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40Ar/39Ar age of a near-basal lava flow from the Chikhaldara section, Satpura Range: implications for early Deccan volcanism

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Research Article

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$^{40}Ar/^{39}Ar$ age of a near-basal lava flow from the Chikhaldara section, Satpura Range: implications for early Deccan volcanism

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Abstract

Tholeiitic lava flows of the Chikhaldara section, with a thickness of ~625 m, are exposed along the Satpura mountain range in the Narmada–Tapi rift of the Northern Deccan Volcanic Province (NDVP). The flows from Chikhaldara show chemical affinity with the younger formations of the Western Ghats, but no radiometric age has been reported from this section so far. This paper reports $^{40}Ar/^{39}Ar$ step-heating ages of a plagioclase separate and its whole rock from the lowest sampled flow (CH'15-11), the second flow above the base of the section. The plagioclase yielded an eight-step plateau age of 67.0 ± 0.4 Ma (2σ). The whole rock gave a slightly older weighted mean age of 67.7 ± 0.3 Ma over only 27.3% of the ^{39}Ar released, which is not a plateau. The inverse isochron ages agree with these ages, and the trapped $^{40}Ar/^{36}Ar$ ratios are atmospheric. The plagioclase age of 67.0 ± 0.4 Ma is taken as the crystallisation age of this flow, which becomes about 67.6 Ma on the current calibration of the $^{40}Ar/^{39}Ar$ system. Three more flows were analysed but gave disturbed spectra. Major and trace element data show that the lower flows (CH'15-9 to -11) are richer in Zr, Sr and Y than the flows above. The age is identical within error to the lower Mhow flows of the Malwa Plateau and is older than the main Western Ghats sequence (~66.4–65.5 Ma). This indicates that the lower part of the Chikhaldara section is among the oldest exposed parts of the Deccan Volcanic Province.

Keywords Deccan Traps · $^{40}Ar/^{39}Ar$ geochronology · Geochemistry · Northern Deccan Volcanic Province · Chikhaldara · Satpura Range

1 Introduction

The Deccan Traps were emplaced when India was resting over the present location of the Réunion hotspot in the Indian Ocean. Western and central India was inundated by extensive floods of lava, which reached a maximum thickness of ~3000 m, particularly in the Western Ghats [1, 2]. These lavas are estimated to have originally covered over 1.5×10^6 km^2 with a total erupted volume of about 2×10^6 km^3 [3]. Most of the flows are quartz- and hypersthene-normative tholeiites [4].

Despite the extensive geological investigation of the Deccan Traps, the duration, age, internal structure and origin of the lava flows have been debated for a long time [5–13]. The early K–Ar and ^{40}Ar/^{39}Ar ages were widely scattered, mainly because the whole-rock samples used were affected by alteration and argon loss [5, 11]. Step heating of mineral separates later narrowed the main phase of volcanism to a short interval around the Cretaceous–Palaeogene (K–Pg) boundary [10, 11, 14]. Recent high-precision U–Pb zircon and ^{40}Ar/^{39}Ar dating places most of the Western Ghats lava pile between about 66.4 and 65.5 Ma [15, 16], although the eruptive tempo and its relation to the Chicxulub impact are still discussed [13, 16].

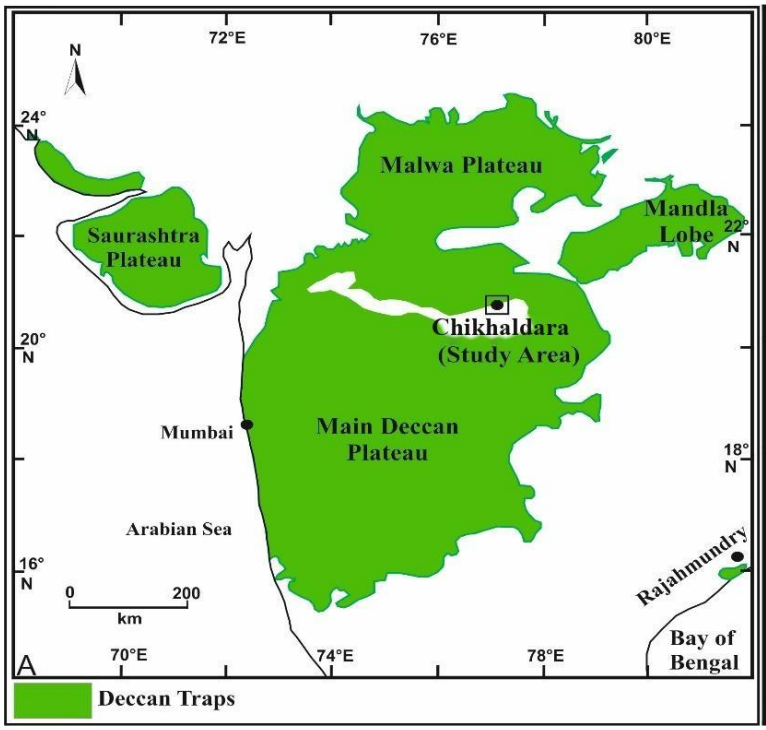
The magnetostratigraphy is also complex in correlating the northern and western Deccan flows. The oldest flows, with C30n normal polarity, are found in the north in the Malwa Plateau [17], while the Western Ghats sequence passes through the C30n, C29r and C29n chrons [18, 19]. Geochemical and geochronological studies of the Malwa Plateau show that the earliest Deccan eruptions took place in this northern region [20, 21], and ^{40}Ar/^{39}Ar dating of 21 Malwa lavas shows that eruption there began before 66.8 Ma, at least 400 kyr before the oldest known lava of the Western Ghats [22]. In contrast, the Mandla lobe in the east gives younger ^{40}Ar/^{39}Ar ages close to 64 Ma [23, 24].

The Chikhaldara flows of the NDVP are exposed along the Satpura mountain range with a lava pile thickness of 625 m and are hosted in the Narmada–Tapi rift valley [25]. The chemistry of these flows and of the neighbouring Satpura and Narmada sections has been studied in detail [25–29], but no radiometric age has been reported from the Chikhaldara section. The lack of geochronological data in Chikhaldara, as well as in the NDVP, led to the present study. This paper reports the first ^{40}Ar/^{39}Ar ages from the Chikhaldara sequence.

2 Materials and methods

2.1 Geological setting and sampling

The Chikhaldara section is exposed along the Chikhaldara–Achalpur ghat road (Survey of India toposheet 55G/3). Deshmukh (Geological Survey of India, unpublished report, 1980) identified 36 tholeiitic flows within a vertical succession of ~625 m between 465 and 1090 m elevation [25] (Fig. 1). The flows are numbered from the base upwards in Fig. 2, after Deshmukh et al. [25]. The flows are thick and tabular (7–50 m), aphanitic to porphyritic, with columnar joints and red and green bole horizons at the flow junctions. Plagioclase (calcic, up to 4.5 mm) and augite dominate, with altered olivine and magnetite in an intersertal to intergranular groundmass. Nine flows were sampled along the road section, from flow 32 near the top of the section down to flow 2 near its base. The sampled flows were correlated in the field with the flows of Deshmukh et al. [25] (Fig. 2); their field (GPS) altitudes, which range from 1051 to 597 m, are given in Table 2. Two more samples (CH'15-1 and -2) were collected from the Melghat area, outside the road section.



Subgroup	Formation
Wai	Desur
	Panhala
	Mahabaleshwar
	Ambenali
	Poladpur
Lonavala	Bushe
	Khandala
Kalsubai	Bhimashankar
	Thakurvadi
	Neral
	Igatpuri
	Jawhar

B

Fig. 1 (A) Regional geological map of the Deccan Volcanic Province showing the main Western Ghats sequence and the northern and eastern sub-provinces (Malwa Plateau, Mandla lobe, Saurashtra). The Chikhaldara study area in the Satpura Range (Narmada–Tapi zone) is boxed. (B) Generalised chemostratigraphy of the Western Ghats.

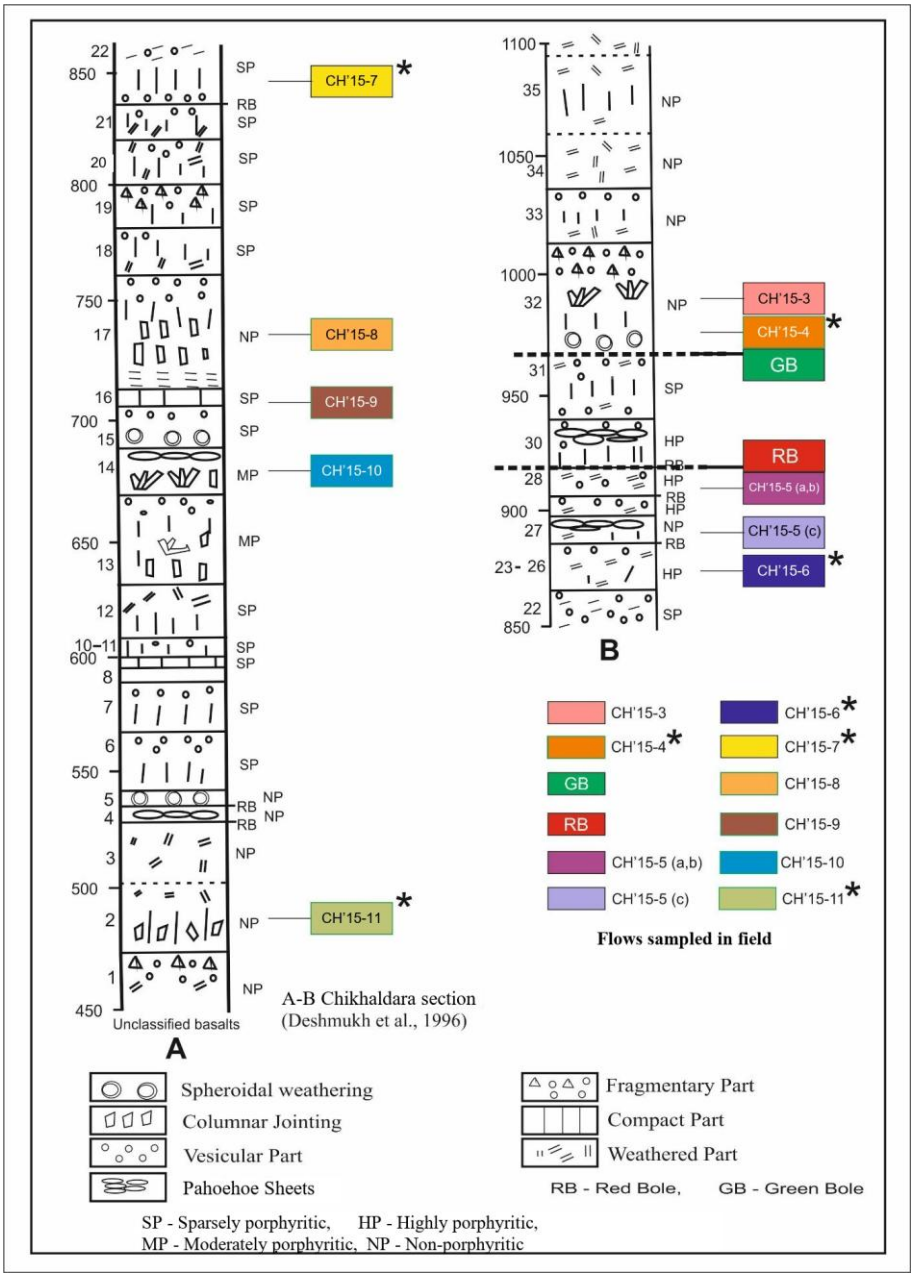


Fig. 2 Columnar lava stratigraphy of the Chikhaldara section (modified after Deshmukh et al. [25]). Flows are numbered from the base upwards; sampled flows are marked with their sample numbers, and asterisks mark the dated samples. CH'15-11, from flow 2, is the lowest dated flow.

2.2 $^{40}Ar/^{39}Ar$ analysis

The samples selected for age determination were the freshest, best crystallised and least weathered, on the basis of petrographic examination. Four flows (CH'15-4, -6, -7 and -11) were selected for dating. CH'15-4, -6 and -7 are aphanitic and were analysed as whole rock, together with a plagioclase separate from CH'15-7. The sample CH'15-11, collected from flow 2 near the base of the section, is the lowest of the sampled flows and is a tholeiitic basalt characterised by large plagioclase phenocrysts (2–5 mm). The rocks were crushed and sieved, and after magnetic and

heavy-liquid separation the plagioclase phenocrysts were handpicked under a binocular microscope. The whole-rock samples were crushed with a mortar and pestle and washed several times in distilled water. The samples were packed in aluminium foil capsules along with the 523.1 ± 2.6 Ma Minnesota hornblende (MMhb-1) monitor [30] and high-purity CaF_2 and K_2SO_4 salts, with nickel wires to monitor the neutron fluence. The capsules were placed in a 0.5 mm thick cadmium cylinder and irradiated in the DHRUVA reactor at the Bhabha Atomic Research Centre (BARC), Mumbai, for 100 h. The interference corrections [31] for Ca- and K-produced argon isotopes were $(^{39}Ar/^{37}Ar)_{Ca}$ = 0.000491, $(^{36}Ar/^{37}Ar)_{Ca}$ = 0.001277 and $(^{40}Ar/^{39}Ar)_{K}$ = 0.013001. The irradiation parameter *J*, calculated from MMhb-1 and corrected for neutron flux variation, is 0.0007018 ± 0.0000035 for plagioclase and 0.0007479 ± 0.0000035 for the whole rock. Fish Canyon sanidine was analysed as an unknown sample to check the *J* value.

The samples were step heated in an ultra-high vacuum furnace, and the argon gas was extracted by heating the sample for 20 min in a series of steps from 400 °C to 1350 °C. The released argon was purified over Ti–Zr getters and measured with a Thermo-Fisher ARGUS VI mass spectrometer installed at the IITB–DST National Facility for $^{40}Ar/^{39}Ar$ Geothermochronology, Department of Earth Sciences, IIT Bombay. Blanks were measured before each sample, and the measured isotopic ratios are corrected for blanks. The raw data were acquired with the IMHOTEP software and processed with an in-house program written in FORTRAN, and the plots were generated with ISOPLOT version 3.75 [32]. The ages were calculated using the decay constants of Steiger and Jäger [33], and a $^{40}Ar/^{36}Ar$ ratio of 295.5 [34] was used for the atmospheric argon correction. A plateau in an age spectrum consists of three or more contiguous steps constituting 50% or more of the total ^{39}Ar released, with apparent ages that overlap with the mean at the 2σ level of error [35], excluding the error contribution from *J*.

Most recent Deccan $^{40}Ar/^{39}Ar$ ages are reported on the calibration of Renne et al. [36]. Recalculating the ages of this study from the MMhb-1 and Steiger and Jäger calibration to that of Renne et al. [36] makes them about 1% older: 67.0 ± 0.4 Ma becomes ~67.6 Ma and 67.7 ± 0.3 Ma becomes ~68.4 Ma. This shift is larger than the analytical uncertainty, so both values are given where the ages are compared with recently published data.

2.3 Geochemical analysis

Thirteen samples were analysed for major and trace elements at the Sophisticated Analytical Instrument Facility (SAIF), IIT Bombay. The rock chips were powdered (<50 μm) in a Retsch ball mill. Major elements were determined by X-ray fluorescence (XRF) on pressed pellets, prepared by mixing 4 g of sample powder with 1 g of methyl cellulose and pressing at 15 tons. Trace elements were determined by inductively coupled plasma atomic emission spectrometry (ICP-AES) after microwave digestion of 0.25 g of powder with HNO_3 and HF. Loss on ignition (LOI) was determined separately by heating 1 g of powder at 950 °C. The XRF analysis of CH'15-11 gave a low total (82.4 wt%), so its major elements are not reported.

3 Results and discussion

3.1 $^{40}Ar/^{39}Ar$ results

Of the four flows analysed, only CH'15-11 produced concordant ages. The whole rocks of CH'15-4, -6 and -7 and the plagioclase of CH'15-7 gave discordant, open-system spectra, which may be due to the low potassium content of these tholeiites and to the alteration and ^{39}Ar recoil that commonly affect Deccan samples [11, 12].

The results obtained from sample CH'15-11 (plagioclase and whole rock) are summarised in Table 1 and illustrated in Fig. 3. The plagioclase separate yielded an eight-step plateau age of 67.0 ± 0.4 Ma (MSWD = 0.24) with 54.8% of the total ^{39}Ar released, and an inverse isochron age of 66.9 ± 0.4 Ma. The whole-rock sample yielded an eight-step age of 67.7 ± 0.3 Ma (MSWD = 0.12) with only 27.3% of the total ^{39}Ar released, and an inverse isochron age of 67.7 ± 0.8 Ma. The $^{40}Ar/^{36}Ar$ intercepts of plagioclase (296.6 ± 2.7) and whole rock (295.5 ± 5.6) are close to the atmospheric value, which shows that there is no excess argon.

Even though the whole rock released only 27.3% of the total ^{39}Ar, both samples show concordant apparent ages over parts of the age spectra. According to the plateau definition of Fleck et al. [35], the whole-rock age is not a plateau age, and it is treated here as a weighted mean age. The whole-rock age is 0.7 Myr older than the plagioclase age, which is slightly more than their combined 2σ uncertainty, so the two ages are not strictly concordant. The low-temperature steps of the whole rock give much younger apparent ages that rise towards the high-temperature steps. Such a

rising spectrum is typical of argon loss from altered groundmass and of ^{39}Ar recoil, which can make the high-temperature steps of whole rocks appear older [11, 12]. Plagioclase is an early crystallising phase and is less affected by recoil and alteration than whole rock [11]. Therefore, 67.0 ± 0.4 Ma is considered the best estimate of the crystallisation age of sample CH'15-11, and the whole-rock age is taken only as support for a latest Cretaceous age.

Table 1 Summary of $^{40}Ar/^{39}Ar$ results for sample CH'15-11, the lowest dated flow of the Chikhaldara section. Errors are 2σ.

Fraction	Steps	^{39}Ar (%)	Age (Ma)	Inverse isochron age (Ma)	$^{40}Ar/^{36}Ar$ intercept	MSWD (age / isochron)
Plagioclase	8	54.8	67.0 ± 0.4	66.9 ± 0.4	296.6 ± 2.7	0.24 / 0.12
Whole rock[a]	8	27.3	67.7 ± 0.3	67.7 ± 0.8	295.5 ± 5.6	0.12 / 0.12

[a] The whole rock releases <50% of its ^{39}Ar, so its age is a weighted mean age, not a plateau age. Ages are on the MMhb-1 (523.1 Ma) and Steiger and Jäger calibration; add ~1% for the calibration of Renne et al. [36].

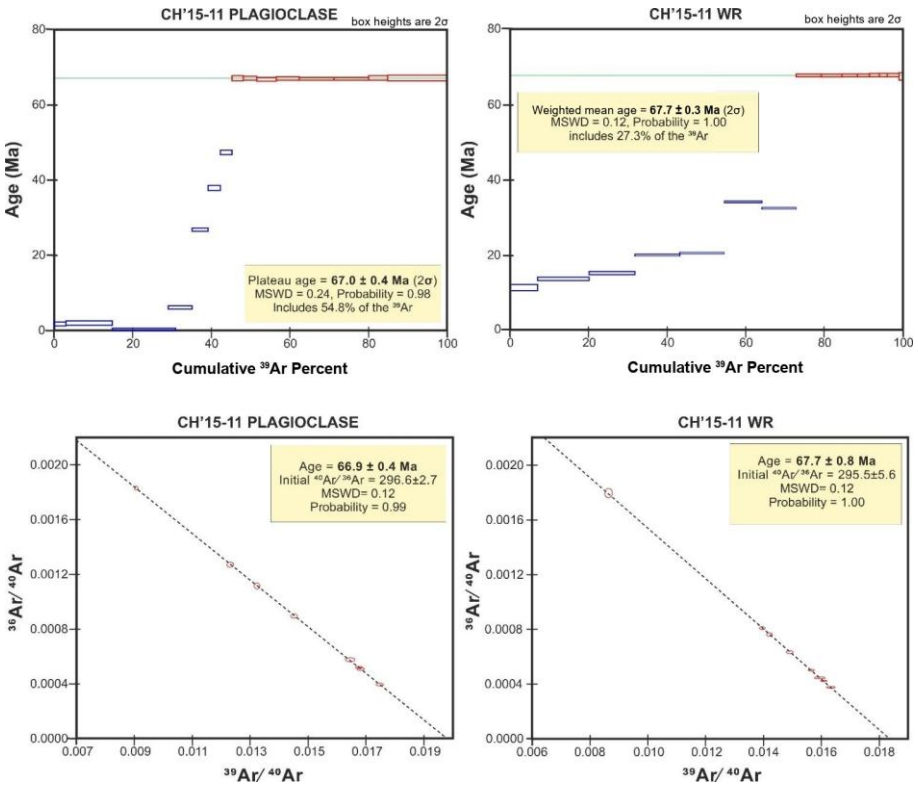


Fig. 3 Age spectra (upper panels) and inverse isochron plots (lower panels) for the plagioclase separate and the whole rock of sample CH'15-11. The whole-rock age includes only 27.3% of the ^{39}Ar and is treated in the text as a weighted mean age, not a plateau age. Errors are 2σ.

3.2 Geochemistry

The major and trace element compositions of the sampled flows are given in Tables 2 and 3. The samples are tholeiitic basalts with low K_2O (0.10–0.60 wt%). The low SiO_2 of CH'15-4, -5(b) and -5(c) (42.1–43.6 wt%) goes with their high LOI (3.2–6.3

wt%) and reflects alteration. The lower flows CH'15-9 and -10 differ from the flows above them: they have high TiO_2 (3.03–3.46 wt%), Zr (229–254 ppm), Sr (247–285 ppm) and Y (40–43 ppm), and low Mg# (38–39). The dated flow CH'15-11 has similar trace element contents (Zr 225 ppm, Sr 300 ppm, Y 42 ppm), and the three lower flows form a chemically distinct group. The upper flows (CH'15-3 to -8) have lower TiO_2 (1.39–2.79 wt%) and Zr (110–172 ppm) and higher Mg# (44–52), and CH'15-3, -4, -5(b), -5(c) and -6 have low Ba (41–72 ppm). CH'15-5(a) and CH'15-7 have the lowest TiO_2 (1.39–1.56 wt%) and Zr (110–127 ppm) of the section.

Deshmukh et al. [25] and Peng et al. [27] analysed many more flows of the Chikhaldara section and correlated them with the Khandala, Poladpur and Ambenali formations of the Western Ghats. Peng et al. [27] found Ambenali-like flows at the top of the section, and low Ba is a characteristic feature of the Ambenali-type basalts [2, 27], as in the upper flows sampled here. The present data, from fewer flows, agree with these studies and show in addition that the lower part of the section is chemically different from the flows above it.

The dated flow CH'15-11 has a low LOI (1.37 wt%), whereas CH'15-4, -6 and -7, which gave disturbed age spectra, have higher LOI (3.06–4.67 wt%) and K_2O of only 0.10–0.33 wt%. This agrees with the interpretation that alteration and low potassium caused the disturbed spectra of these flows. A detailed correlation of the flows with the Western Ghats formations needs isotopic data and is beyond the scope of this paper.

Table 2 Major element compositions (wt%) of the Chikhaldara flows, determined by XRF, in stratigraphic order from the base of the section.

Sample	Flow[a]	Alt.[a]	SiO_2	TiO_2	Al_2O_3	$Fe_2O_3^T$	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Mg#
CH'15-11	2	597	n.d.[c]	n.d.[c]	n.d.[c]	n.d.[c]	n.d.[c]	n.d.[c]	n.d.[c]	n.d.[c]	n.d.[c]	n.d.[c]	1.37	n.d.[c]	n.d.[c]
CH'15-10	14	629	49.53	3.46	14.02	15.69	0.23	4.32	9.94	2.49	0.42	0.21	2.04	102.34	39
CH'15-9	16	808	48.03	3.03	13.49	16.35	0.24	4.31	10.13	2.46	0.34	0.15	1.48	99.99	38
CH'15-8	17	909	48.70	2.68	14.63	14.73	0.22	5.17	10.74	2.50	0.49	0.21	1.03	101.09	45
CH'15-7	22	974	46.36	1.39	14.71	14.03	0.21	4.68	11.35	1.54	0.10	0.11	4.67	99.14	44
CH'15-6	23–26	994	45.94	2.79	14.63	15.43	0.20	5.46	10.77	2.19	0.14	0.20	3.06	100.82	45
CH'15-5(c)	27	1019	42.72	2.34	13.88	15.23	0.21	6.04	10.41	1.85	0.11	0.21	4.16	97.15	48
CH'15-5(b)	28	1019	42.10	2.69	13.77	15.39	0.23	7.23	11.08	1.61	0.13	0.21	6.29	100.74	52
CH'15-5(a)	28	1019	48.75	1.56	15.41	13.69	0.19	4.53	10.63	2.13	0.30	0.12	3.07	100.37	44
CH'15-4	32	1040	43.63	2.56	12.53	15.23	0.23	5.86	10.98	1.87	0.33	0.15	3.20	96.56	47
CH'15-3	32	1051	48.46	2.60	15.07	15.31	0.20	6.01	11.32	2.42	0.18	0.18	2.40	104.15	48
CH'15-2[b]	–	642	49.07	2.68	15.34	14.51	0.21	5.00	10.78	2.76	0.60	0.21	0.58	101.73	45
CH'15-1[b]	–	599	47.99	1.95	13.93	15.21	0.23	5.15	10.77	2.47	0.46	0.22	1.31	99.70	44

[a] Flow number of Deshmukh et al. [25] (Fig. 2); Alt., field (GPS) altitude in m. [b] Collected from the Melghat area, outside the road section. [c] Not determined: the XRF analysis of CH'15-11 gave a low total (82.4 wt%) and is not reported. $Fe_2O_3^T$, total iron as Fe_2O_3; Total includes LOI; Mg# = 100 Mg/(Mg + Fe^{2+}), with $Fe^{2+}/\Sigma Fe = 0.85$. The totals of CH'15-3 (104.2 wt%), CH'15-4 (96.6 wt%) and CH'15-5(c) (97.2 wt%) lie outside 98–102 wt% and these analyses should be used with caution.

Table 3 Trace element concentrations (ppm) of the Chikhaldara flows, determined by ICP-AES, in the same order as Table 2.

Sample	Sr	Ba	Y	Zr	Ni	Cr	Co	V	Zn	Cu	Sc	Pb
CH'15-11	300	235	42	225	61	142	57	381	116	275	32	8
CH'15-10	285	211	43	254	61	145	58	399	120	283	33	8
CH'15-9	247	141	40	229	49	68	63	418	122	266	36	7
CH'15-8	220	136	32	172	85	141	56	383	97	238	35	8
CH'15-7	202	111	26	110	49	69	48	310	87	142	40	8
CH'15-6	208	53	31	172	104	218	63	398	112	221	35	8
CH'15-5(c)	204	47	31	155	109	222	65	408	121	244	36	8
CH'15-5(b)	184	41	30	147	115	233	63	401	118	250	36	8
CH'15-5(a)	146	140	31	127	53	120	45	316	90	165	41	8
CH'15-4	216	56	28	151	87	163	58	377	106	215	35	8
CH'15-3	216	72	27	134	86	164	60	373	108	203	33	8
CH'15-2[b]	217	130	33	153	84	149	56	381	100	259	34	8
CH'15-1[b]	194	119	34	147	65	93	61	408	115	227	36	7

[b] Collected from the Melghat area, outside the road section.

3.3 Comparison with regional ages and correlation

The $^{40}Ar/^{39}Ar$ age obtained from Chikhaldara is limited to a single lower flow of the section, and thus it is hard to correlate the whole section with the Western Ghats formations. Chemically, the Chikhaldara flows are similar to those of the Western Ghats [25, 27, 28, 37]. Peng et al. [27] showed that the top of the section is isotopically and chemically indistinguishable from the Ambenali Formation, and that the flows beneath resemble the Poladpur and Khandala formations, although many of the northeastern flows differ from the southwestern formations in their Pb isotopic compositions. A similar Western-Ghats-like chemical stratigraphy has been described from the Toranmal and Bijasan Ghat sections of the Satpura Range [28, 29].

The age of 67.0 ± 0.4 Ma obtained in this study is identical within error to the 67.12 ± 0.44 Ma age of the lower Mhow flows of the Malwa Plateau [17]. Schöbel et al. [17] used the decay constants of Renne et al. [38] and a trapped $^{40}Ar/^{36}Ar$ ratio of 298.56, whereas the present study used the Steiger and Jäger [33] constants and a ratio of 295.5 [34]. On the same calibration, the Chikhaldara age becomes ~67.6 Ma, which still overlaps the Mhow age within the 2σ uncertainties. The Chikhaldara age is also older than, or as old as, the oldest Malwa lavas dated by Tholt et al. [22], which began to erupt before 66.8 Ma. Within the uncertainties, it also overlaps the 66.56 ± 0.42 Ma age of the Mohpani feeder dyke on the northern slope of the Satpura Mountain [39] and the oldest age of 66.60 ± 0.35 Ma from the Phenai Mata area of the northern Deccan [40] (Fig. 4).

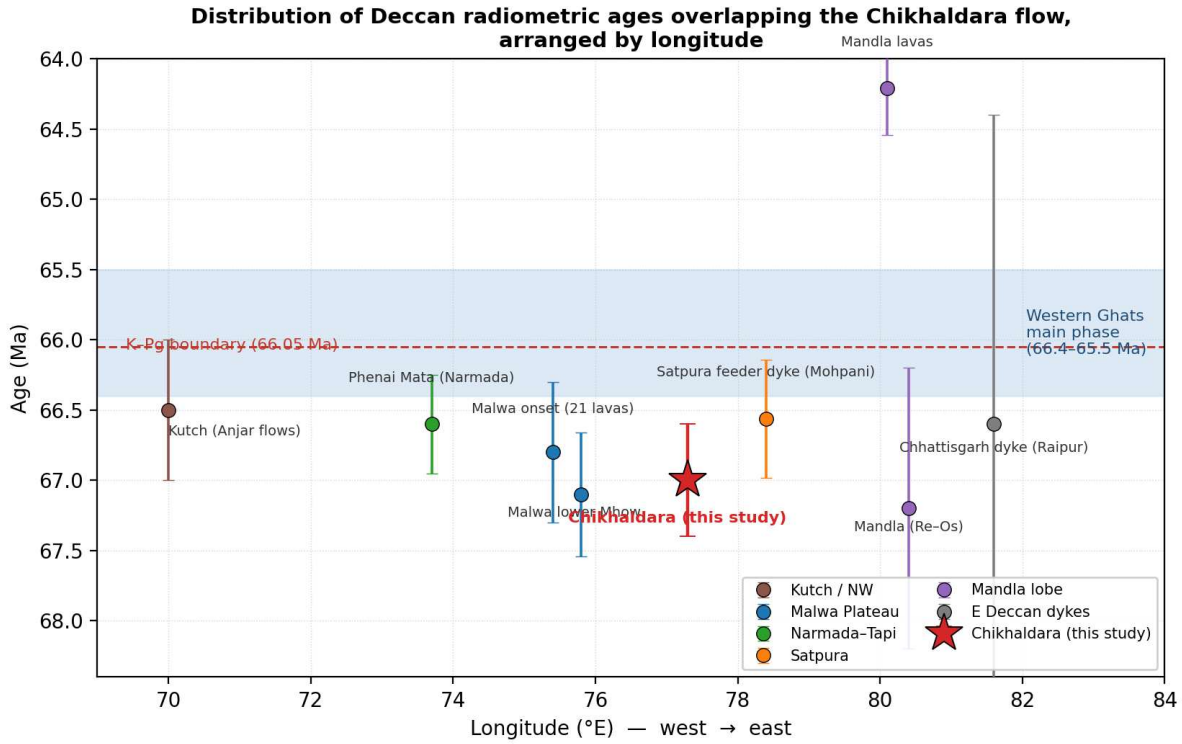


Fig. 4 $^{40}Ar/^{39}Ar$ and Re–Os ages from the northern and eastern Deccan compared with the Chikhaldara flow, arranged from west to east. The shaded band marks the main-phase Western Ghats interval (about 66.4–65.5 Ma); the dashed line marks the K–Pg boundary (66.05 Ma). Ages are plotted as published, on their original calibrations. Error bars are 2σ. Ages compiled from Allègre et al. [41], Venkatesan et al. [42], Schöbel et al. [17], Lala et al. [43], Shrivastava et al. [23, 39], Parisio et al. [40] and Tholt et al. [22]; Western Ghats interval after Schoene et al. [15] and Sprain et al. [16].

Allègre et al. [41] estimated an average age of 67.2 ± 1.0 Ma for the Mandla lobe using $^{187}Re–^{187}Os$ systematics. However, Shrivastava et al. [23] reported an $^{40}Ar/^{39}Ar$ age of 64.21 ± 0.33 Ma for the Mandla lavas, which is younger than the ages of the present study and of the Malwa region. The main Western Ghats sequence (~66.4–65.5 Ma) [15, 16] is also younger than the Chikhaldara flow. The Chikhaldara flows are spatially related to the Malwa flows. Thus, the lower part of the Chikhaldara section can be correlated with the lower flows of the Malwa Plateau, and it is among the oldest exposed parts of the Deccan Volcanic Province at present.

The new age also shows that chemical similarity alone cannot be used to correlate the Chikhaldara flows in time with the Western Ghats formations, because the dated flow is older than the Poladpur and Khandala formations of the Western Ghats, which the flows below the top of the section resemble [27]. The Malwa lavas likewise show chemical affinities with the Western Ghats formations but are out of their stratigraphic order [22]. Present elevation is also not a reliable guide, as the flows of the Northern Deccan are warped and displaced by reactivated faults along the Narmada–Tapi

zone [18, 44]. A crystallisation age of 67.0 Ma (or ~67.6 Ma on the current calibration) places the lower Chikhaldara flow within magnetochron C30n, as in the lower Mhow flows [17]. Chemical and magnetic stratigraphy has been described from parts of the Narmada region [26]. However, the present age constrains only the lower part of the pile. The flows above the dated flow, separated by several bole horizons, may have erupted soon after it within C30n, across the C30n–C29r reversal, or after a hiatus during the main Western Ghats phase in C29r, in which case they would be of the same age as their chemical equivalents in the Western Ghats. A flow-by-flow palaeomagnetic study and dating of the upper flows of the Chikhaldara section are needed to decide between these possibilities.

4 Conclusions

The $^{40}Ar/^{39}Ar$ dating of the lowest sampled flow of the Chikhaldara section gives a plagioclase plateau age of 67.0 ± 0.4 Ma (~67.6 Ma on the current calibration), the first radiometric age reported from this section. The age is identical within error to the lower Mhow flows of the Malwa Plateau and older than the main Western Ghats sequence. The lower flows of the section (CH'15-9 to -11) are richer in Zr, Sr and Y and differ chemically from the flows above them. This indicates that the lower part of the Chikhaldara section belongs to an early, northern phase of Deccan volcanism in the Narmada–Tapi rift and is among the oldest exposed parts of the Deccan Volcanic Province. Because the lower flows are chemically similar to younger Western Ghats formations, chemistry alone cannot be used for time correlation in the Northern Deccan. The age of the upper part of the section is still unknown, and palaeomagnetic study and further dating of the Chikhaldara section are the next steps.

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Author contributions

Y.J. carried out the fieldwork and sample preparation, acquired and interpreted the $^{40}Ar/^{39}Ar$ data, prepared the figures and wrote the manuscript. The author read and approved the final manuscript.

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Data availability

The $^{40}Ar/^{39}Ar$ results and the geochemical data supporting this study are given in Tables 1–3. The full step-heating data are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Clinical trial number Not applicable.

Competing interests The author declares no competing interests.

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