^{40}Ar–^{39}Ar age of a national geological monument: The Gilbert Hill basalt, Deccan Traps, Bombay

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The Deccan Trap geology of Bombay (Mumbai) differs from the main Deccan flood basalt province in several ways. Very few geological, geochemical and geochronological studies exist on the Deccan geology of Bombay. The basalt of Gilbert Hill, Andheri occupies a special place in Bombay geology on account of its spectacular columnar jointing, more than 50 m high, and for this has been designated a National Geological Monument by the Geological Survey of India. We have obtained an ^{40}Ar–^{39}Ar plateau age of 60.5 ± 1.2 Ma (2σ) for the Gilbert Hill basalt, and this basalt can be argued to have erupted considerably later (~ 6 m.y.) than the lower part of the Western Ghats lava pile, and the total duration of Deccan volcanism as a whole appears to have been at least ~ 8 m.y.

THE Deccan province of India (Figure 1) is one of the best studied continental flood basalt (CFB) provinces of the world. The province covers today an area of ~ 500,000 km^2 after ~ 65 million years (m.y.) of erosion and this figure excludes the substantial area down-faulted into the Arabian Sea to the west[1]. The western coast of India, along which Bombay lies, is part of a typical rifted continental margin[2–5]. Studies existing on Deccan volcanics of the Bombay area are very few and the complete lack of any radiometric dating study is especially noteworthy.

The Deccan geology of Bombay city is rather unusual compared to that of the main Deccan flood basalt province, particularly the Western Ghats, in several aspects[6]: (1) Unlike the monotonously tholeiitic basalt sequence forming the Western Ghats, Bombay geology comprises not only basalts but also considerable volumes of evolved rock types like rhyolites and trachytes, and a large volume of felsic and basic tuffs[7,8]. (2) Unlike the horizontal lava pile of the Western Ghats, the Bombay lavas (basalts, rhyolites and trachytes alike) exhibit pronounced westerly (seaward) dips of up to ~ 25° and define part of the 'Panvel flexure'[9,10]. (3) Unlike the wholly subaerially erupted lavas of the Western Ghats, several basalt flows in Bombay are partly or wholly subaqueous eruptions (as identified from pillow structures, spilitic petrology and the presence of hyaloclastites). (4) Unlike the Western Ghats, where significant weathering profiles and red bole horizons between successive lava flows are rare or absent and intertrappean sedimentary beds are completely absent, many Bombay lava flows are commonly separated by 'intertrappean' freshwater sedimentary beds or red boles. (5) Unlike the Western Ghats sequence which is relatively free of dykes, Bombay and the western Indian coast exhibit widespread intrusive activity in the form of dyke swarms and other intrusions.

Thus Bombay city seems to once have been a unique petrological museum. Regrettably, due to heavy urbanization, most of the original geology of Bombay stands destroyed today, or at least, is highly inaccessible. The basalt of Gilbert Hill, situated very close to Bhavan's College in the suburb of Andheri (West), has a prominent place in Bombay geology on account of its spectacular columnar jointing, and has been designated a National Geological Monument by the Geological Survey of India, India's premier geological mapping agency. The columns are ~ 50 m high (the height of a 10-storey building), continuous and vertical. The basalt originally covered a greater area; most of this has unfortunately been quarried for road metal and today Gilbert Hill stands surrounded by housing colonies. For this reason, both exposure and accessibility are severely limited and only spot sampling is possible. The basalt is seen to overlie intertrappean sediments and appears to be a sill-like intrusion and not a lava flow, though its original top is eroded. The basalt is fresh, both in hand sample and in thin section. In hand sample it appears to be aphyric, but under the microscope very sparse plagioclase microphenocrysts are seen. The groundmass minerals are plagioclase, clinopyroxene and opaques, with fresh interstitial glass and the texture is intersertal.

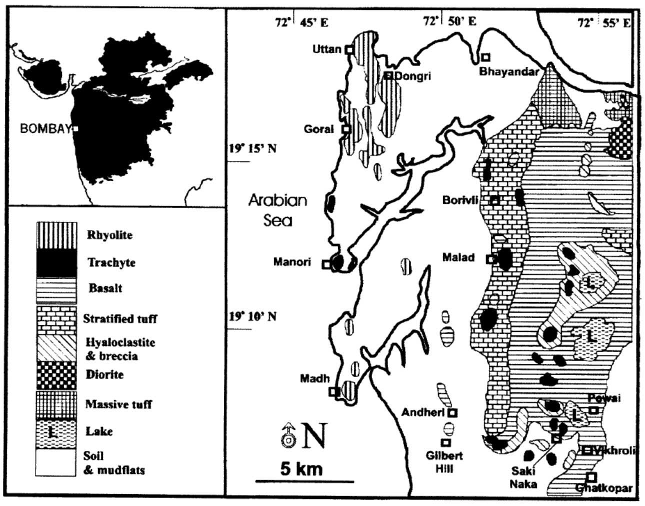

Figure 1. Geological map of Bombay, showing the distribution of various rock types and important localities (after ref. 24). (Inset) Outcrop area of the Deccan flood basalt province (black) and location of Bombay.

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We dated the Gilbert Hill basalt by the ^{40}Ar–^{39}Ar incremental heating, following the methods of Venkatesan *et al.*[11]. About 1 g of ultrasonically cleaned sample powder was sealed in a quartz capsule and irradiated for 100 h cumulative, along with the flux monitor standard Minnesota Hornblende Mmhb-1 (520.4 ± 1.7 Ma)[12], in the central core of the light-water-moderated APSARA reactor (rated power of 1 MW) at the Bhabha Atomic Research Centre, Bombay. Because the reactor was not operated continuously, appropriate correction for ^{37}Ar decay between segmented irradiations was made following McDougall and Harrison[13]. Pure nickel wires were enclosed in both sample and monitor capsules to measure and correct for the variation in neutron fluence. Interference corrections[14] were applied based on measurements on pure CaF_2 and K_2SO_4 salts irradiated with the sample. 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. Argon was then extracted from the sample in an electrically heated ultra-high-vacuum furnace, in a series of twenty steps of increasing temperature, starting at 400°C and going up to fusion (1350°C). The steps were arranged in 50°C temperature increments and the last step was repeated. The argon released in each step was subjected to a two-stage purification and its isotopic composition measured using an AEI MS10 mass spectrometer in static mode. 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

Table 1. Step-wise argon compositions for the Gilbert Hill basalt

Temperature (°C)	$^{36}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$	Age (Ma)	^{39}Ar (%)	$^{40}Ar^*$ (%)	$^{37}Ar/^{39}Ar$	$^{40}Ar/^{36}Ar$
400	0.1060	45.99	59.00	1.16	31.75	1.830	432.9
	0.0130	1.49	16.4, 16.4			0.021	55.8
450	0.0833	39.40	59.73	2.47	37.51	2.542	472.9
	0.0067	0.65	8.21, 8.22			0.040	38.5
500	0.0450	28.47	61.35	2.68	53.34	3.056	633.2
	0.0035	0.41	4.46, 4.47			0.060	50.7
550	0.0227	21.58	60.11	3.64	68.91	3.554	950.4
	0.0025	0.43	3.37, 3.39			0.007	105.8
600	0.1501	59.64	61.70	5.93	25.61	4.227	397.2
	0.0043	0.40	5.25, 5.26			0.019	11.7
650	0.0164	20.27	62.27	8.01	76.08	4.805	1235.4
	0.0014	0.22	1.84, 1.89			0.020	105.9
700	0.0134	18.98	60.67	11.45	79.11	5.450	1414.4
	0.0001	0.17	1.31, 1.36			0.011	102.8
750	0.0133	19.19	61.71	9.95	79.60	5.833	1448.2
	0.0011	0.19	1.50, 1.55			0.015	123.5
800	0.0186	19.89	58.19	6.82	72.37	6.449	1069.3
	0.0013	0.24	1.81, 1.85			0.014	76.9
850	0.0242	21.92	59.70	7.33	67.38	6.977	905.8
	0.0014	0.16	1.78, 1.82			0.014	53.7
900	0.0226	21.52	59.92	4.98	68.90	7.836	950.2
	0.0018	0.35	2.25, 2.28			0.025	77.4
950	0.0224	20.88	57.69	2.83	68.33	9.560	933.2
	0.0027	0.19	3.28, 3.31			0.033	114.2
1000	0.0242	21.61	58.41	3.38	66.86	13.849	891.7
	0.0022	0.18	2.67, 2.70			0.029	81.3
1050	0.0341	24.94	60.02	4.52	59.56	19.394	730.8
	0.0035	0.21	4.15, 4.17			0.039	74.6
1100	0.0144	20.49	65.49	6.97	79.21	36.010	1421.1
	0.0041	0.87	5.93, 5.94			0.072	411.1
1150	0.0149	19.30	60.24	8.55	77.23	35.956	1297.9
	0.0025	0.65	3.93, 3.95			0.072	225.4
1200	0.0281	23.85	62.74	3.23	65.14	27.679	847.6
	0.0044	0.93	6.38, 6.40			0.070	138.0
1250	0.0621	33.46	61.10	1.59	45.16	25.610	538.9
	0.0097	1.97	13.8, 13.8			0.220	90.0
1300	0.0780	37.80	60.10	3.13	39.36	25.074	487.3
	0.0110	3.02	17.2, 17.2			0.050	76.8
1350	0.2380	85.34	60.30	1.37	17.49	18.893	358.1
	0.0320	7.37	47.6, 47.6			0.096	57.1
Total	0.03543	25.52	60.80	100.00	58.97	13.021	720.2
	0.00084	0.18	1.21, 1.27			0.010	17.8

$N = 20$, $J = 0.0022782 \pm 0.0000150$; $^{39}Ar_{(Total)} = 0.11806 \times 10^{-8} \times 0.85796 \times 10^{-12}$ ccSTP/g; $^{40}Ar^*$ is the radiogenic argon.
The second row of numbers for each step gives the analytical uncertainties associated with each parameter. The two uncertainty values listed in the age (Ma) column correspond to the uncertainties calculated without and with the uncertainty in the irradiation parameter *J*.

the *J* value, with a total ^{39}Ar release of 60% or more. The plateau age and the associated error, however, is calculated by weighing each step age by the inverse of its variance which includes the error in *J*. The isochron and inverse isochron ages were determined using the regression method of York[15] 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 1350°C. Complete analytical data for the twenty-two steps are given in Table 1.

The Gilbert Hill basalt yields a good plateau age spectrum and isochron (Figure 2), albeit with somewhat large error bars because of relatively small amounts of radiogenic argon. It has a 20-step plateau age of 60.5 ± 1.2 Ma, with the age spectrum comprising 99.9% of total ^{39}Ar released (Figure 2 *a*). Its isochron age (60.2 ± 2.2 Ma) is identical with its plateau age and the isochron has an extremely low MSWD (mean square weighted deviate) of 0.062, along with a ^{40}Ar/^{36}Ar intercept of 296.5 ± 17.9 (Figure 2 *b*) which is the same as the atmospheric value of 295.5, which indicates no inherited argon. The inverse isochron age for the basalt is 60.5 ± 6.2 Ma and the inverse isochron also has an atmospheric value for trapped argon composition (295.7 ± 17.4) and an extremely low MSWD of 0.061 (Figure 2 *c*). 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[16]. The concordant plateau, isochron and inverse isochron ages for the Gilbert Hill basalt, the large amount (99.9%) of total released ^{39}Ar for the plateau steps, the atmospheric values of the trapped ^{40}Ar/^{36}Ar component and the remarkably low MSWD value for the isochron together imply that this age is a true crystallization age and passes the criteria for true crystallization ages listed in a recent important work[17].

This age shows conclusively that the Gilbert Hill basalt and the Bombay volcanics in general 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[11]. Thus Deccan volcanism unquestionably endured in the Palaeocene. Considering the early alkaline phases of magmatism in the northern part of the Deccan province, previously dated at ~ 68.5 Ma (ref. 18), the total duration of Deccan volcanism is no less than 8 m.y., much longer than generally supposed (e.g. refs 19–22). Interestingly, doleritic dykes south of Bombay, in Goa (Figure 1) along the western coast of India, some 50–80 km south of the southernmost limit of the Deccan lavas, have yielded ^{40}Ar–^{39}Ar ages of about 62 Ma (weighted mean age of four dykes is 62.8 ± 0.2 Ma)[23]. Some of these plateau age spectra are saddle-shaped, so this age is an upper estimate. The Gilbert Hill basalt age constitutes clear evidence that Deccan

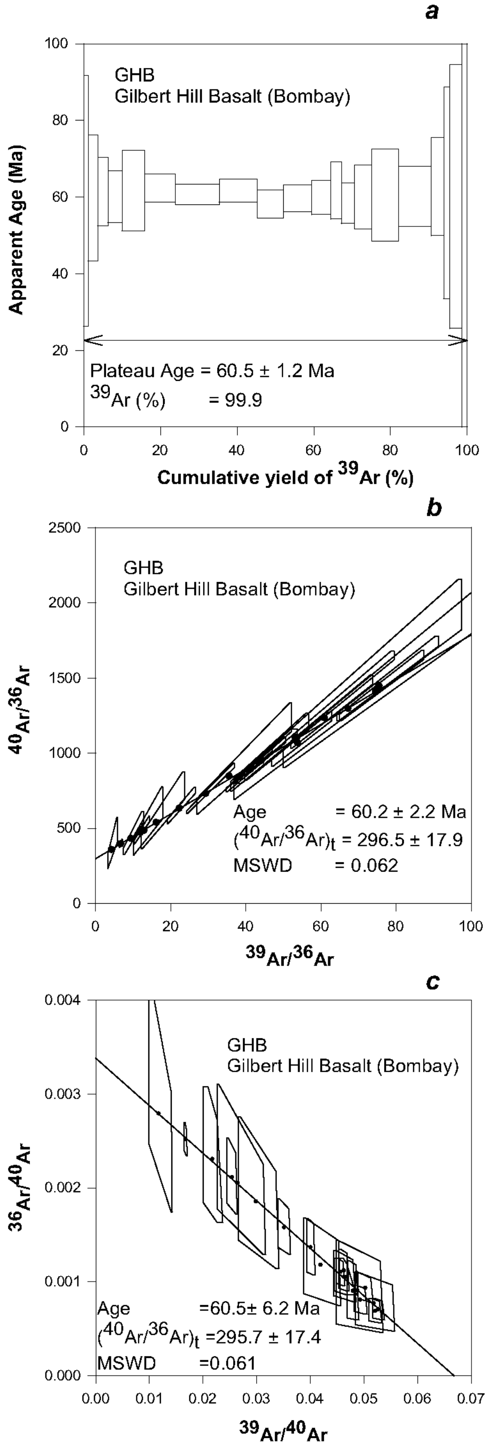

Figure 2. ***a***, Step-heating age spectrum for the Gilbert Hill Basalt (GHB), showing apparent ages as a function of cumulative fraction of ^{39}Ar released. Each plateau age and the corresponding 2σ uncertainty shown includes 2σ error on *J*, but the vertical width of the individual steps indicates 2σ error calculated without propagating the error on *J*. ***b***, Isotope correlation diagram (^{40}Ar/^{36}Ar vs ^{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 GHB. ***c***, Isotope correlation diagrams (^{36}Ar/^{40}Ar vs ^{39}Ar/^{40}Ar) for the plateau steps, showing 2σ error envelopes and the best-fit regression line for each. Inverse isochron ages (± 2σ), intercept values (trapped ^{40}Ar/^{36}Ar, ± 2σ) and MSWD (mean square weighted deviate) for the GHB.

volcanism continued into the Palaeocene in Bombay and that the Bombay basalts as a whole may be substantially younger than the main phase of Deccan volcanism manifested in the Western Ghats.

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Discovery and sedimentology of microstromatolites from Menga Limestone (Neoproterozoic/Vendian), Upper Subansiri district, Arunachal Pradesh, NE Himalaya, India

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Microstromatolites and filamentous cyanobacteria have been discovered from cherty limestone facies of Menga Limestone well exposed along Menga–Mara road section of Upper Subansiri district, Arunachal Pradesh, NE Himalaya, India. The microstromatolites are mm size in dimension and show well-developed cycles of columnar overhanging, enveloping and conical structures in petrographic thin sections. The other characteristic features of microstromatolitic facies are fibrous radial fabric, zoned dolomite, recrystallized oolites and intraclasts. These microbial facies suggest that sedimentation is controlled by microbial mats in extensive tidal flat complex where photosynthesis was taking place. The deposition took place mainly in subtidal to intertidal zone and the influx of coarser sediments indicates high-energy intertidal environment.

The Menga Limestone is regionally correlated with Dedza Formation in the Arunachal Pradesh. The Bomdila Group with Lower Tenga Formation and Upper Dedza Formation has been correlated with Daling–Buxa Formation of Darjiling and Sikkim Himalaya by earlier workers. A Riphean/Mesoproterozoic age is assigned to these carbonates. The stromatolitic assemblage is characterized by Vendian or Neoproterozoic build-ups of *Stratifera* and *Nucliella* only in the present area. The present discovery of microstromatolites and the complete absence of Riphean assemblage from the Menga Limestone suggest a Vendian/Terminal Neoproterozic age for the Menga–Dedza/Buxa Dolomite of NE Himalaya.

MICROBIAL build-ups with special reference to microstromatolites and their microstructures from Meso-Neoproterozoic Deoban and Krol carbonates of the Lesser Uttaranchal Himalaya in the central sector have been studied earlier[1–4]. The present discovery is a report of microstromatolites and microbiota *Eomycetopsis* from the Menga (Buxa) Limestone of the Upper Subansiri district, Arunachal Pradesh, NE Himalaya. The microstromatolite locality and the geological map of the area are shown in Figure 1 *a–d* (ref. 5). The litholog showing the details of the microstromatolitic facies of Menga Limestone, exposed about 2 km from Menga village on Menga–Mara

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