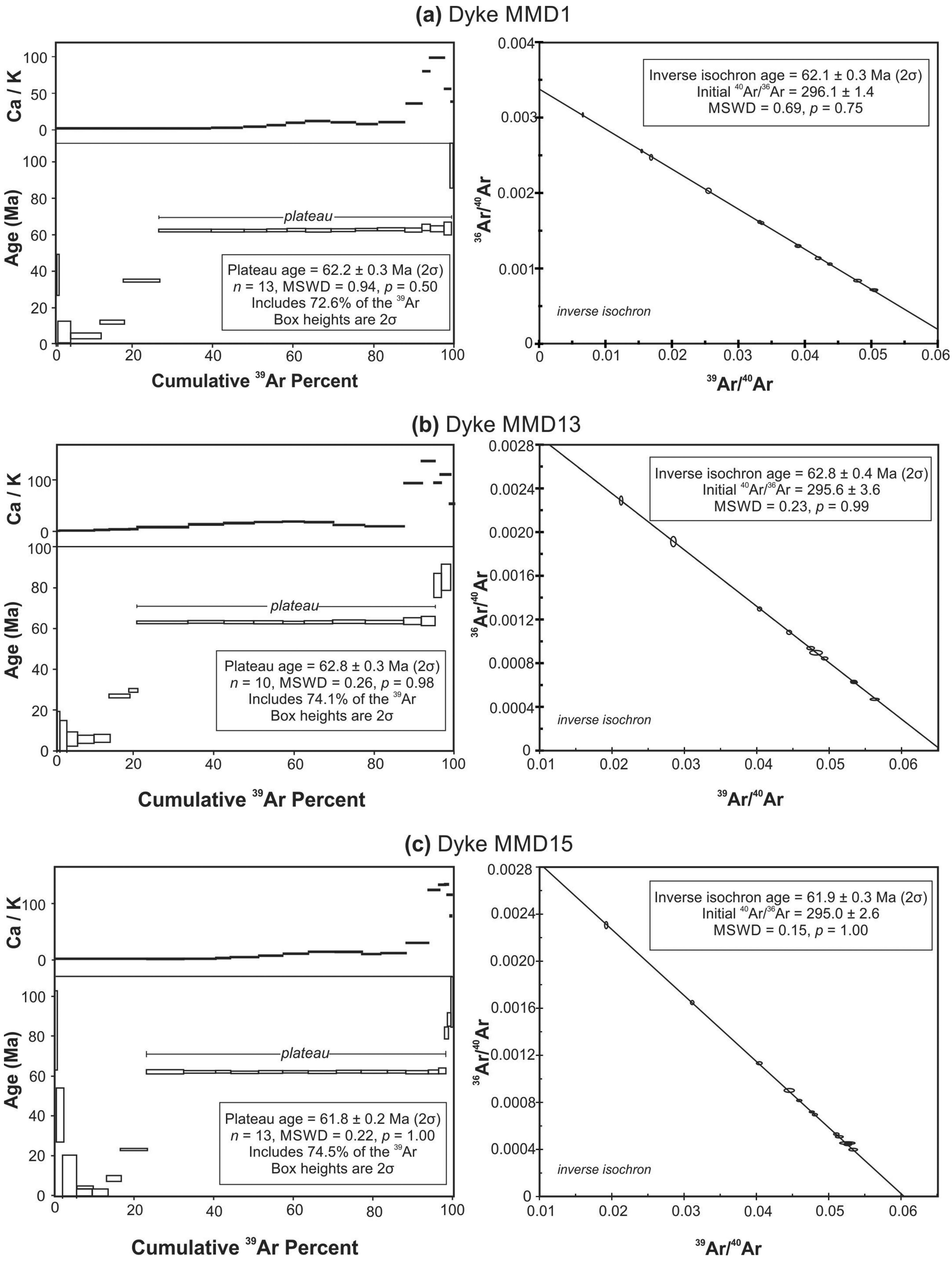

Figure 6. $^{40}Ar/^{39}Ar$ plateau spectra, Ca/K ratios and inverse isochrons for Ghatkopar-Powai tholeiitic dykes (a) MMD1, (b) MMD13 and (c) MMD15. Note that in the plateau plot for MMD13 (b), the final, non-plateau step constituting 1.23 per cent of total ^{39}Ar release and with an apparent age of 613 Ma is not shown, so as to truncate the vertical scale at 100 Ma, which would allow proper visual inspection of the plateau.

extrusion and intrusion in the Ghatkopar-Powai area of Mumbai occurred very rapidly, in fact essentially contemporaneously. The Panvel flexure formed after the tholeiitic flows (and any early dykes, not exposed) were tilted, but before the subvertical dykes (not tilted) were emplaced (see Fig. 3). Because the $^{40}Ar/^{39}Ar$ ages of the Ghatkopar-Powai flows and dykes are identical, the Panvel flexure is indicated to have formed very rapidly, practically instantaneously, at the same time, that is, 62.5 Ma. We note that a similar inference—syn-tectonic and syn-magmatic flexure formation—has been made for the Disko flexure in West Greenland (Geoffroy *et al.* 1998; see also a structural-tectonic study of the East Greenland coastal flexure by Klausen & Larsen 2002).

The age of 62.5 Ma is significant also in terms of the tectonic events which occurred in the deep offshore regions adjacent to the Indian mainland, formed due to the continental rifting and subsequent seafloor spreading between the Seychelles, Laxmi Ridge and India. One major event coinciding with this time is the onset of seafloor spreading between the Seychelles and Laxmi Ridge, which created the conjugate Arabian (Laxmi Ridge side) and the Eastern Somali (Seychelles side) basins. This inference is based on the oldest magnetic lineation identified in the Arabian Basin (Figs 7a and b), corresponding to chron C28ny (∼62.5 Ma; C27r/C28n boundary; Chaubey *et al.* 2002). Another event which occurred offshore western India at this time was the formation of the seamount chain consisting of the Raman Seamount, the Panikkar Seamount and the Wadia Guyot in the axial part of the Laxmi Basin (Fig. 7b). The genesis of these seamounts was attributed to anomalous volcanism (Bhattacharya *et al.* 1994a). The recently revised magnetic lineations in the Laxmi Basin (Bhattacharya & Yatheesh 2015, Figs 7a and b) suggest that the extent of this seamount chain is restricted within the conjugate magnetic lineations corresponding to chron C28ny (∼62.5 Ma), which implies that a substantial offshore volcanic event was initiated during C28ny (∼62.5 Ma).

Based on the combined observations, we infer that the emplacements of the onshore Ghatkopar-Powai tholeiitic flows and dykes and of the offshore Raman-Panikkar-Wadia seamount chain were contemporaneous. All these volcanic products arguably represent a single intense phase of Deccan volcanism at ∼62.5 Ma, during the rift-to-drift transition associated with the breakup of the Seychelles from the Laxmi Ridge and India. This scenario appears well corroborated by other $^{40}Ar/^{39}Ar$ ages available from Mumbai. The $^{40}Ar/^{39}Ar$ ages of the Ghatkopar-Powai tholeiites, obtained in this study, completely overlap that of the Dongri rhyolite flow in the uppermost part of the Mumbai stratigraphic sequence (62.6 ± 0.6 and 62.9 ± 0.2 Ma, Sheth & Pande 2014). Notably, both sets of ages have been calculated relative to the same monitor age (523.1 ± 2.6 Ma on MMhb-1, Renne *et al.* 1998) and are thus directly comparable.

Pre-rift magmatism is also present in Mumbai. Hooper *et al.* (2010) have reported a $^{40}Ar/^{39}Ar$ age of 64.55 ± 0.59 Ma (2σ) on plagioclase from a tholeiitic basalt flow in Jogeshwari (sample Bom18 of Cripps *et al.* 2005; flow dips west by 8°). This age is relative to an age of 98.79 Ma for biotite monitor GA1550, equivalent to the MMhb-1 age of 523.1 ± 2.6 Ma used here (Renne *et al.* 1998). This flow is significantly older than the other dated Mumbai units (Fig. 8). Because seafloor spreading between the Seychelles and the conjoined Laxmi Ridge-India was initiated at around 62.5 Ma (the age of the oldest magnetic lineation in the Arabian Basin), we ascribe the ∼64.55 Ma Jogeshwari tholeiitic basalt flow to a pre-rift stage of Deccan volcanism in Mumbai. Corresponding pre-rift magmatism on the Seychelles side is apparently represented in 63.5–63.0 Ma intrusions (Ganerød *et al.* 2011; Shellnutt *et al.* 2017).

Post-rift magmatism is abundant in Mumbai. Sheth *et al.* (2001a,b) dated the Saki Naka trachyte intrusion at 61.8 ± 0.6 Ma, the Manori trachyte intrusion at 60.4 ± 0.6 Ma and the Gilbert Hill basalt intrusion at 60.5 ± 1.2 Ma, all relative to a MMhb-1 age of 520.4 ± 1.7 Ma (Samson & Alexander 1987). The recalculated ages of these intrusive units relative to a MMhb-1 age of 523.1 ± 2.6 Ma, used here, are 62.2 ± 0.6 Ma (Saki Naka trachyte), 60.8 ± 0.6 Ma (Manori trachyte) and 60.9 ± 1.2 Ma (Gilbert Hill basalt), respectively. The latter two are coeval within analytical uncertainties, but are significantly younger than the Ghatkopar-Powai tholeiites, the Dongri rhyolite flow and the Saki Naka trachyte (Fig. 8). We therefore consider the Manori trachyte intrusion (60.8 ± 0.6 Ma) and the Gilbert Hill basalt intrusion (60.9 ± 1.2 Ma) to represent post-rift, onshore Deccan magmatism. The Mumbai trachytes were hypothesized to have formed by remelting of mafic sill complexes in the crust (Lightfoot *et al.* 1987), and the Manori-Gorai trachytes themselves contain mingled alkali basalt enclaves produced by mafic recharge in trachytic magma chambers (Zellmer *et al.* 2012). This shows that both felsic-alkalic magmatism (the various trachytic intrusions), alkali basalt magmatism (mafic enclaves in the Manori-Gorai trachytes) and tholeiitic basalt magmatism (represented in the Gilbert Hill intrusion) were active as late as 60.8–60.9 Ma, a post-rift and syn-drift stage of Seychelles-Laxmi Ridge/India breakup. Similarly, $^{40}Ar/^{39}Ar$ dating of K-feldspar, biotite and amphibole (Ganerød *et al.* 2011) and zircon U–Pb dating (Ganerød *et al.* 2011; Shellnutt *et al.* 2017) show that post-rift intrusions, many of them syenitic, were emplaced in the Seychelles as late as 60.6 ± 0.7 Ma. The $^{40}Ar/^{39}Ar$ ages of Ganerød *et al*. (2011) are reported relative to Taylor Creek rhyolite monitor age of 28.34 ± 0.16 Ma (corresponding to the MMhb-1 age of 523.1 ± 2.6 Ma used here), and the same decay constants and initial $^{40}Ar/^{36}Ar$ ratios as in our study.

Though the spread of all hitherto available $^{40}Ar/^{39}Ar$ ages on Mumbai rocks is about 64.5–60.8 Ma, we reach the important conclusion that there was an intense 62.5 Ma phase of both extrusion and intrusion in Mumbai, represented in the Ghatkopar-Powai tholeiitic flows and dykes, the Dongri rhyolite flow and the Saki Naka trachyte, whose $^{40}Ar/^{39}Ar$ ages show complete overlap. Concurrently with this intense eruptive and intrusive phases, the whole Mumbai sequence was affected by the Panvel flexure as a single package, at 62.5 Ma but no earlier (see also Sheth & Pande 2014). These eight $^{40}Ar/^{39}Ar$ ages of several distinct rock units throughout the Mumbai stratigraphy, with a weighted mean age of 62.4 ± 0.1 Ma (2 SEM), show intense and essentially instantaneous magmatism throughout Mumbai. This magmatism coincides with the rift-to-drift transition of the Seychelles and Laxmi Ridge-India breakup, magmatism in the Seychelles, and offshore volcanism forming a seamount chain in the axial part of the Laxmi Basin (Figs 7a and b).

5 CONCLUSIONS

We have dated, with the $^{40}Ar/^{39}Ar$ incremental heating method, tholeiitic flows and dykes exposed in the Ghatkopar-Powai area of Mumbai City, located in the structurally disturbed Panvel flexure zone, western Deccan Traps. The prominently seaward-dipping, pre-flexure flows and the subvertical, post-flexure dykes yield mutually indistinguishable $^{40}Ar/^{39}Ar$ ages of 62.5 Ma, indicating that the Panvel flexure should also have formed very rapidly, almost instantaneously, at 62.5 Ma. The same inference was reached by Sheth & Pande (2014) based on their 62.5 Ma $^{40}Ar/^{39}Ar$ age of the Dongri rhyolite flow in the uppermost part of the Mumbai volcanic sequence. These rock units and the Saki Naka trachyte intrusion (62.2 ± 0.6 Ma) are coeval, and indicate an intense, 62.5 Ma

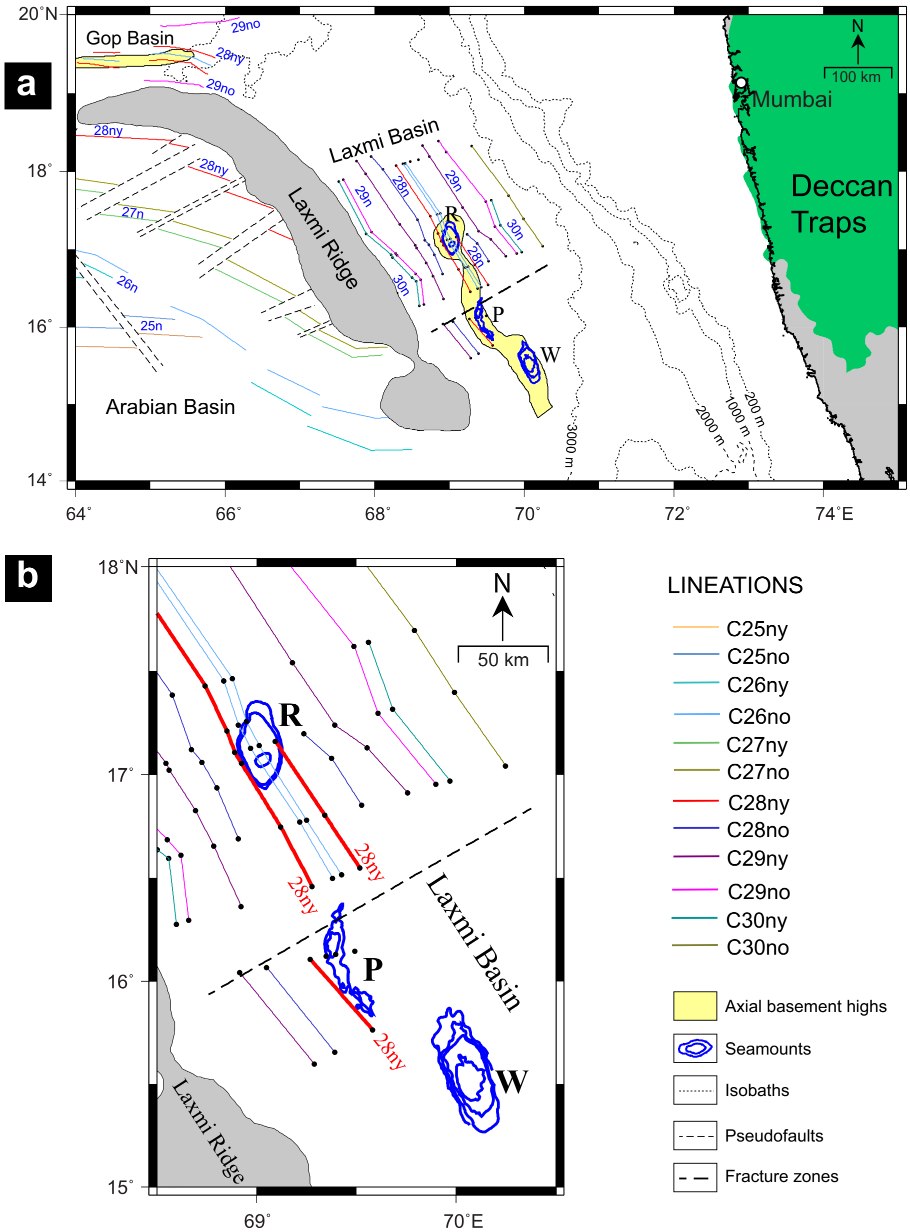

Figure 7. Maps showing (a) the tectonic setting of the deep offshore regions adjacent to the western continental margin of India and (b) the location and extent of the Raman, Panikkar and Wadia seamount chain in the Laxmi Basin and its relationship with the inferred magnetic lineations in the Laxmi Basin. The offshore tectonic elements are compiled from several sources (Bhattacharya *et al.* 1994a,b; Malod *et al.* 1997; Chaubey *et al.* 2002; Srinivas 2004; Yatheesh *et al.* 2009; Bhattacharya & Yatheesh 2015). The axial basement highs in the Laxmi and Gop basins represent the Panikkar and Palitana ridges, respectively. R is Raman Seamount, P is Panikkar Seamount and W is Wadia Guyot. Black dots represent magnetic anomaly picks and the coloured lines represent magnetic lineations (after Bhattacharya & Yatheesh 2015). The thick blue lines represent the seamounts defined by isobaths (after Bhattacharya *et al.* 1994a). The thick red lines in (b) represent chron C28ny isochrons.

extrusive and intrusive phase throughout Mumbai. Eight $^{40}Ar/^{39}Ar$ ages of distinct rock units throughout the Mumbai stratigraphy, with a weighted mean age of 62.4 ± 0.1 Ma (2 SEM), show intense and essentially instantaneous magmatism. These units are coeval with the rift-to-drift transition of the breakup between the Seychelles and the Laxmi Ridge-India (as identified from the oldest magnetic lineation in the Arabian Basin), with dated magmatic units in the Seychelles, and with the formation of the Raman-Panikkar-Wadia seamount chain in the axial part of the Laxmi Basin. All this voluminous onshore and offshore Deccan magmatism is temporally and causally related. The strong ∼N-S preferred orientations of the numerous Ghatkopar-Powai tholeiitic dykes, as well as dykes and faults on Elephanta Island just south of Mumbai, indicate considerable E-W or ESE-WNW crustal extension during this late (though magmatically vigorous) rift-to-drift stage of Deccan volcanism. The 64.55 Ma Jogeshwari tholeiitic basalt in Mumbai and 63 Ma intrusions in the Seychelles represent pre-rift Deccan volcanism, whereas the Manori trachyte (60.8 ± 0.6 Ma) and Gilbert Hill basalt (60.9 ± 1.2 Ma) intrusions in Mumbai (Sheth *et al.* 2001a,b) and ∼60–61 Ma syenitic intrusions in the Seychelles (Ganerød *et al.* 2011; Shellnutt *et al.* 2017) represent post-rift, syn-drift Deccan magmatism.

Our new $^{40}Ar/^{39}Ar$ data, combined with previously available data on the Mumbai eruptive and intrusive units, significantly improve

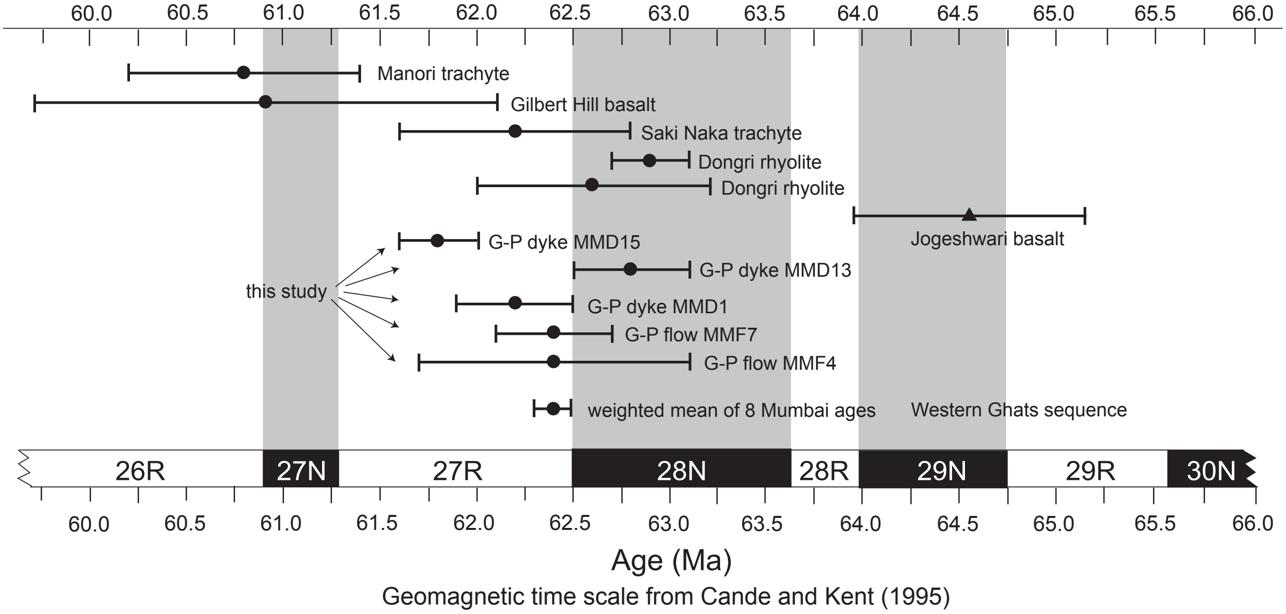

Figure 8. $^{40}Ar/^{39}Ar$ ages from Mumbai superposed on the geomagnetic polarity timescale of Cande & Kent (1995). The weighted mean $^{40}Ar/^{39}Ar$ age of eight samples is 62.4 ± 0.1 Ma (2 SEM) and falls near the chron 28ny (27R/28N boundary). Ages of three additional samples (the Manori trachyte, the Gilbert Hill basalt and the Jogeshwari basalt) are outside this distribution and were not included in this mean age. The partial overlap of the Gilbert Hill age with some others is only because of the former's rather high 2σ uncertainty of 1.2 Myr. However, all Mumbai rock units are significantly younger than the Western Ghats sequence, which falls mainly in chron 29R and extends into chron 29N (Baksi 2014; Renne *et al.* 2015).

our understanding of the interplay of volcanism, intrusion and tectonic deformation along an archetypal volcanic rifted margin, the western continental margin of India. They also unambiguously identify pre-, syn- and post-rift Deccan magmatism associated with the breakup of the Seychelles from the Laxmi Ridge and India.

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SUPPORTING INFORMATION

Supplementary data are available at *GJI* online.

Table S1. Stepwise heating results: Argon isotopic composition (corrected for blank, mass discrimination and interference), apparent Age and percentage of nucleogenic and radiogenic argon for the dated samples.