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^{40}Ar-^{39}Ar ages of Bombay trachytes: evidence for a Palaeocene phase of Deccan volcanism

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Abstract. We present ^{40}Ar-^{39}Ar ages of 60.4 ± 0.6 Ma and 61.8 ± 0.6 Ma (2σ) for Deccan Trap trachytes from Manori and Saki Naka, Bombay, situated in the tectonized Panvel flexure zone along the western Indian rifted continental margin. These ages provide clear evidence that (i) these trachytes are of Palaeocene age and therefore substantially younger than the lower part of the main flood basalt sequence exposed in the Western Ghats, which precedes the K-T Boundary in age and (ii) the formation of the Panvel flexure along the west coast must have been subsequent to ~60 Ma. Considering early alkaline Deccan rocks previously dated at ~68.5 Ma, the total duration of Deccan volcanism was at least ~8 MY.

1. Introduction

The Deccan province of India covers today an area of ~500,000 km^2 after ~65 million years (MY) of erosion, excluding the substantial area known to have been downfaulted into the Arabian Sea to the west [*Wadia*, 1975] (Fig. 1). The ~2 km thick Deccan basalt sequence of the Western Ghats region has been extensively studied for geochemistry, palaeomagnetism and geochronology [e.g., *Mahoney*, 1988 and references therein; *Subbarao*, 1988 and references therein; *Venkatesan et al.*, 1993; *Baksi*, 1994], but very few geological, geochemical and geochronological studies on Deccan volcanics of the Bombay area exist [e.g., *Sukheswala and Poldervaart*, 1958; *Sethna and Battiwala*, 1977; *Lightfoot et al.*, 1987; *Sethna*, 1999]. Here we present the first ^{40}Ar-^{39}Ar dates for two trachyte lava flows from Bombay, and discuss their implications for the timing of volcanism in Bombay in relation to that in the Western Ghats, the duration of Deccan volcanism locally and on a province-wide basis, and the timing of post-volcanic tectonic deformation along the western Indian continental margin and formation of the 'Panvel flexure'.

2. Field Geology and Petrography

The Deccan geology of Bombay differs from that of the major part of the Deccan, particularly the Western Ghats, in several respects [*Sethna*, 1981]: (i) Unlike the ~2 km thick uniformly tholeiitic basalt petrology of the Western Ghats, the Bombay basalts are clearly associated with several evolved rock types like rhyolites and trachytes with a large volume of felsic and basic tuffs (Fig.1). (ii) Unlike the horizontally disposed Western Ghats lava pile, the Bombay lavas exhibit pronounced westerly (seaward) dips of up to ~25° and constitute a part of the Panvel flexure [*Auden*, 1949; *Sheth*, 1998]. (iii) The Western Ghats lavas were erupted subaerially, but several basalt flows in Bombay are partly or wholly subaqueous eruptions, as identified from pillow structures, spilitic compositions, and the presence of hyaloclastites [*Sethna*, 1999]. (iv) Significant weathering profiles and red bole beds between successive flows are uncommon in the Western Ghats immediately east of Bombay, and intertrappean sedimentary beds are completely absent. In Bombay, consecutive flows are commonly separated by "intertrappean" freshwater sedimentary beds or red boles. (v) Unlike the Western Ghats, the Bombay region and the west coast exhibit widespread intrusive activity in the form of dyke swarms and plugs.

The Panvel flexure runs for about 150 km north and south of Bombay, with a roughly N-S axis. Such coastal flexures are exhibited by several continental flood basalt (CFB) provinces of the world besides the Deccan, namely Karoo (South Africa), Parana (South America), East Greenland, West Greenland, and Yemen [*Cox*, 1988; *Sheth*, 1998]. The Panvel flexure was interpreted by *Blanford* [1867], *Wynne* [1886] and *Auden* [1949] as due to simple monoclinal bending of the lava pile. Devey and *Lightfoot* [1986], *Widdowson* [1997] and *Widdowson and Gunnel* [1999] related it to post-rift passive margin evolution involving subsidence of margin and uplift of the Western Ghats. *Dessai and Bertrand* [1995] interpreted the flexure as an extensional fault structure, and *Sheth* [1998], going a step further, interpreted it as a listric-fault-controlled reverse drag structure. Whatever may have been the cause of the flexing all the authors are unanimous that the flexing postdated the volcanism and is of tectonic origin. Here we constrain the timing of Panvel flexure formation based on ^{40}Ar-^{39}Ar ages for two west-dipping trachytes: as the dips are not primary but secondary tectonic dips, the youngest ^{40}Ar-^{39}Ar age would be the upper time limit for flexure formation.

The field relationships of the Bombay basalts with the rhyolites and trachytes, or even those of the trachytes with the rhyolites, are not clear [*Lightfoot et al.*, 1987], but because the rhyolites and trachytes are generally confined to the coast, and the regional dips are westward, they are presumably younger than the basalts (Fig. 1). Few, if any, Bombay basalt lava flows are suitable for ^{40}Ar-^{39}Ar dating due to the extremely severe alteration suffered by them. Besides, heavy urbanization has resulted in the inaccessibility or destruction of many outcrops shown in an older geological map [*Sethna and Battiwala*, 1977] (Fig. 1). The trachytes and rhyolites also constitute some intrusions, and some basaltic dykes also

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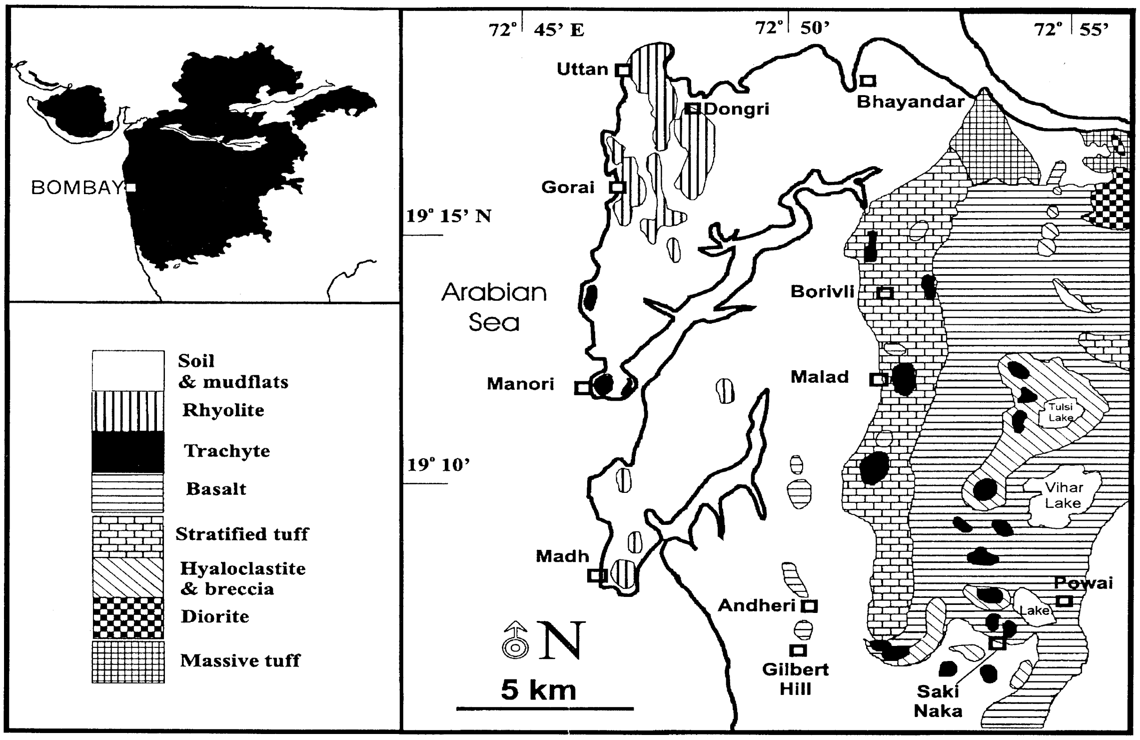

Figure 1. Geological map of Bombay, showing the distribution of various rock types and important localities [after *Sethna and Battiwala*, 1977]. Inset shows the outcrop area of the Deccan flood basalt province (black) and the location of Bombay.

intrude the trachyte and rhyolite lava flows. *Lightfoot et al.* [1987] presented a detailed major and trace element and Nd-Sr-Pb isotopic study of the Bombay rhyolites and trachytes and derived Rb-Sr "isochron ages" of ~60 Ma for them. They plotted the present-day ^{87}Rb/^{86}Sr and ^{87}Sr/^{86}Sr ratios for 9 rhyolite samples, fitting a best-fit line to them with an MSWD of 0.54 (see their Fig. 5), based on which they calculated an isochron age of 61.5 ± 1.9 Ma for the rhyolites and an initial ^{87}Sr/^{86}Sr ratio of 0.7085 ± 0.0018. Data points for 11 trachyte samples did not yield a clear isochron, and clustered around a 60 Ma reference line.

The Manori trachyte flow (sample MnTr) shows well-developed columnar jointing, strikes N10°W-S10°E and dips 25°W. In places it contains abundant, partly assimilated basalt xenoliths with corroded margins [*Sethna and Battiwala*, 1974], but at the sampling spot the trachyte was free of them. The rock is fine-grained and has small but abundant phenocrysts of plagioclase, however, their volume is only about 2% of the whole rock. Under the microscope preferred alignment of groundmass feldspars is observed in some areas. Glass is absent in the interstices between them. The Saki Naka trachyte flow (sample SnTr) shows distinct columnar jointing and dips west by ~13°. The glassy chilled margin of a basaltic dyke is seen to intrude this flow. The trachyte flow is fine-grained, and is aphyric both in hand sample and in thin section. Both Manori and Saki Naka trachytes are very fresh in outcrop, hand sample and thin section, and are completely free of vesicles and secondary minerals.

3. Results of ^{40}Ar-^{39}Ar Dating

Fresh whole rock samples of both the trachytes were analyzed by the ^{40}Ar-^{39}Ar incremental heating technique following methods detailed in *Venkatesan* et al. [1993]. The standard Minnesota Hornblende Mmhb-1 (520.4 ± 1.7 Ma) [*Samson and Alexander Jr.*, 1987] was used, and appropriate correction for ^{37}Ar decay between segmented irradiations was made following *McDougall and Harrison* [1988]. Interference corrections [*Dalrymple et al.*, 1981] were applied based on measurements on pure CaF_2 and K_2SO_4 salts irradiated with the samples. The mean values for $(^{36}Ar/^{37}Ar)_{Ca}$, $(^{39}Ar/^{37}Ar)_{Ca}$ and $(^{40}Ar/^{39}Ar)_K$ are 0.0001640, 0.0007456, and 0.069205, respectively. We define a plateau as comprising four or more contiguous steps in an apparent age spectrum with apparent ages that overlap with the mean at the 2σ level of error excluding the error contribution from the error in the *J* value, with a total ^{39}Ar release of 60% or more. The plateau age and the associated error, however, is calculated by weighting each step age by the inverse of its variance which includes the error in *J* following the scheme outlined by *Baksi* [1999]. The isochron and inverse isochron ages were determined using the regression method of *York* [1969] through the selected step gas composition using the ^{40}Ar-^{36}Ar vs. ^{39}Ar/^{36}Ar and ^{36}Ar/^{40}Ar vs. ^{39}Ar/^{40}Ar isotope correlation diagrams respectively. ^{40}Ar blanks were typically about 1-2% of sample ^{40}Ar for the lower temperatures up to 1000°C, and increased gradually to <20% at 1400°C.

Table 1 shows the analytical results with the errors quoted at 2 σ level. Both the trachytes yield good plateaus and isochrons. The Manori trachyte MnTr (Fig. 2a) has a 17-step plateau age of 60.4 ± 0.6 Ma, with the age spectrum comprising 99.6% of total ^{39}Ar released. Its isochron age 60.2 ± 0.9 Ma (Fig. 2b) is statistically indistinguishable from its plateau age, and the isochron has a low MSWD of 1.10 along with a ^{40}Ar/^{36}Ar intercept of 296 ± 10 which matches the atmospheric value of 295.5. Its inverse isochron age is 60.5 ± 3.1 Ma, the isochron having an MSWD of 1.16 and an atmospheric value for the ^{40}Ar/^{36}Ar intercept, 292 ± 10. The Saki Naka trachyte sample SnTr (Fig. 2a) has a 17-step plateau age of 61.8 ± 0.6 Ma, the age spectrum comprising

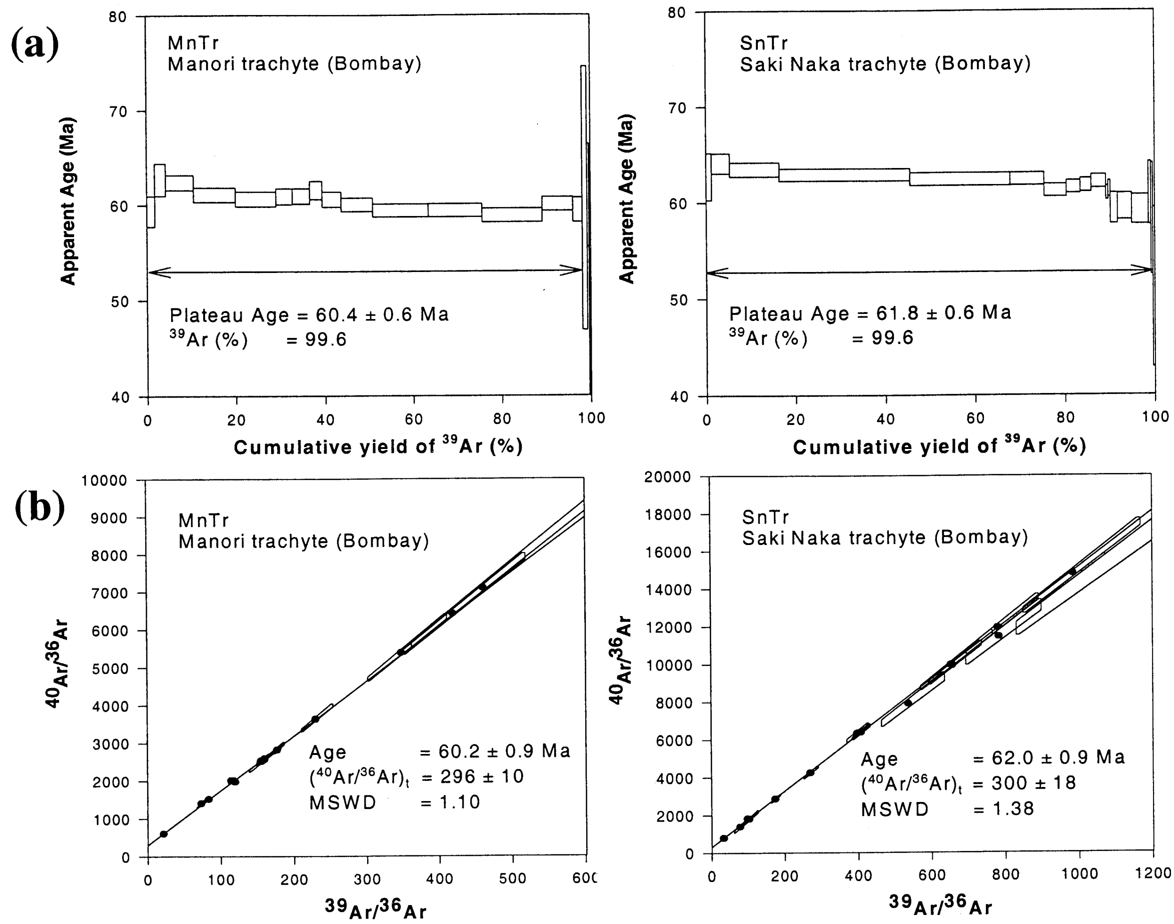

Figure 2. (a) Step-heating age spectra for the Manori trachyte (MnTr) and Saki Naka trachyte (SnTr), showing apparent ages as a function of cumulative fraction of ^{39}Ar released. Each plateau age and the corresponding 2σ uncertainty shown includes 2σ error on *J* but the vertical width of the individual steps indicates 2σ error calculated without propagating the error on *J*. (b) Isotope correlation diagrams ($^{40}Ar/^{36}Ar$ versus $^{39}Ar/^{36}Ar$) for the plateau steps, showing 2σ error envelopes and the best-fit regression line for each. Isochron ages (± 2σ), intercept values (trapped $^{40}Ar/^{36}Ar$, ± 2σ) and MSWD (mean square weighted deviate) for the Manori trachyte (MnTr) and Saki Naka trachyte (SnTr) are given.

99.6% of total ^{39}Ar released. Its isochron age of 62.0 ± 0.9 Ma (Fig. 2b) is concordant with its plateau age and the isochron has a low MSWD of 1.38, while its trapped $^{40}Ar/^{36}Ar$ composition of 300 ± 18 is again atmospheric. Its inverse isochron age is 61.8 ± 5.2 Ma, the isochron having an MSWD of 1.36 and an atmospheric value for the $^{40}Ar/^{36}Ar$ intercept, 312 ± 18.

4. Discussion and Conclusions

Experiments that yield an acceptable measure of goodness of fit, an atmospheric $^{40}Ar/^{36}Ar$ intercept, and concordant plateau and isochron ages, define reliable crystallization ages [*Lanphere and Dalrymple*, 1978]. Thus, the concordant plateau and isochron ages for both MnTr and SnTr, the large amounts (99.6%) of total released ^{39}Ar for the plateau steps, the atmospheric values of the trapped $^{40}Ar/^{36}Ar$ component, and the low MSWD values for the isochrons, imply that these ages represent true crystallization ages. Our data successfully pass the criteria for true crystallization ages listed by *Baksi* [1999]. Even though the plateau, isochron and inverse isochron ages are identical, we prefer the plateau ages for the present discussion due to their smaller age uncertainties. These plateau ages of 60.4 ± 0.6 Ma and 61.8 ± 0.6 Ma, for

Table 1. Summary of results of ^{40}Ar-^{39}Ar dating of Bombay trachytes

Sample	Plateau			Isochron			Inverse Isochron		
	Steps	% ^{39}Ar	Age(Ma)	Age (Ma)	Trap	MSWD	Age (Ma)	Trap	MSWD
MnTr	17	99.6	60.4±0.6	60.2 ± 0.9	296±10	1.10	60.5± 3.1	292± 10	1.16
SnTr	17	99.6	61.8±0.6	62.0 ± 0.9	300±18	1.38	61.8±5.2	312±18	1.36

Note: MnTr is Manori trachyte and SnTr is Saki Naka trachyte. Trap is the initial $^{40}Ar/^{36}Ar$ ratio (trapped argon); MSWD is Mean Square Weighted Deviate. Errors are 2σ and the monitor standard is Mmhb-1 (520.4 ± 1.7 Ma).

the Manori and Saki Naka trachytes respectively, are more precise than the 60 Ma estimate of *Lightfoot et al.* [1987]. Also, the plateau ages do not overlap at the 95% critical value (CV) [*Baksi*, 1999], the CV being 0.83 MY. Hence these ages suggest that Deccan volcanism in the Bombay region lasted at least ~1 MY. Besides, these ages conclusively show that the Bombay trachytes are substantially younger than the main phase of flood basalt volcanism in the Western Ghats, which commenced at ~67 Ma, preceding the Cretaceous-Tertiary boundary [*Venkatesan et al.*, 1993]. In a study of coastal doleritic dykes in Goa, located some 50-80 km south of the southernmost limit of the Deccan lavas (Fig. 1), *Widdowson et al.* [2000] dated four dykes and reported a weighted mean ^{40}Ar-^{39}Ar age of 62.8 ± 0.2 Ma, though some of these plateau age spectra are saddle-shaped, and the isochrons appear to be the errorchrons due to the large values of degree-of-fit parameter (lowest 1.61, highest 8.04). However, their work suggests that these dykes were emplaced at ~62-63 Ma. These dykes may have been coeval with the Bombay trachytes. Note that the (undated) basaltic dyke intruding the Saki Naka trachyte flow should be even younger than ~61.8 Ma. Also, the data constrain the formation of the Panvel flexure to have been no earlier than the age of the younger trachyte (MnTr), i.e., no earlier than ~60 Ma. More importantly, these data conclusively show that Deccan volcanism continued well into the Palaeocene. Early alkaline rocks in the northern part of the Deccan province have previously yielded ^{40}Ar-^{39}Ar ages of ~68.5 Ma [*Basu et* al., 1993]. Thus the total duration of Deccan volcanism is no less than ~8 MY, much longer than often supposed [e.g., *Courtillot et al.*, 1986, 1988; *Allègre et al.*, 1999].

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