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Geological and $^{40}Ar/^{39}Ar$ age constraints on late-stage Deccan rhyolitic volcanism, inter-volcanic sedimentation, and the Panvel flexure from the Dongri area, Mumbai

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A B S T R A C T

Post-K–Pg Boundary Deccan magmatism is well known from the Mumbai area in the Panvel flexure zone. Represented by the Salsette Subgroup, it shows characters atypical of much of the Deccan Traps, including rhyolite lavas and tuffs, mafic tuffs and breccias, spilitic pillow basalts, and "intertrappean" sedimentary or volcanosedimentary deposits, with mafic intrusions as well as trachyte intrusions containing basaltic enclaves. The intertrappean deposits have been interpreted as formed in shallow marine or lagoonal environments in small fault-bounded basins due to syn-volcanic subsidence. We report a previously unknown sedimentary deposit underlying the Dongri rhyolite flow from the upper part of the Salsette Subgroup, with a westerly tectonic dip due to the Panvel flexure. We have obtained concordant $^{40}Ar/^{39}Ar$ ages of 62.6 ± 0.6 Ma (2σ) and 62.9 ± 0.2 Ma (2σ) for samples taken from two separate outcrops of this rhyolite. The results are significant in showing that (i) Danian inter-volcanic sedimentary deposits formed throughout Mumbai, (ii) the rock units are consistent with the stratigraphy postulated earlier for Mumbai, (iii) shale fragments known in some Dongri tuffs were likely derived from the sedimentary deposit under the Dongri rhyolite, (iv) the total duration of extrusive and intrusive Deccan magmatism was at least 8–9 million years, and (v) Panvel flexure formed, or continued to form, after 63 Ma, possibly even 62 Ma, and could not have formed by 65–64 Ma as concluded in a recent study.

1. Flood basalts, rifted continental margins, and monoclinal flexures

Continental flood basalt (CFB) provinces are frequently associated with rifted continental margins, and typically exhibit monoclinal flexures at the rifted margins. Prominent examples are the Karoo province of southern Africa, the Paraná province of South America, the East Greenland province, and the Deccan province of India. In a monoclinal flexure zone, the otherwise essentially flat-lying CFB lava pile shows significant seaward dips (as much as 45° in the Karoo), and this is where significant volumes of evolved magmas like rhyolites and trachytes, scarce over the rest of the province, are concentrated (e.g., Nielsen and Brooks, 1981; Lightfoot et al., 1987; Cox, 1988; Peate, 1997; Klausen and Larsen, 2002; Klausen, 2009).

The Panvel flexure of the Deccan province runs parallel to the NNW–SSE-trending western Indian rifted margin for >150 km, and has a width of ~30 km (see Fig. 1b of Sheth et al., 2014). It has been suggested to have formed due to simple monoclinal bending of the basalt pile (Blanford, 1867; Wynne, 1886; Auden, 1949), as an extensional fault structure (Dessai and Bertrand, 1995), and as a reverse drag structure on an east-dipping listric master fault (Sheth, 1998). These models are not completely mutually exclusive, but another important issue is the timing of flexure formation relative to flood volcanism and continental breakup. 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 occur together, and because geochronological studies have focussed on the thickest CFB sections to evaluate their links to mass extinctions (e.g., Baksi, 2014 and references therein), critical age data on key eruptive units in flexure zones are often scarce.

Hooper et al. (2010) have argued, based on geochemical and $^{40}Ar/^{39}Ar$ age data for mafic lavas and dykes in the Panvel flexure zone, that the flexure formed by 65–64 Ma, soon after the Deccan CFB eruptions. Here, we present two $^{40}Ar/^{39}Ar$ ages on a key rhyolite unit from the Dongri area of Mumbai, also in the Panvel flexure zone. Based on geological considerations which we describe in detail, and the $^{40}Ar/^{39}Ar$ ages, we conclude that the Panvel flexure formed as late as 63 Ma, possibly even 62 Ma, and could not have formed by 65–64 Ma. This result is significant for understanding the tectonic evolution of the western Indian rifted margin.

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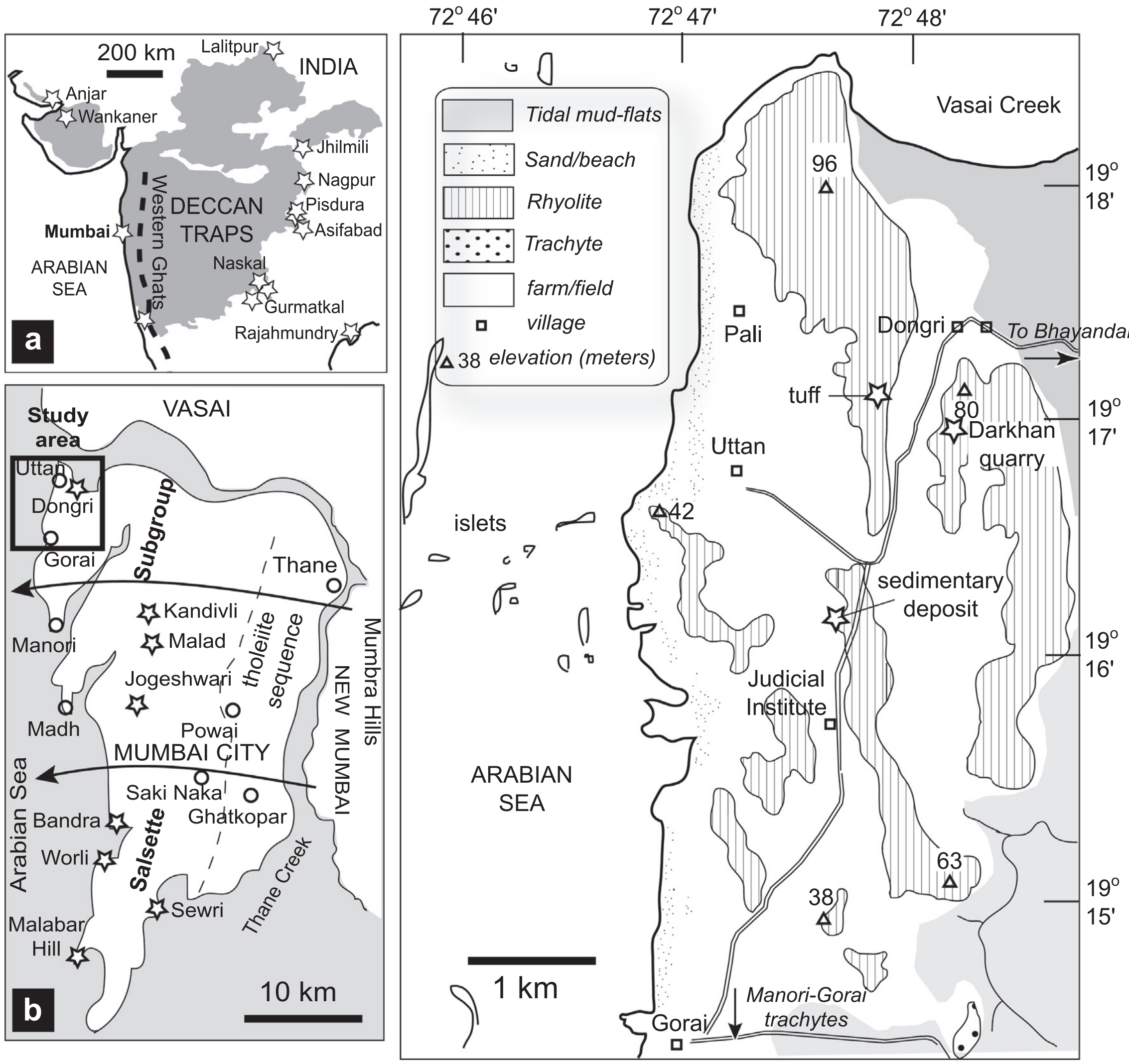

Fig. 1. (a) Map of India and the Deccan Traps (gray), showing the Western Ghats type section, Mumbai, and other localities of Deccan intertrappean and infratrappean sedimentary deposits (stars), some of which are named (based on Shekhawat and Sharma, 1996; Jay and Widdowson, 2008). (b) Map of Mumbai, showing the localities of the intertrappean deposits (stars), including the newly discovered one at Dongri (based on Sethna, 1999; Singh, 2000; Cripps et al., 2005; this study). Curved arrows indicate the Panvel flexure. (c) Geological map of the Uttan–Dongri area (based on Zellmer et al., 2012 and references therein), showing the locations of the outcrops studied in the present work.

2. Deccan geology of Mumbai, Panvel flexure zone

Deccan flood basalt volcanism (Fig. 1a) overlapped with, and has been directly implicated in, the major Cretaceous–Palaeogene (K–Pg) Boundary mass extinctions at ~65.5 Ma (e.g., Keller et al., 2008). Though dominated by tholeiitic flood basalts, the Deccan province shows alkalic and silicic rocks concentrated in regions such as Mumbai and the Panvel flexure zone, and the Saurashtra peninsula, both on the western Indian rifted margin (e.g., Sukheswala and Poldervaart, 1958; Sukheswala, 1974; Sethna and Battiwala, 1977; Godbole and Ray, 1996; Sheth et al., 2011, 2012).

The Ghatkopar–Powai area of Mumbai (Fig. 1b) exposes prominently seaward-dipping (17°) tholeiitic basalt flows intruded by many tholeiitic dykes (Sheth, 1998; Sheth et al., 2014). The southern and western parts of Mumbai show volcanic and volcanosedimentary deposits as well as intrusions of considerable compositional diversity, all belonging to a post-K–Pg Boundary phase of Deccan magmatism (Sethna and Battiwala, 1977, 1980; Sethna, 1999; Sheth et al., 2001a,b; Cripps et al., 2005). This Danian sequence also prominently dips west. Sethna (1999) named it the Salsette Subgroup, and considered it to be younger than the entire Western Ghats stratigraphic sequence (Table 1). He divided the Salsette Subgroup into a Mumbai Island Formation, made up of subaqueous lavas including spilitic pillow basalts, tuffs, and shales, followed by a Madh–Uttan Formation made up of rhyolite lava flows, followed by a Manori Formation, comprising trachyte intrusions (Table 1). The "intertrappean" sedimentary beds of tuffs, clays and shales have yielded fossil frogs, ostracods, turtle skulls and crocodilian eggshell fragments (e.g., Owen, 1847; Carter, 1852a,b; Blanford, 1867, 1872; Chiplonker, 1940; Cripps et al., 2005). The shales contain considerable volcanic ash input, and are often carbonaceous (Singh, 2000).

Sheth et al. (2001a,b) dated two distinctly west-dipping trachyte units from Manori and Saki Naka (Fig. 1b) at 60.4 ± 0.6 Ma (2σ) and 61.8 ± 0.6 Ma (2σ) respectively ($^{40}Ar/^{39}Ar$), and the Gilbert Hill basalt intrusion near Andheri (Fig. 1b) at 60.5 ± 1.2 Ma (2σ). Interpreting the trachytes as dipping lava flows, they suggested that the Panvel flexure had formed after 60 Ma. Careful reading of earlier work on these trachytes (Sethna and Battiwala, 1974, 1976) as well as more detailed field and geochemical work (Zellmer et al., 2012) shows that these trachytes are exhumed subvolcanic intrusions, and their 60–62 Ma ages cannot

Table 1
Mumbai volcanic stratigraphy relative to the Western Ghats lava stratigraphy.

Group	Subgroup	Formation	Rock types
	Salsette	Manori	Trachyte intrusions with mingled basalt enclaves
		Madh–Uttan	Rhyolite lava flows
		Mumbai Island	Hyaloclastites, spilites, basalts and shales
Deccan Basalt Group	Wai	Poladpur, Ambenali, Mahabaleshwar, Panhala, and Desur	Subaerial tholeiitic flood lavas
	Lonavala	Khandala and Bushe	Subaerial tholeiitic flood lavas
	Kalsubai	Jawhar, Igatpuri, Neral, Thakurvadi, and Bhimashankar	Subaerial tholeiitic flood lavas

Notes: The Salsette Subgroup (Sethna, 1999) has been placed by him above the three stratigraphic subgroups of the Deccan Basalt Group in the Western Ghats sequence (Subbarao and Hooper, 1988 and references therein). Cripps et al. (2005) have considered the Salsette Subgroup to be contemporaneous with the last eruptions of the Wai Subgroup lavas.

constrain the age of the Panvel flexure. Ages obtained on *eruptive* units can, but no radio-isotopic ages have been obtained on any of the Mumbai rhyolites with the exception of a Rb–Sr isochron age of 61.5 ± 1.9 Ma (Lightfoot et al., 1987). Sheth and Ray (2002) questioned this age on several grounds including possible mixing relationships.

In this study, we have obtained two $^{40}Ar/^{39}Ar$ ages on the Dongri rhyolite flow from the Madh–Uttan Formation of the Salsette Subgroup. We have also found, under this rhyolite, a hitherto unknown sedimentary deposit, as well as a tuff deposit nearby which contains shale fragments. We now describe the geology of these rock units with some interpretations about their formation environment, and follow with details of the $^{40}Ar/^{39}Ar$ dating of the Dongri rhyolite and its bearing on the question of the age of the Panvel flexure.

3. Geology of the Dongri rhyolite and associated rock units

3.1. The rhyolite

A detailed geochemical study of the Mumbai rhyolites was presented by Lightfoot et al. (1987) who mentioned up to five rhyolite units 20–100 m thick and with a strike length of 20 km. The Dongri rhyolite is a thick (>70 m), prominently columnar-jointed lava flow exposed in the Darkhan quarry just to the south of Dongri village, east of the Dongri–Gorai road (Fig. 1c). The rhyolite is light brown, fine-grained, essentially aphyric and non-vesicular, and made up of quartz and K-feldspar. We sampled its exposed base in the quarry (sample UTRH). Owing to the westerly dip the Dongri rhyolite flow is encountered at a lower level in a valley on the western side of the Dongri–Gorai road, 1.7 km south–southwest of the Darkhan quarry and 800 m north of the Judicial Institute (Fig. 1c).

Here the rhyolite shows well-developed columns which dip steeply east, suggesting that the flow dips ~10° west (Fig. 2a and b), based on the general principle that columnar joints in a solidifying tabular igneous body (whether a lava flow, sill, or dyke) propagate perpendicular to the isotherms (surfaces of equal temperature), which in an undisturbed magma body are parallel to its margins (e.g., Spry, 1962; DeGraff and Aydin, 1987; Lyle, 2000). We are aware of many possible complications, as when columns form in highly random orientations in the "entablature" zones of solidifying lava flows, typically due to ingress of rainwater (e.g., Tomkeieff, 1940; Long and Wood, 1986; De, 1996). There are also cases where stacks of parallel columns may be inclined to the flow margins, owing to late-stage flow (Waters, 1960). In the present case, westward dip of the Dongri rhyolite flow is visible in an oblique view afforded by the exposure (Fig. 2b). Besides, all Mumbai rhyolites including those at Madh (Fig. 1b), as well as the other Salsette Subgroup units, have westward dips, as do also the Ghatkopar–Powai tholeiites (Sheth et al., 2014). For the latter

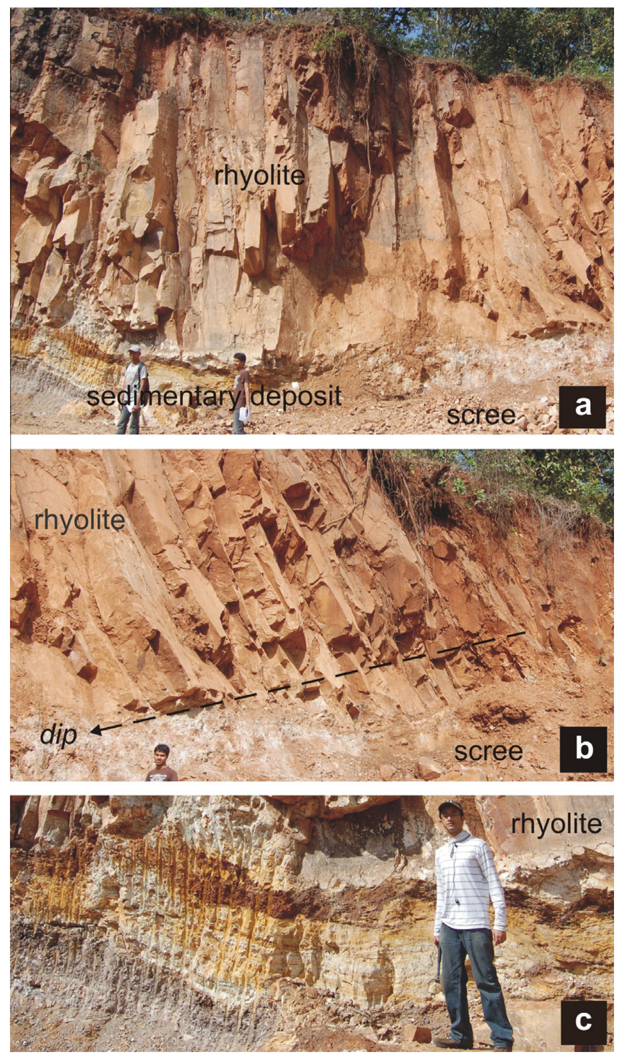

Fig. 2. (a–c) Field photographs of the Dongri rhyolite and sedimentary deposit. Students provide a scale.

reason, the westward dip of the Dongri rhyolite cannot be explained in an isolated manner by invoking eruption of the Dongri rhyolite on an already inclined surface. The consistent westward dips shown by all these rock units are tectonic dips produced by the Panvel flexure.

The Dongri rhyolite is underlain by a sedimentary deposit (Fig. 2a and c). We sampled the base of the rhyolite flow (sample UTRH-1) just above the sedimentary deposit, and this is petrographically similar to the Darkhan quarry rhyolite. We consider the two samples UTRH and UTRH-1 to represent the same lava flow.

3.2. The sedimentary deposit

This deposit, discovered by us in March 2011, was not exposed during many prior visits to the area over several years, but has become available due to recent excavation for clay under the rhyolite by local villagers. The outcrop becomes inundated by water during the vigorous Mumbai monsoons due to its low elevation (only a few meters above sea level) and proximity to the coastline (1 km). The exposed thickness of the sedimentary deposit is 2.5–3 m, and the exposed lateral extent ~20 m (Fig. 2a and c). Dark gray shales in the lower part of the Dongri sedimentary deposit are overlain by light gray, patchy yellow–gray, dark brown, and light gray shales and clays (Fig. 2c). They are all laminated on the millimeter-scale, soft and fragile. Intertrappean sedimentary deposits in the Deccan Traps are generally only a few meters thick, an exception being a 150-m-thick black carbonaceous shale encountered in a construction tunnel at Bandra (Fig. 1b), indicating long local volcanic quiescence there (Sethna, 1999).

3.3. The Dongri tuff

We have found a tuff deposit on the 96 m hill exactly west of the Darkhan rhyolite quarry (Fig. 1c), in a residential property undergoing construction work in 2007. Because the volcanic sequence becomes younger westwards, we consider this tuff to overlie the Dongri rhyolite. The tuff has a light gray ash matrix with many dark gray shale fragments, a few reaching 2 cm (Fig. 3a). The tuff also shows occasional subangular to subrounded fragments 5–6 cm in diameter, made up of very fine, vesicular material and lacking internal structure (Fig. 3b). These are probably the same as the "coalesced ash bombs" described by Sukheswala (1956) from Mumbai intertrappean volcanosedimentary deposits, and by Cripps et al. (2005, sample 3/99) from the Amboli quarry at Jogeshwari (Fig. 1b).

Photomicrographs of the Dongri tuff are given in Fig. 3c and d. In thin section this tuff shows shows shale fragments (isotropic), basalt fragments, as well as clinopyroxene crystals. The tuff has

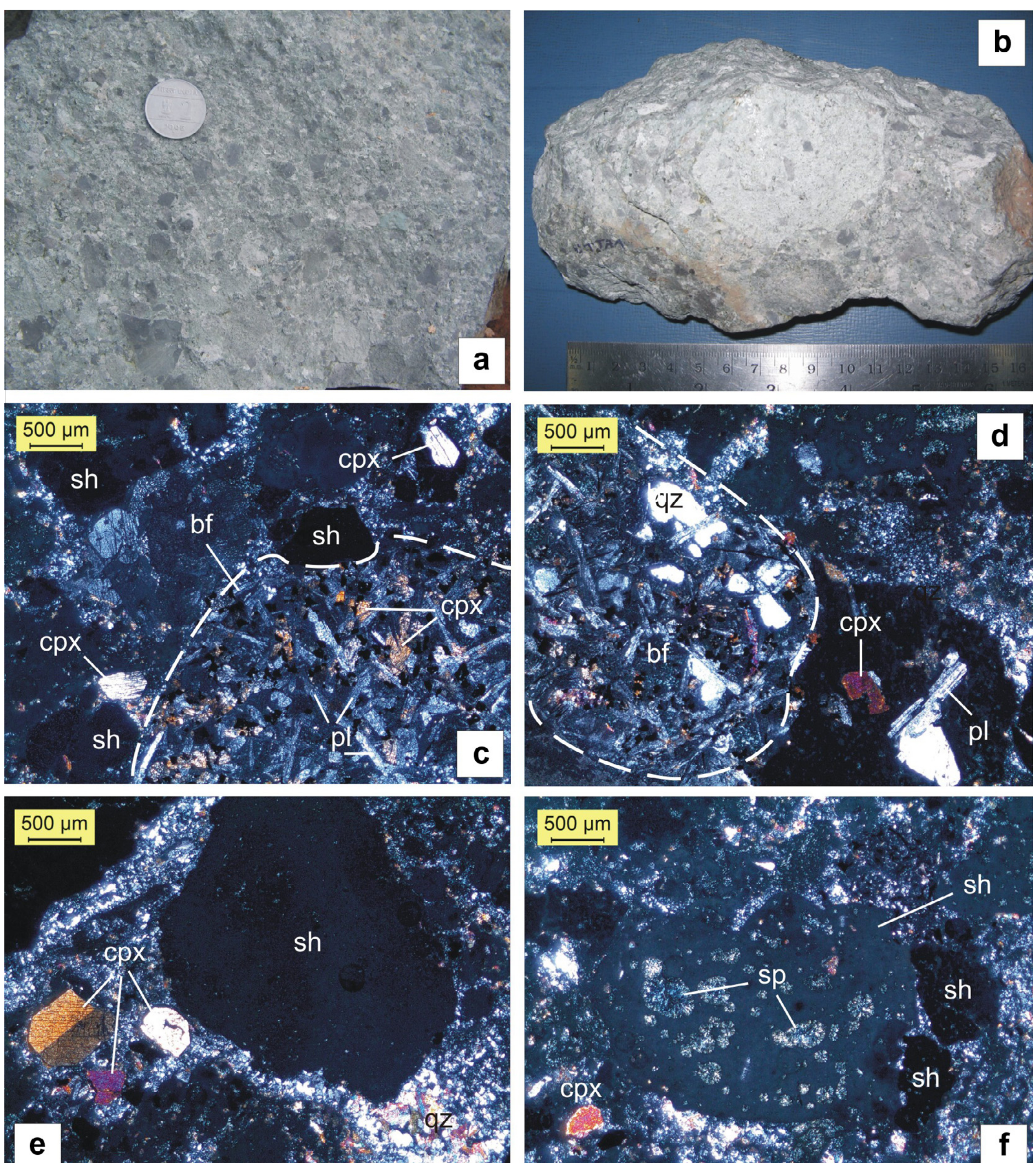

Fig. 3. (a and b) Hand specimens of the Dongri tuff. (b) Shows a large fragment. Ruler is in centimeters. (c–f) Photomicrographs of the Dongri tuff. The abbreviations are: bf, basaltic fragment (shown by white dashed lines); cpx, clinopyroxene; pl, plagioclase; qz, quartz; sh, shale; sp, spherulitic quartz.

experienced much silicification, with veins of quartz and spherulitic quartz infilling shale fragments. Singh (2000) classified Mumbai intertrappean tuffs into vitric and lithic tuffs from petrographic studies, though these tuffs also contained crystals of pyroxene and feldspars. He observed much devitrification of glass, and diagenesis. Sukheswala (1956) also identified pyroxenes and feldspars in the Worli ash beds. Based on the Dongri tuff's componentry we term it a mixed lithic–crystal–vitric tuff (following the terminology of Schmid, 1981).

3.4. Interpretation

The sedimentary deposit underlying the Dongri rhyolite is consistent with the Mumbai volcanic stratigraphy proposed by Sethna (1999) (Table 1), in which the Madh–Uttan–Dongri area rhyolite lavas overlie the intertrappean shales (and older lavas) of the Mumbai Island Formation. The Dongri area shows that volcanism and sedimentation succeeded each other during the deposition of the Salsette Group, as they did over much of Mumbai (e.g., Sethna, 1999; Cripps et al., 2005). Detailed studies of the Salsette Group intertrappean deposits by Singh (2000) and Cripps et al. (2005) have indicated deposition in shallow marine or lagoonal environments, in small fault-founded basins, due to synvolcanic subsidence.

The Dongri sedimentary deposit explains the occurrence of fragments of baked carboaceous shale in tuffs of the Uttan–Dongri area as reported by Sethna and Mousavi (1994). Shale baking may have been caused by intrusions, as at the Amboli quarry (Singh, 2000), or by incorporation of the shale fragments in hot erupting ash as in the Uttan–Dongri area. The angularity of the volcanic and shale fragments and crystal shapes in the Dongri tuff suggests minimum transport (cf. Singh, 2000). The lack of bedding or laminations suggests rapid deposition, possibly from vents nearby. The pale color of the tuff despite the mafic content may be due to bleaching by vapors. The ash aggregates (Fig. 3b) appear to be of the nature of large accretionary lapilli (see also Cripps et al., 2005), though they lack the typical concentric structure, and would then indicate wet explosive eruptions (e.g., Brown et al., 2010). The shale fragments in the Dongri tuff do not appear to have come from explosions under the exposed, undisturbed sedimentary deposit. The explosions probably occurred under the current outcrop of the tuff, and given the 1 km distance between the sedimentary outcrop and the tuff, the lateral subsurface extent of the former is at least that much. Carter (1852b) has mentioned that the small rocky islets west of Uttan (Fig. 1c) are also made up of tuffs.

4. $^{40}Ar/^{39}Ar$ dating of the Dongri rhyolite

A key point we make is that the westward dips of the Dongri rhyolite flow, the rest of the Salsette Subgroup, and the Ghatkopar–Powai tholeiites, are tectonic, and were acquired after eruption when the Panvel flexure formed. The crystallization age (=eruption age) of the Dongri rhyolite flow, from the uppermost levels of the Salsette Subgroup, should therefore provide an *upper* limit on the formation of the Panvel flexure. With this understanding, we carried out $^{40}Ar/^{39}Ar$ dating of the two samples of the Dongri rhyolite flow.

4.1. Analytical methods

Rock chips of the Dongri rhyolite (samples UTRH and UTRH-1) were crushed and sieved and the 120–180 μm size-fraction was leached with a 1% HCl solution to eliminate secondary carbonates. The sample material was cleaned in deionised water in an ultrasonic bath and about 0.2 g of each was packed in aluminum 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 about 5%. The aluminum capsules were kept in a 0.5 mm thick cadmium cylinder and irradiated, in two separate batches, in the light-water moderated CIRUS reactor at the Bhabha Atomic Research Centre (BARC), Mumbai, for ~100 h. The irradiated samples were repacked in aluminum 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 ultra-high vacuum furnace. After purification using Ti–Zr getters, the argon released in each step was measured with a Thermo-Fisher ARGUS mass spectrometer located at the National Facility for $^{40}Ar–^{39}Ar$ Geo-thermochronology in the Department of Earth Sciences, IIT Bombay. The mass spectrometer is equipped with five Faraday cups fitted with 10^{11} ohm resistors.

Interference corrections for Ca- and K-produced Ar isotopes based on analysis of pure CaF_2 and K_2SO_4 salts were $(^{36}Ar/^{37}Ar)_{Ca}$, $(^{39}Ar/^{37}Ar)_{Ca}$ and $(^{40}Ar/^{39}Ar)_K$ = 0.000438, 0.000921 and 0.004451, respectively, for sample UTRH. The same parameters were 0.000334, 0.000762, and 0.000808, respectively, for sample UTRH-1. ^{40}Ar blank contributions were 1–2% or less for all temperature steps. The irradiation parameter J for the sample was corrected for neutron flux variation using the activity of nickel wires irradiated with each sample. Value of fluence-corrected J is 0.001545 ± 0.000006 for UTRH, and 0.002317 ± 0.000009 for UTRH-1.

4.2. Results

The $^{40}Ar/^{39}Ar$ step heating data were plotted using the program ISOPLOT v. 3.75 (Ludwig, 2012) and are tabulated in Online Appendix I. We define a plateau in an argon release spectrum as comprising a minimum of 60% of the total ^{39}Ar released and four or more successive degassing steps with mean ages overlapping at the 2σ level including the error contribution from the J value (e.g., Sen et al., 2012).

Sample UTRH yielded a 18-step plateau age of 62.6 ± 0.6 Ma (2σ), with the age spectrum comprising 69.0% of total ^{39}Ar released (Fig. 4a). Higher-temperature steps than the plateau spectrum yielded progressively increasing apparent ages, which we ascribe to excess argon (see e.g., Lanphere and Dalrymple 1971, 1976; Kaneoka, 1974, 1980; Balasubrahmanyan and Snelling, 1981; Iwata and Kaneoka, 2000; Kelley, 2002). This excess argon may reside in fluid inclusions in minerals (e.g., Kelley, 2002). The sample UTRH's isochron age of 62.9 ± 0.7 Ma (2σ) and inverse isochron age of 62.9 ± 0.6 Ma (2σ) are statistically indistinguishable from the plateau age (Fig. 4b and c).

Sample UTRH-1 also yielded a 18-step plateau age of 62.9 ± 0.2 Ma (2σ), with the age spectrum comprising 90.1% of total ^{39}Ar released (Fig. 5a). Its isochron age of 62.9 ± 0.6 Ma (2σ) and inverse isochron age of 62.9 ± 0.3 Ma (2σ) are statistically indistinguishable from the plateau age (Fig. 5b and c). The concordant plateau, isochron and inverse isochron ages of both rhyolite samples, the large amount of total released ^{39}Ar for the plateau steps, the acceptable MSWD values of the isochron and inverse isochron, as well as the atmospheric value (295.5) of the $^{40}Ar/^{36}Ar$ ratio of trapped argon given by their intercepts, suggest that these ages represent crystallization ages. We take the identical $^{40}Ar–^{39}Ar$ plateau ages of 62.6 ± 0.6 Ma (2σ) and 62.9 ± 0.2 Ma (2σ) as the crystallization and eruption age of the Dongri rhyolite flow.

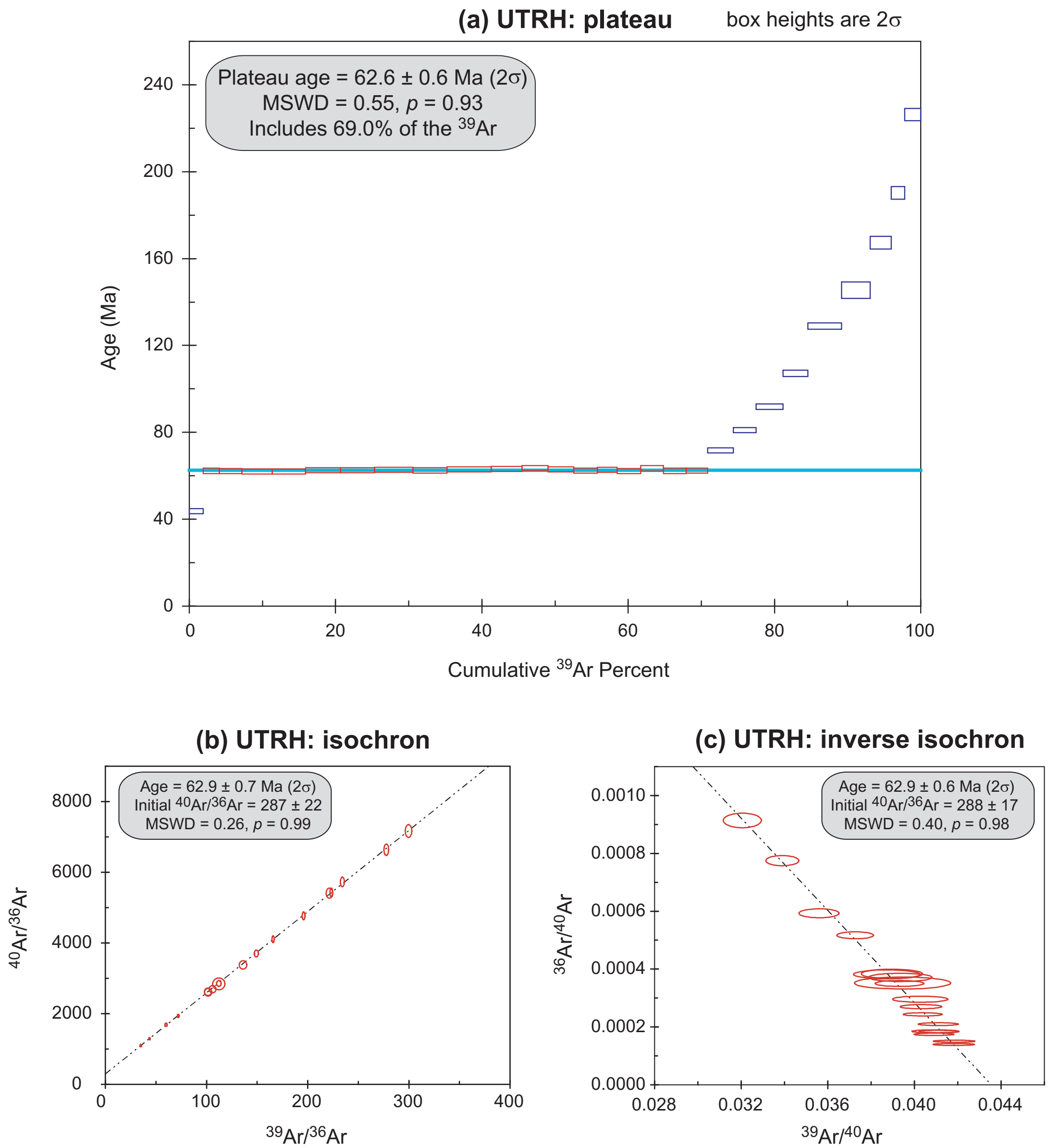

Fig. 4. (a–c) $^{40}Ar/^{39}Ar$ plateau, isochron, and inverse isochron plots for the Dongri rhyolite sample UTRH. In the plateau spectrum (a), the plateau steps are shown with red outlines and the non-plateau steps with dark blue outlines. Also shown are values of the MSWD (mean square weighted deviate) and probability (*p*). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. Discussion

5.1. The distribution of intertrappean sedimentary deposits in Mumbai

Fig. 1b shows the localities of intertrappean sedimentary deposits in Mumbai. The northernmost outcrops so far known were at Malad and Kandivli (and have been destroyed since they were originally mapped). The outcrop and subsurface rock samples studied in detail by Cripps et al. (2005) came from the Amboli quarry at Jogeshwari (which has since been destroyed), as well as Bandra and Worli. The new find of the sedimentary deposit under the Dongri rhyolite (Fig. 1b) shows that these deposits have a Mumbai-wide distribution. This is not to say that all these localities represent a single phase of sedimentation or a continuous sedimentary basin, because they have their differences. The Worli and Bandra tunnel intertrappean sequences are dominated by shales, including an almost uninterrupted 150 m thick shale (Sethna, 1999), suggesting a long local eruptive hiatus. The Amboli intertrappeans had much more pyroclastic input, from eruption centers located nearby (Singh, 2000; Cripps et al., 2005). It can be said that isolated small, shallow basins developed from time to time in the western parts of Mumbai due to syn-volcanic faulting and subsidence, and these became the depocenters for sediments and pyroclastic products (Cripps et al., 2005). All would nevertheless be broadly correlatable in age with the same faunal-floral assemblage. The $^{40}Ar/^{39}Ar$ ages of the Dongri rhyolite flow (62.6 ± 0.6 Ma and 62.9 ± 0.2 Ma, 2σ) indicate that the Dongri sedimentary deposit was formed no later than 63–62 Ma.

Localities of intertrappean sedimentary beds in the entire Deccan Traps are few and widely spaced (Fig. 1a). With the exception of those at Rajahmundry on the eastern Indian coast, and Mumbai on the west coast, the interior ones have been interpreted as lacustrine and palustrine, and formed under semiarid conditions, during Maestrichtian time (e.g., Mohabey et al., 1993; Khosla and Sahni, 2003). In contrast, Mumbai intertrappeans represent shallow marine or lagoonal conditions during Danian time (Cripps

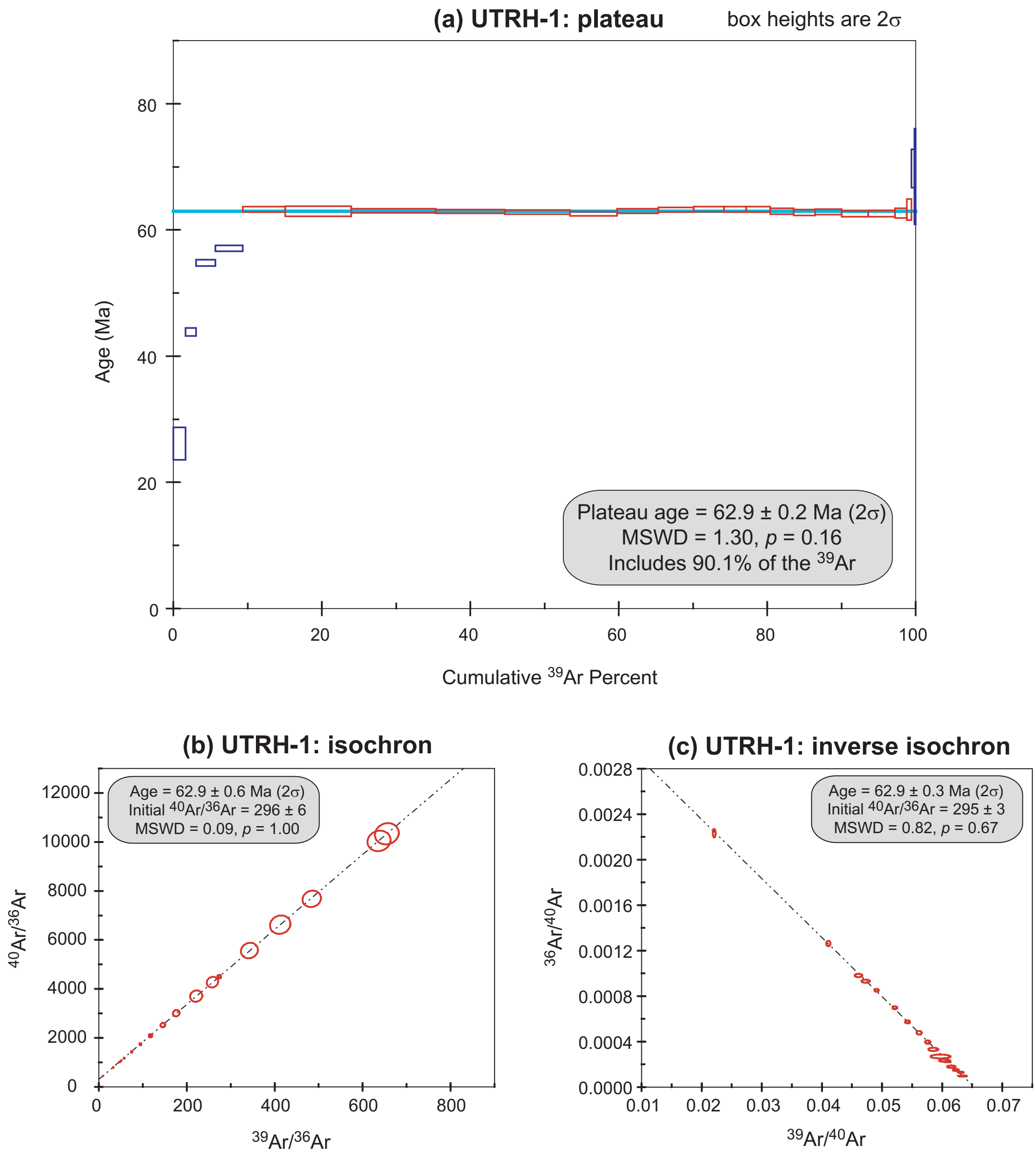

Fig. 5. (a–c) $^{40}Ar/^{39}Ar$ plateau, isochron, and inverse isochron plots for the Dongri rhyolite sample UTRH-1. In the plateau spectrum (a), the plateau steps are shown with red outlines and the non-plateau steps with dark blue outlines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2005). Interestingly, at Jhilmili in central India there was a brief period of incursion of a shallow sea, indicated by Danian planktonic foraminifera (Keller et al., 2009). Tertiary-age Deccan intertrappeans are extremely scarce (Singh and Kar, 2002), underscoring the significance of the newly discovered Dongri sedimentary deposit.

5.2. The overall duration of Deccan magmatism

Sheth et al. (2001a,b) argued, based on their $^{40}Ar/^{39}Ar$ ages of 62–60 Ma on the Manori and Saki Naka trachytes and the Gilbert Hill basaltic intrusion, and noting alkaline magmatism at ~68.5 Ma in the northwestern Deccan Traps (Basu et al., 1993), that the total duration of Deccan magmatism was at least 8–9 million years. The new $^{40}Ar/^{39}Ar$ ages of 63–62 Ma for the Dongri rhyolite flow, presented here, provide further evidence that both intrusive and extrusive activity in the Deccan Traps occurred well into the Palaeocene.

5.3. The timing of formation of the Panvel flexure

Hooper et al. (2010) have suggested, based on geochemical and $^{40}Ar/^{39}Ar$ dating work on coastal lavas and dykes of the Panvel flexure zone south of Mumbai, that the Panvel flexure had already formed by 65–64 Ma. Hooper et al. (2010) dated a subaqueous spilitic basalt flow from the lower part of the Salsette Subgroup (sample Bom18, $^{40}Ar/^{39}Ar$) at 64.55 ± 0.59 Ma (2σ). They argued that the Mumbai Island Formation (including many spilitic pillow basalts like Bom18) had formed in a seaway developed *due to* the Panvel flexure and the associated normal faulting, which therefore should have occurred by 65–64 Ma.

The Madh–Uttan–Dongri rhyolite lavas are much younger than this, noting our ^{40}Ar/^{39}Ar ages of 62.6 ± 0.6 Ma (2σ) and 62.9 ± 0.2 Ma (2σ) for the Dongri rhyolite. If the Panvel flexure had formed by 65–64 Ma as Hooper et al. (2010) suggest, how did the youngest rhyolite lavas acquire prominent westward dips, with the rest of the Salsette Subgroup and the Ghatkopar–Powai tholeiitic sequence? And if the spilitic basalts formed after the Panvel flexure had developed, how did *they* acquire westward tectonic dips?

The basic geological observation that the whole Mumbai sequence is west-dipping, from the Ghatkopar–Powai tholeiites through the lowermost spilitic pillow basalts to the uppermost rhyolite lavas of the Salsette Subgroup, implies that the whole sequence was affected by the Panvel flexure as a single package. It is possible that the Panvel flexure formed in a single, rapid event, which must then postdate the eruption of the youngest rhyolite lavas. This scenario would be consistent with a tectonic model of the Panvel flexure involving a listric master fault in the western Indian margin (Sheth, 1998). Alternatively, the Panvel flexure may have developed incrementally, over time, such that it *continued to form* after the youngest rhyolite lavas, and flexed them after they formed. This scenario appears consistent with a tectonic model of the Panvel flexure involving extensional faulting, repeated dyke injection and volcanic loading, of the type proposed for the East Greenland flexure by Klausen and Larsen (2002). In either scenario, the Panvel flexure cannot predate the 64–65 Ma spilitic basalt lavas.

If so, what about the subaqueous eruption, seaway, and the Panvel flexure postulated by Hooper et al. (2010)? We believe that a seaway (or a quasi-marine basin) existed at 65–64 Ma, but this does not require the Panvel flexure. In other words, such a basin probably developed at 65–64 Ma due to early extension and subsidence along the rifted margin, the spilitic pillow basalts of the Mumbai Island Formation formed in it, as did other volcanosedimentary units, and finally the Madh–Uttan–Dongri rhyolites were erupted much later, some partly under water (Sethna and Mousavi, 1994) and others like the Dongri rhyolite subaerially. The Panvel flexure only formed subsequently, imparting a tectonic dip to all units down from the rhyolites to the spilitic pillow basalts and the Ghatkopar–Powai tholeiites. Considering the analytical uncertainties on the two ^{40}Ar/^{39}Ar ages of the Dongri rhyolite, the Panvel flexure formed no earlier than 63.2 Ma, and may have formed as late as 62 Ma. The 65–64 Ma spilitic pillow basalts of Hooper et al. (2010), far from requiring the Panvel flexure to form, were affected and tilted by the Panvel flexure 2–3 million years after their eruption.

6. Conclusions

The mechanism and timing of formation of monoclinal flexures, found in CFB provinces located on rifted continental margins, has been a contentious issue. In the Mumbai area of the Deccan Traps CFB province, India, the volcanic sequence shows a prominent westerly (seaward) dip and forms the western limb of the Panvel flexure. We have obtained precise and concordant ^{40}Ar/^{39}Ar ages of 62.6 ± 0.6 Ma (2σ) and 62.9 ± 0.2 Ma (2σ) for the Dongri rhyolite flow from the upper part of this volcanic sequence, and have also discovered a sedimentary deposit under this rhyolite. Our results lead to the following significant inferences:

(i) Post-K–Pg Boundary inter-volcanic sedimentary deposits formed throughout the length of Mumbai due to periodic, syn-volcanic faulting and subsidence (e.g., Cripps et al., 2005).
(ii) The Dongri sedimentary deposit has a lateral subsurface extension of at least 1 km and is consistent with the volcanic stratigraphy previously postulated for Mumbai (Sethna, 1999).
(iii) Shale fragments known in the Uttan–Dongri area tuffs (Sethna and Mousavi, 1994) were sourced from Dongri sedimentary deposit, which formed no later than 63–62 Ma.
(iv) The total duration of Deccan magmatism, including intrusive and extrusive manifestations, was at least 8–9 million years (cf. Sheth et al., 2001a,b).
(v) The Panvel flexure, a major, unquestionably post-volcanic tectonic structure, formed, or continued to form, after 63 Ma, possibly even 62 Ma, and cannot have formed by 65–64 Ma as concluded in a recent study (Hooper et al., 2010). This result is of particular interest and significance in understanding the interplay of volcanism, intrusion, and tectonic deformation at rifted continental margins.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jseaes.2013.08.003.

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