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$^{40}Ar/^{39}Ar$ dating of mineral separates and whole rocks from the Western Ghats lava pile: further constraints on duration and age of the Deccan traps

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Abstract

There has been an ongoing debate for almost two decades on the age and duration of Deccan trap volcanism. Some of the best available ages have been determined using the $^{40}Ar/^{39}Ar$ method, but differences in sample location, laboratory procedure, type of analyzed material, and ages of monitors may have been responsible for much of the apparent spread in the data. We have collected and analyzed samples from close to the bottom and top of the main lava pile in the Western Ghats near Bombay. We confirm previous findings that alteration and Ar recoil strongly affect these rocks, particularly measurements made on whole rocks. When mineral separates (mostly plagioclase) are analyzed, the spread is much reduced. We find a mean age of 65.4 ± 0.7 Ma for five flows near the base of the section (Jahwar and Igatpuri formations) and 65.2 ± 0.4 Ma for a dyke cross-cutting the Poladpur formation, below the topmost Mahabaleshwar formation. This implies that at least 1800 m out of the 2500 m composite trap section were erupted in a short interval, less than 1 Ma long and close to 65.5 Ma, i.e. close to the Cretaceous–Tertiary boundary. We find that older ages (near 67 Ma) found by several authors are essentially based on whole rock samples, which display disturbed spectra (when this can be checked, i.e. when the spectra are published).

Keywords: Deccan Traps; absolute age; Ar-40/Ar-39; K–T boundary

1. Introduction

Accurate dating of the huge lava pile in the Deccan traps of India has been the focus of many geochronology papers in the last 20 years. Results obtained prior to 1990 using the $^{40}Ar/^{39}Ar$ method have been summarized by Vandamme et al. [1]. The main papers from that period were those of Kaneoka [2], Venkatesan et al. [3], Duncan and Pyle [4], Courtillot et al. [5] and Pande et al. [6]. Based on a compilation of 22 data, Vandamme et al. [1] concluded that the absolute age of the traps was 65.5 ± 2.5 Ma; they proposed that much of the spread in ages reflected alteration and problems of excess argon rather than the actual duration of volcanism, and that the most active phase of Deccan volcanism (up to 80% in

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volume) was concentrated in reversed chron 29R and lasted less than a million years. Both the date and duration of volcanism have been the subject of controversy (e.g. [7–9]. The Deccan traps cover a vast area, and reach their maximum thickness along the so-called Western Ghats (Fig. 1). The composite stratigraphic thickness there is in excess of 2500 m. Some of the spread in the data comes from the fact that scattered sampling, different laboratories, methods, analyzed material (whole rock or minerals) and standards were used and that not all these heterogeneities could be corrected for. One simple test would be to analyze samples from the base and top of the section where the thickness reaches a maximum.

With this in mind, seven flows were sampled in 1995, northeast of Bombay, along the Bombay to Igatpuri road section (samples JW1–7, Fig. 1). The samples span 400 m of the Jawhar and Igatpuri formations, which form the lowermost part of the trap sequence in the Ghats. Then, in 1996, one of the topmost flows of the Mahabaleshwar cliff (and formation) was sampled at 1300 m altitude near the town of Mahabaleshwar (MA1 and 2), 150 km to the southsoutheast of Bombay (lat. 17°55.21′N, lon. 73°37.84′E). Measurements were also performed on dykes provided by H. Bertrand in 1994 and sampled by A. Dessai some 70 km south of Bombay; five generations of dykes were recognized. Sample D90 (a porphyritic texture rock) comes from the youngest generation; although the field relations to the flow formations are not straightforward, these dykes apparently crosscut the Poladpur formation [10]. Another 40 km to the south, near Murud-Jamjira, three samples were collected from dykes cutting across the upper trap formations (Ambenali formation), but did not yield useful results. The Mahabaleshwar formation is the uppermost one in the traps, with Ambenali and Poladpur just below. The Igatpuri samples should therefore provide age estimates very close to the onset of volcanism in the main Deccan pile, and the dyke and Mahabaleshwar flow estimates close to the end of this phase.

Much of the experimental work on these samples can be found in Hofmann [11] and is described and complemented below. Significant work published after 1990 and not listed by Vandamme et al. [1] is compiled by Hofmann [11] and is included in Section 5 of the present paper.

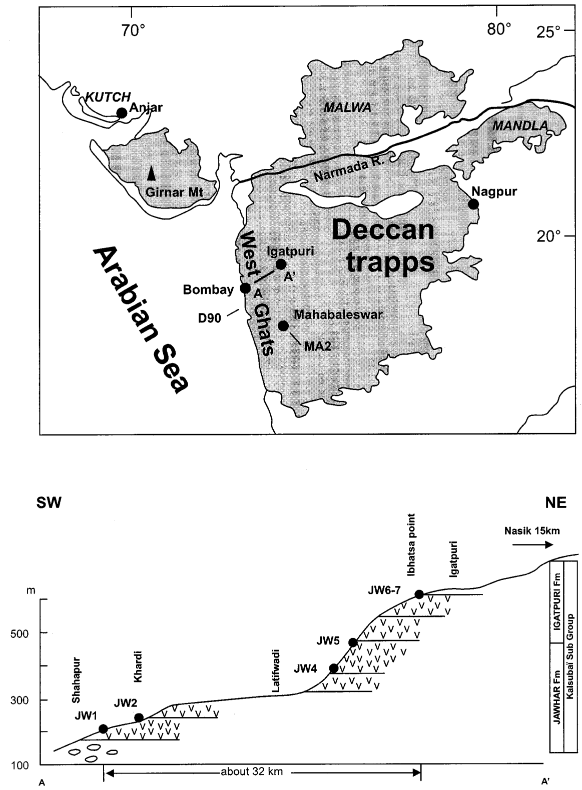

Fig. 1. Outline of the Deccan traps and location of sites investigated by the $^{40}Ar/^{39}Ar$ method.

2. Analytical procedure

Minerals were extracted from the bulk basaltic samples. Plagioclase (160–200 μm fraction) were separated using a Frantz magnetic separator, then carefully selected under a binocular microscope, in order to analyze only transparent grains (weight of about 30 mg). Single grains of amphibole and biotite were directly sampled out of crushed whole rock. The samples were irradiated in the nuclear reactor at McMaster University in Hamilton, Canada, in position 5c. The total neutron flux density during irradiation was 8.8×10^{18} n cm^{-2}. We used the Hb3gr hornblende as a flux monitor, with an age of 1072 Ma [12]. This K–Ar

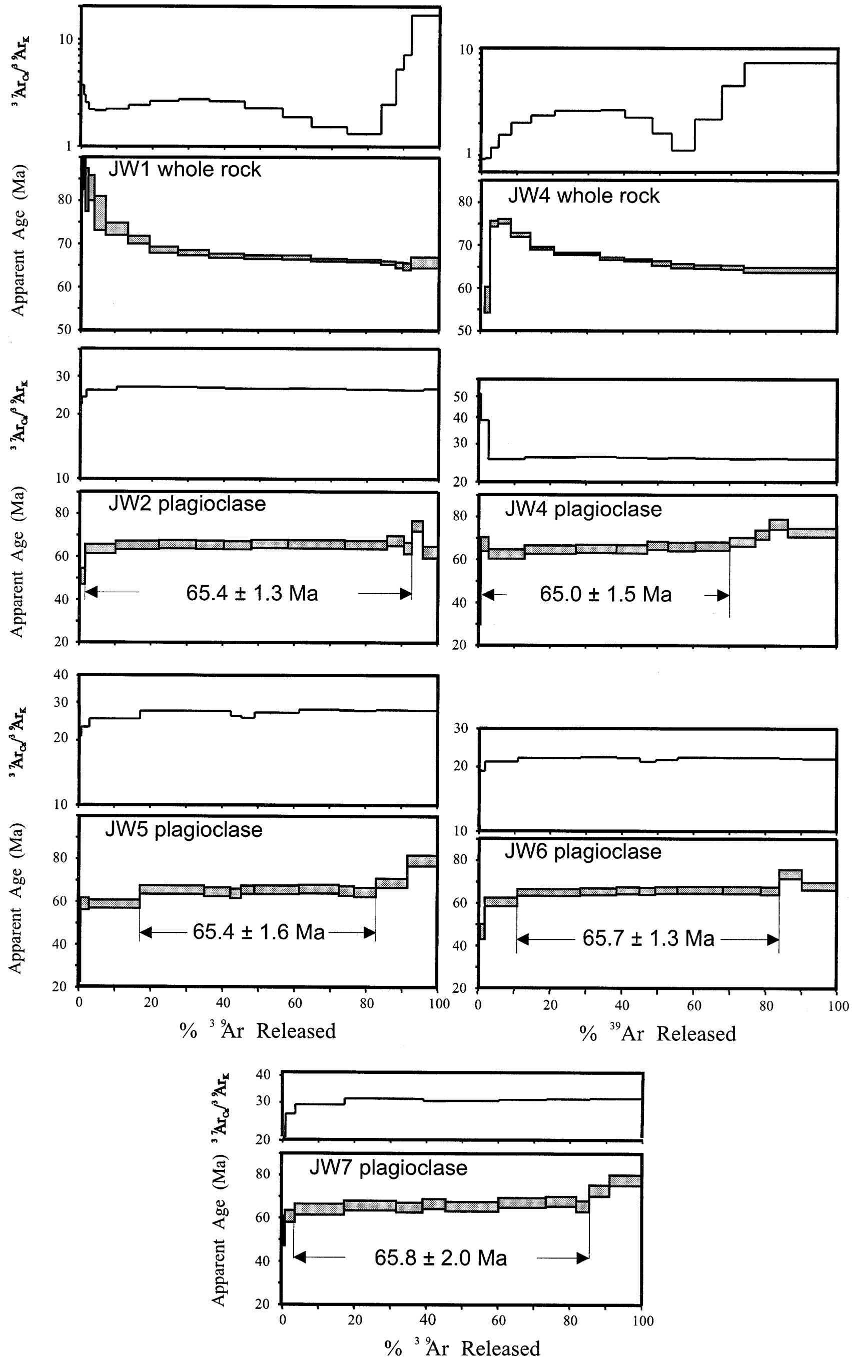

Fig. 2. $^{40}Ar/^{39}Ar$ age and $^{37}Ar_{Ca}/^{39}Ar_K$ ratio spectra obtained on plagioclase bulk samples and whole rocks from a section of the basal part of the Deccan traps in the Western Ghats (Igatpuri, see Fig. 1). Uncertainties on apparent ages are given at the 1σ level, whereas plateau ages are given at the 2σ level for comparison with other data.

Table 1
Detailed $^{40}Ar/^{39}Ar$ analytical results obtained on lava flows and dykes from the Western Ghats (Deccan traps)

Step number	Atmospheric contamination (%)	^{39}Ar (%)	$^{37}Ar_{Ca}/^{39}Ar_K$	$^{40}Ar^*/^{39}Ar_K$	Age (Ma)
JW1 whole rock, $J=0.016429$					
1	100	0.84	3.755	–	–
2	94.2	0.46	3.047	3.250	93.85 ± 11.23
3	88.9	0.87	2.597	2.846	82.45 ± 4.97
4	83.1	1.66	2.234	2.863	82.91 ± 2.91
5	82.0	3.20	2.186	2.655	77.03 ± 3.94
6	74.0	6.29	2.256	2.528	73.42 ± 1.41
7	63.4	5.96	2.444	2.439	70.88 ± 0.88
8	55.2	7.96	2.680	2.359	68.61 ± 0.71
9	46.3	8.56	2.779	2.335	67.92 ± 0.59
10	37.3	9.81	2.663	2.311	67.24 ± 0.47
11	28.3	10.61	2.300	2.301	66.93 ± 0.40
12	21.4	8.08	1.905	2.299	66.89 ± 0.47
13	16.9	9.96	1.538	2.278	66.29 ± 0.33
14	13.3	9.57	1.329	2.272	66.10 ± 0.29
15	16.0	4.04	2.498	2.257	65.68 ± 0.37
16	13.0	2.12	5.324	2.238	65.14 ± 0.62
17	15.1	2.15	7.225	2.226	64.80 ± 0.80
fuse	18.4	7.86	16.728	2.258	65.71 ± 1.2
Integrated age					66.89 ± 1.11
JW2 plagioclase bulk sample, $J=0.016363$					
1	100	0.06	24.704	–	–
2	100	0.24	22.147	–	–
3	83.346	1.29	24.016	1.747	50.84 ± 3.73
4	70.848	8.49	25.862	2.192	63.57 ± 2.18
5	16.721	12.14	26.793	2.254	65.33 ± 1.94
6	15.830	10.28	26.698	2.265	65.66 ± 1.92
7	19.440	7.71	26.511	2.257	65.41 ± 1.92
8	11.501	7.74	26.259	2.251	65.24 ± 1.91
9	14.014	10.23	26.265	2.273	65.88 ± 1.90
10	17.029	15.88	26.312	2.268	65.74 ± 1.88
11	21.957	11.84	26.039	2.259	65.48 ± 1.88
12	41.989	4.66	25.944	2.327	67.43 ± 2.32
13	37.841	2.20	25.854	2.206	63.98 ± 2.62
14	70.180	3.06	25.895	2.569	74.29 ± 2.37
fuse	54.115	4.19	26.250	2.141	62.13 ± 2.70
Integrated age					64.96 ± 0.62
JW4 plagioclase bulk sample, $J=0.016360$					
1	100	0.09	37.108	–	–
2	94.5	0.45	51.394	1.317	38.46 ± 8.69
3	69.3	2.16	38.742	2.314	67.03 ± 3.24
4	68.2	10.09	25.488	2.157	62.57 ± 2.19
5	21.2	14.36	25.986	2.230	64.64 ± 1.92
6	20.0	11.31	26.163	2.241	64.95 ± 1.89
7	21.0	8.65	25.952	2.236	64.82 ± 1.91
8	27.0	5.77	25.732	2.298	66.59 ± 1.92
9	26.6	7.61	25.932	2.279	66.03 ± 1.92
10	26.9	9.53	25.750	2.286	66.25 ± 1.90
11	43.2	7.17	25.624	2.358	68.30 ± 2.00
12	60.4	3.89	25.654	2.478	71.68 ± 2.18
13	65.6	5.15	25.756	2.651	76.58 ± 2.36
fuse	50.4	13.76	25.624	2.512	72.65 ± 1.99
Integrated age					66.98 ± 0.62

Table 1 (*continued*)

Step number	Atmospheric contamination (%)	^{39}Ar (%)	$^{37}Ar_{Ca}/^{39}Ar_K$	$^{40}Ar^*/^{39}Ar_K$	Age (Ma)
JW4 whole rock, $J = 0.016479$					
1	90.2	1.14	0.920	1.107	32.62 ± 3.04
2	56.8	1.47	0.937	1.958	57.30 ± 3.02
3	31.6	2.22	1.181	2.576	75.00 ± 0.66
4	27.6	3.54	1.557	2.595	75.55 ± 0.53
5	18.4	5.57	2.013	2.486	72.43 ± 0.45
6	9.4	6.59	2.365	2.375	69.27 ± 0.29
7	6.4	12.91	2.618	2.332	68.02 ± 0.26
8	6.0	6.85	2.666	2.292	66.88 ± 0.29
9	6.8	7.68	2.269	2.280	66.53 ± 0.27
10	8.7	5.38	1.611	2.254	65.81 ± 0.54
11	10.1	6.42	1.113	2.233	65.20 ± 0.49
12	11.1	7.54	2.191	2.226	64.99 ± 0.44
13	14.3	6.34	4.504	2.222	64.87 ± 0.47
fuse	13.4	26.35	7.366	2.201	64.27 ± 0.56
Integrated age					66.31 ± 0.18
JW5 plagioclase bulk sample, $J = 0.016360$					
1	99.9	0.12	17.054	0.624	18.31 ± 96.73
2	97.4	0.38	20.785	1.187	34.68 ± 11.95
3	81.1	2.30	23.048	2.030	58.95 ± 2.78
4	62.1	14.18	25.162	2.029	58.92 ± 1.93
5	14.6	17.92	27.389	2.264	65.61 ± 1.96
6	20.8	7.23	27.408	2.230	64.65 ± 2.03
7	38.2	3.00	25.979	2.206	63.97 ± 2.26
8	27.3	3.69	25.475	2.266	65.65 ± 1.95
9	17.3	12.43	26.937	2.268	65.72 ± 1.96
10	19.1	11.15	27.898	2.281	66.11 ± 2.03
11	23.6	4.20	27.660	2.251	65.23 ± 2.22
12	25.1	6.12	27.458	2.230	64.63 ± 2.14
13	47.4	8.79	27.760	2.380	68.92 ± 2.10
fuse	61.0	8.50	27.580	2.748	79.33 ± 2.48
Integrated age					65.67 ± 0.68
JW6 plagioclase bulk sample, $J = 0.016360$					
1	100	0.06	25.833	–	–
2	100	0.25	19.450	–	–
3	89.3	1.28	19.122	1.599	46.59 ± 3.60
4	75.5	9.16	21.132	2.084	60.49 ± 2.00
5	17.0	17.60	21.955	2.242	64.99 ± 1.58
6	15.9	10.15	22.185	2.255	65.34 ± 1.61
7	27.5	6.39	21.957	2.274	65.91 ± 1.62
8	30.8	4.46	21.149	2.265	65.65 ± 1.62
9	21.0	6.11	21.574	2.279	66.04 ± 1.59
10	20.6	12.70	22.120	2.284	66.19 ± 1.62
11	27.7	10.56	22.084	2.283	66.17 ± 1.64
12	19.9	5.17	22.078	2.272	65.83 ± 1.76
13	64.9	6.33	21.916	2.549	73.71 ± 2.06
fuse	36.7	9.77	21.789	2.353	68.13 ± 1.76
Integrated age					65.27 ± 0.54

Table 1 (*continued*)

Step number	Atmospheric contamination (%)	^{39}Ar (%)	$^{37}Ar_{Ca}/^{39}Ar_K$	$^{40}Ar^*/^{39}Ar_K$	Age (Ma)
JW7 plagioclase bulk sample, $J = 0.016356$					
1	100	0.13	15.266	–	–
2	90.2	0.67	20.700	1.857	53.99 ± 6.80
3	75.7	2.71	26.524	2.094	60.76 ± 2.74
4	75.7	13.71	29.303	2.208	64.00 ± 2.53
5	21.9	14.50	31.269	2.267	65.70 ± 2.25
6	29.8	7.37	31.213	2.239	64.87 ± 2.27
7	40.7	6.36	30.509	2.298	66.56 ± 2.30
8	22.5	14.73	30.566	2.255	65.35 ± 2.21
9	24.9	13.19	31.020	2.322	67.25 ± 2.24
10	22.8	8.46	31.225	2.343	67.84 ± 2.29
11	9.9	3.57	31.115	2.263	65.58 ± 2.52
12	30.1	5.62	31.343	2.520	72.86 ± 2.61
fuse	51.8	8.98	31.374	2.689	77.66 ± 2.46
Integrated age					66.95 ± 0.77
D90 amphibole single grain, $J = 0.016812$					
1	17.2	0.32	0.761	27.179	678.95 ± 24.01
2	13.1	0.24	0.379	2.891	85.62 ± 43.85
3	6.0	3.18	2.244	2.249	66.97 ± 3.36
4	2.3	3.46	2.638	2.184	65.05 ± 1.18
5	1.1	7.46	2.745	2.202	65.57 ± 0.47
6	1.1	8.62	2.780	2.191	65.26 ± 0.48
7	0.0	3.61	2.827	2.223	66.19 ± 1.30
8	4.5	3.60	2.742	2.114	63.01 ± 1.51
9	2.5	13.00	2.789	2.189	65.21 ± 0.43
10	1.2	28.78	2.786	2.209	65.79 ± 0.29
11	1.4	17.21	2.791	2.186	65.12 ± 0.37
fuse	3.1	10.50	2.860	2.157	64.26 ± 0.90
Integrated age					67.68 ± 0.26
D90 biotite single grain, $J = 0.016826$					
1	85.9	0.53	0.058	2.041	60.92 ± 14.63
2	33.3	1.76	0.020	1.768	52.88 ± 4.24
3	11.2	4.54	0.009	2.097	62.56 ± 1.64
4	1.4	9.87	0.000	2.279	67.88 ± 0.28
5	0.6	7.87	0.001	2.276	67.81 ± 0.37
6	0.7	10.21	0.001	2.266	67.51 ± 0.56
7	1.1	7.95	0.000	2.266	67.51 ± 0.32
8	1.4	7.57	0.001	2.252	67.10 ± 0.36
9	2.0	1.83	0.000	2.237	66.67 ± 1.20
10	0.0	4.40	0.003	2.284	68.03 ± 0.43
11	1.0	9.19	0.001	2.271	67.64 ± 0.29
12	0.5	20.87	0.002	2.283	68.02 ± 0.17
13	0.6	7.97	0.000	2.279	67.90 ± 0.28
14	0.6	4.11	0.000	2.276	67.80 ± 0.56
fuse	0.0	1.320	0.000	2.283	67.99 ± 1.38
Integrated age					67.20 ± 0.17

Table 1 (*continued*)

Step number	Atmospheric contamination (%)	^{39}Ar (%)	$^{37}Ar_{Ca}/^{39}Ar_K$	$^{40}Ar^*/^{39}Ar_K$	Age (Ma)
MA2 plagioclase bulk sample, $J = 0.018036$					
1	93.5	0.15	19.081	10.301	307.4 ± 31.04
2	79.9	0.54	26.888	3.606	113.69 ± 5.38
3	53.8	2.59	42.638	2.104	67.18 ± 3.72
4	49.3	6.19	54.035	2.017	64.45 ± 4.27
5	15.5	9.49	57.811	1.990	63.61 ± 4.49
6	16.5	26.80	59.916	1.959	62.65 ± 4.67
7	14.0	12.65	61.010	1.983	63.41 ± 4.76
8	22.7	14.00	61.313	1.997	63.84 ± 4.78
9	18.2	9.92	60.548	1.998	63.86 ± 4.71
10	39.1	4.24	60.113	2.054	65.63 ± 4.72
11	43.4	4.03	59.577	2.095	66.91 ± 4.74
12	24.2	3.35	60.050	2.031	64.91 ± 4.75
13	33.5	2.60	60.035	2.146	68.52 ± 4.74
fuse	31.1	3.45	57.663	2.156	68.82 ± 4.61
Integrated age					64.8 ± 1.7
MA2 whole rock, $J = 0.018032$					
1	88.5	0.41	1.618	2.247	71.66 ± 12.53
2	76.2	9.36	0.851	1.674	53.66 ± 1.33
3	47.8	9.85	1.011	1.985	63.46 ± 1.27
4	35.5	9.28	1.782	2.134	68.11 ± 0.80
5	30.9	10.51	3.261	2.078	66.36 ± 0.67
6	24.3	9.21	5.556	2.003	64.01 ± 0.70
7	19.9	9.71	6.996	1.966	62.85 ± 1.29
8	18.7	7.22	9.260	1.883	60.25 ± 1.10
9	27.1	25.34	7.477	1.956	62.52 ± 0.75
10	26.3	3.58	30.491	1.798	57.57 ± 3.50
fuse	18.1	5.52	66.789	1.735	55.57 ± 5.59
Integrated age					62.2 ± 0.5

$^{40}Ar^*$ = radiogenic ^{40}Ar; Ca and K: produced by Ca and K neutron interference, respectively. J = irradiation parameter. Decay constants are those of Steiger and Jäger [27]. Correction factors for interfering isotopes were $(^{39}Ar-^{37}Ar)_{Ca} = 7.06\times10^{-4}$, $(^{36}Ar-^{37}Ar)_{Ca} = 2.79\times10^{-4}$, $(^{40}Ar-^{39}Ar)_K = 3.6\times10^{-2}$. Uncertainties are given at the 1σ level.

age was recently confirmed by Renne [13] who measured ages of 1073 ± 4 and 1074 ± 4 Ma relatively to the Fish Canyon sanidine at 28.02 Ma. Additional work performed in Nice gave an age of 520.2 ± 1.1 Ma for the MMhb-1 standard, calculated with reference to the 1072 Ma age for Hb3gr. Eleven groups of hornblende grains were distributed along the irradiation can, every eight samples, and one to four hornblende single grains were measured for each group. This allowed us to obtain a maximum error bar on the $^{40}Ar^*/^{39}Ar_K$ ratio of ± 0.5% in the volume where the samples were included. The plagioclase bulk samples were step heated with a high frequency furnace, purified in a pyrex line directly connected to a 120°/12 cm M.A.S.S.E. mass spectrometer working with a Baur-Signer source and a Balzers SEV 217 electron multiplier. For single grains and whole rock analyses, the analytical procedures are described in detail by Ruffet et al. [14] and Hofmann [11]. Gas extraction was carried out with a Coherent Innova 70-4 continuous laser; the mass spectrometer is a VG 3600, working with a Daly detector system. The typical blank values for the extraction and purification laser system are in the range 8–11, 0.1–0.5, and 0.10–0.15×10^{-13} ccSTP for masses 40, 39, and 36 respectively (measured every third step). The criteria for defining plateau ages were the following: (1) at least 70% of released ^{39}Ar, (2) at least three successive steps in the plateau, and (3) the integrated age of the plateau should agree with each apparent age of the plateau within a 2σ confidence interval. Uncertainties on the apparent ages on each step (Table 1 and age spectra) are quoted at the 1σ level and do not include the uncertainties on the age of the monitor. All other uncertainties in the tables and figures are given at the 2σ level. The uncertainties on the $^{40}Ar^*/^{39}Ar_K$ ratios of the monitor are included in the calculation of the plateau age uncertainty. Detailed analytical data are given in Table 1.

3. $^{40}Ar/^{39}Ar$ results

1. In the Igatpuri section, six out of seven samples were analyzed either using plagioclase bulk samples (JW2, 4–7), and/or whole rock (JW1–4). The five plagioclase samples provide plateau ages ranging from 65.0 ± 1.5 to 65.8 ± 2.0 Ma, corresponding to 66–91% of ^{39}Ar released (Fig. 2). The Ca/K ratio, which is proportional to the $^{37}Ar_{Ca}/^{39}Ar_K$ ratio (with the relationship $Ca/K = 1.83 \times {}^{37}Ar_{Ca}/^{39}Ar_K$), shown in Fig. 2, is between about 41 and 57 for more than 90% of the total ^{39}Ar released, showing that nearly pure plagioclase was analyzed. The correlation diagram plots ($^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$) display ages ranging from 65.0 ± 1.2 to 66.5 ± 1.4 Ma and initial $^{40}Ar/^{36}Ar$ ratios have atmospheric or slightly lower (JW7 sample) composition (Table 2). The two whole rock samples (JW1 and 4) display decreasing apparent ages versus temperature (except for the very first steps in JW4) which converge towards 64–65 Ma at high temperatures. This shape for age spectra is characteristic of whole rocks affected by strong ^{39}Ar recoil during irradiation, with loss of ^{39}Ar clearly shown by decreasing ages at low temperature. In both cases, the last 3–4 steps correspond to the degassing of K-poor, Ca-rich mineral phases (plagioclase, pyroxene), as shown by the $^{37}Ar_{Ca}/^{39}Ar_K$ ratio spectra, which probably incorporated ^{39}Ar during the recoil, and which could suffer ^{37}Ar loss by recoil as well. It is therefore likely that the last apparent ages are too young; therefore, despite the lower uncertainties obtained for apparent ages on whole rocks, due to lower Ca/K ratios, the whole rock data do not provide useful age constraints.
2. In the Mahabaleshwar section, a whole rock and a plagioclase bulk sample from the same sample MA2 were analyzed. The plagioclase displays a plateau age at 63.8 ± 3.7 Ma, with 93.3% of the total ^{39}Ar. It represents a nearly pure mineral, as shown by its $^{37}Ar_{Ca}/^{39}Ar_K$ ratio spectrum (Fig. 3). The large uncertainties are due to a high $^{37}Ar_{Ca}/^{39}Ar_K$ ratio of the order of 60, which corresponds to a Ca/K ratio of about 111, inducing a high Ca interference correction. The isochron plot displays an age of 63.0 ± 2.0 Ma, and an initial $^{40}Ar/^{36}Ar$ ratio slightly higher than atmospheric. The whole rock of the same sample displays a humped-shaped age spectrum also characteristic of ^{39}Ar recoil during irradiation. The apparent ages converge at high temperatures (the last two steps excepted, because they represent the degassing of high Ca content minerals which may have received recoiled ^{39}Ar from high K phases) towards a weighted mean value of 62.5 ± 2.0 Ma, which is concordant with the plagioclase plateau age.
   Companion sample MA1 was analyzed using the K/Ar method of Cassignol and Gillot [15] in the Orsay geochronology laboratory (X.

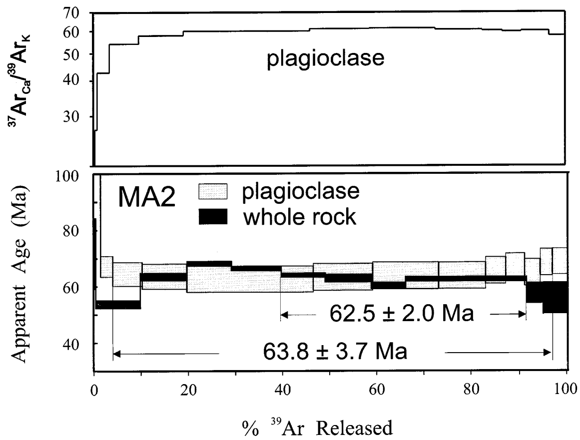

Fig. 3. $^{40}Ar/^{39}Ar$ age and $^{37}Ar_{Ca}/^{39}Ar_K$ ratio spectra obtained on a plagioclase bulk sample and a whole rock from the upper part of the Deccan traps in the Western Ghats, near Mahabaleshwar (see Fig. 1). Same legend as Fig. 2.

Quidelleur, personal communication, 1999). Whereas the groundmass yielded an age of 60.3 ± 1.1 Ma, the plagioclase separate gave 64.7 ± 2.6 Ma (all at 2σ). The rock and plagioclase are very low in potassium (K = 0.09% in the plagioclase) but the two plagioclase results found in the two laboratories using different techniques are in agreement. However, we might remain cautious about possible effects of alteration on either mineral phase from this sample; further $^{40}Ar/^{39}Ar$ measurements are in progress to check this.
We also collected a sample at the same site for paleomagnetic analysis (MH1). Alternating field demagnetization yields a superb two component diagram with a recent remagnetization which is removed by 15 mT and a characteristic magnetization isolated between 15 and 80 mT (Y. Gallet, personal communication, 1999). This component is clearly primary, at $D = 330.8°$ and $I = -31.7°$, a typical Deccan trap southern hemisphere normal polarity result, as expected for the Mahabaleshwar formation.

3. In the coastal dyke swarm to the south of Bombay, amphibole and biotite single grains from one dyke only provided useful data. The age spectra (Fig. 4) show two plateau ages at 65.2 ± 0.4 Ma and 67.7 ± 0.6 Ma, respectively. The Ca/K ratio of the analyzed amphibole is very constant, the first steps excepted, demonstrating the high purity of the analyzed grain. The biotite shows a higher plateau age that is probably due to undetectable excess argon. This is supported by very variable plateau ages obtained on other dykes (also porphyritic) from the same region, and interpreted as resulting from excess argon [11]. The isochron plot for the amphibole displays an age of 64.8 ± 1.2 Ma, but because of the very clustered data near the $^{39}Ar/^{40}Ar$ axis, it provides no information on the initial $^{40}Ar/^{36}Ar$ ratio.

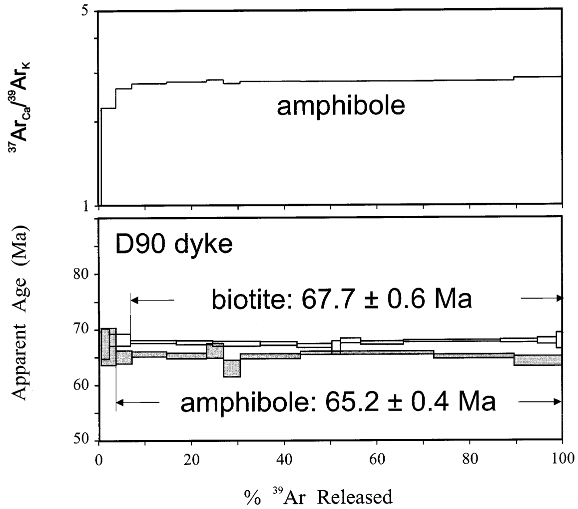

Fig. 4. $^{40}Ar/^{39}Ar$ age and $^{37}Ar_{Ca}/^{39}Ar_K$ ratio spectra obtained on amphibole and biotite single grains from a dyke crosscutting the Deccan traps, south of Bombay (Western Ghats). Same legend as Fig. 2.

4. Interpretation of the $^{40}Ar/^{39}Ar$ data

The five plateau ages obtained on plagioclase from the Igatpuri section are indistinguishable

Table 2
$^{40}Ar/^{39}Ar$ plateau ages and correlation diagram data obtained on lava flows and one dyke from the Western Ghats (Deccan traps)

Location	Sample nb	Step nb	Plateau age (Ma)	$(^{40}Ar/^{36}Ar)_i$	Isochron age (Ma)	MSWD
Igatpuri section	JW2 plag.	4–13	65.4 ± 1.3	291.8 ± 3.6	65.7 ± 1.0	0.2
	JW4 plag.	3–10	65.0 ± 1.5	292.9 ± 7.0	65.7 ± 1.6	0.6
	JW5 plag.	5–12	65.4 ± 1.6	279.8 ± 14.4	66.2 ± 1.2	0.1
	JW6 plag.	5–12	65.7 ± 1.3	305.5 ± 14.6	65.0 ± 1.2	0.1
	JW7 plag.	3–11	65.8 ± 2.0	289.5 ± 3.8	66.5 ± 1.4	0.4
Mahabaleshwar	MA2 plag.	4–13	63.8 ± 3.7	311.6 ± 16.0	63.0 ± 2.0	0.1
Dyke	D90 amph.	4–12	65.2 ± 0.4	431 ± 660	64.8 ± 1.2	1.0

$(^{40}Ar/^{36}Ar)_i$ = initial ratio from correlation diagram plot. Uncertainties are given at the 2σ level.

within 1σ uncertainties, which are in the order of ±1%, or slightly more. This shows that this 400 m thick section was emplaced in a short period of time. The weighted mean age is 65.4±0.7 Ma. For the top of the traps, our data are less straightforward. The amphibole from dyke D90 displays a plateau age at 65.2±0.4 Ma, which is indistinguishable from the weighted mean obtained on the Igatpuri samples. If this plateau age is valid, this implies that most of the Deccan flood basalts were indeed emplaced in a very short period of time. This high quality plateau age is concordant, within uncertainties, with the plateau age displayed by plagioclase MA2 from one of the uppermost flows of the Mahabaleshwar region (63.8±3.7 Ma). The uncertainty on MA2 is unfortunately large, yet it is compatible with the age of the Igatpuri section. Fortunately, the D90 dyke provides a much better constraint from the underlying Poladpur formation. As a consequence of our data, at least some 1800 out of 2500 m of the Western Ghat section (from the Jawhar to the Poladpur formations) would have been produced near 65.2–65.5 Ma with an uncertainty (maximum duration?) in the order of 0.5 Ma. Because much of the lava pile has reversed magnetization (see e.g. [1], figure 10), and certainly the Poladpur and Ambenali formations (ibidem, and more recently from a borehole in Killari village, Latur district, Maharashtra [16]), the only possible correlation is with chron 29R (ages 65.58–64.74 Ma in Cande and Kent's time scale [17]). The Mahabaleshwar sample is normal, i.e. in 29N as expected. This would vindicate the conclusions defended by Courtillot et al. [5,18] and Vandamme et al. [1] and the correlation between the main phase of Deccan trap volcanism and the Cretaceous–Tertiary boundary and mass extinction (e.g. [19,20]).

5. Discussion

We still have to see how these new results fit in the (slowly) growing data base of Deccan trap $^{40}Ar/^{39}Ar$ ages. A critical analysis of previously published data can be found in Hofmann [11] and is updated here. Deccan basalts are often altered due to unfavorable climatic conditions, and therefore whole rocks, which represent the most abundant material analyzed by the $^{40}Ar/^{39}Ar$ method, often display disturbed age spectra. Moreover, as described in detail by Féraud and Courtillot [9], whole rocks from the Deccan are very often affected by ^{39}Ar recoil, giving decreasing apparent ages versus increasing temperature. In that case, the best estimate of the age is given by the high temperature steps, excepting the very last steps which correspond to degassing of K-poor phases containing recoiled ^{39}Ar in excess, such as plagioclase or pyroxene. This phenomenon is clearly demonstrated by our new data from the Igatpuri section, for which integrated ages of the whole rocks are higher than the plagioclase plateau ages. Some previous data, such as the early age spectra published by Kaneoka [2], are quite perturbed, because of such alteration and recoil effects. Only two samples from a flow near the top of the Western Ghats and a dyke pass our criteria for plateau selection, but both unfortunately have 2σ uncertainties in excess of 4 Ma. Results from Venkatesan et al. [3] come from whole rock analyses, with only two or three steps and overestimated uncertainties [21], and cannot be used.

Duncan and Pyle [4] show only four out of nine of their age spectra, two of which are affected by Ar recoil not mentioned in the paper [9]. These tend to define ages near 65 Ma (high temperature steps) rather than the 66.6 and 67.5 Ma values they propose (which include steps with apparent ages affected by ^{39}Ar loss, hence too old). Recoil effects also affect the isochron ages which they finally use. From their analysis, although the existence of plateau ages may be the result of both effects of alteration (loss of radiogenic ^{40}Ar) and recoil (^{39}Ar loss), we can retain two ages that pass all our criteria, one at 68.6±2.4 Ma 400 m above the base, and one at 66.9±1.4 Ma 200 m below the top of the series. These two ages do reflect the authors' conclusion that there is no resolvable age difference within uncertainties between the top and bottom of the sequence. Duncan and Pringle [22] provide two further ages from the Western Ghats (unfortunately only in an abstract without a subsequent paper). They quote two 'high preci-

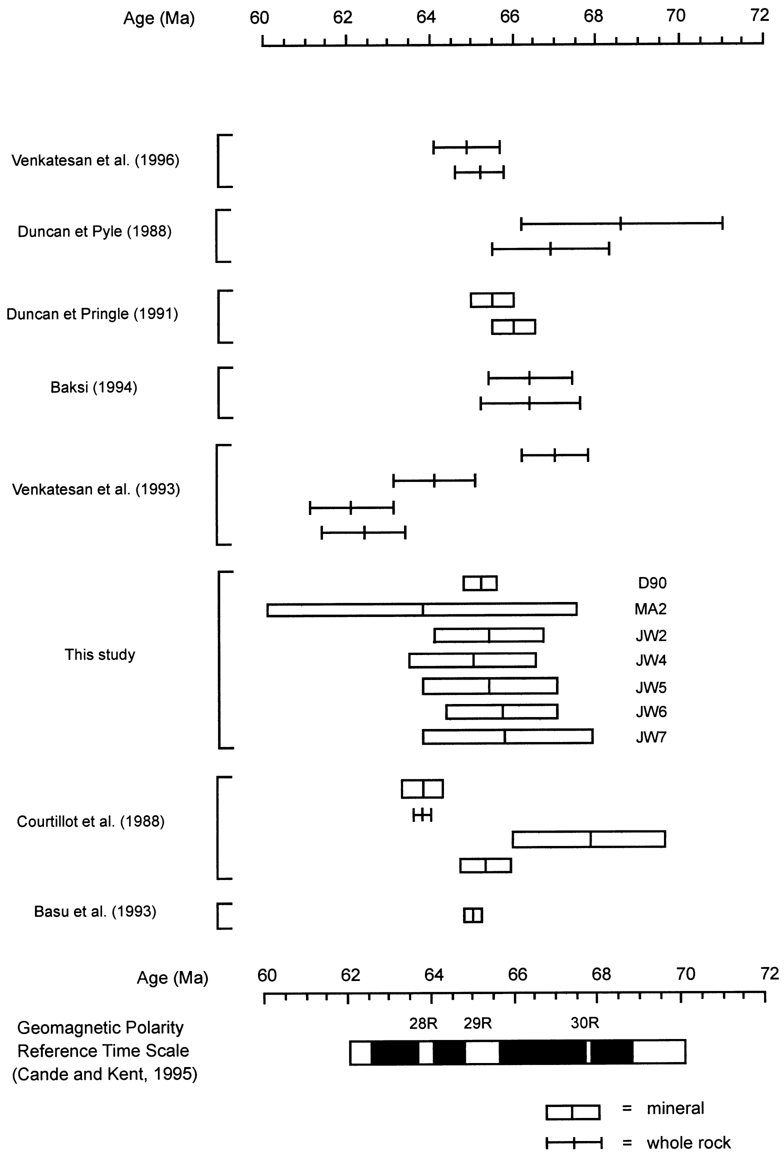

Fig. 5. A compilation of 24 selected plateau ^{40}Ar-^{39}Ar ages from the Deccan traps (see text and Table 3). Note that data obtained on mineral separates (rectangles) are better clustered, except for two values. When necessary, data from authors are recalculated with an age of 520.4 Ma for the MMhb-1 standard. Uncertainties are given at the 2σ level. The geomagnetic reference polarity time scale is from Cande and Kent [17].

sion feldspar plateau ages', which we have corrected for a difference between MMhb-1 monitor ages (from 513.9 to 520.4 Ma). Other ages are uncommented whole rocks, a sill from the northeast and a top flow south of the Ghats, which we cannot use with the same confidence but which all support fast eruption of the traps. Note that the Duncan and Pringle [22] results on separate K-feldspar are a million years or more younger than the Duncan and Pyle [4] whole rock results.

Courtillot et al. [5] give results along sections in the northeastern part of the traps, on both sides of the Narmada river, and in the eastern part of the traps (Dongargaon area). These include con-

Table 3
A compilation of 33 selected $^{40}Ar/^{39}Ar$ plateau ages from the Deccan traps (see text)

Reference/Area	Quality/Comments	Plateau age (Ma)	Location	Material
Western Ghats				
Kaneoka [2]	B (standard)	63.2 ± 4.6	(top)	WR
Duncan and Pyle [4]	A: saddle shape	68.6 ± 2.4	(400 m from bottom)	WR
	A: three low temperature steps	66.9 ± 1.4	(200 m from top)	WR
Duncan and Pringle [22]	A: spectrum unknown	**65.5 ± 0.5**		KF
	A: spectrum unknown	**66.0 ± 0.5**		KF
Baksi [23]	A: 4 steps	66.4 ± 1.0		WR
	A: 4 steps	66.4 ± 1.2		WR
Venkatesan et al. [7]	B: recoil	66.8 ± 0.6	(from bottom to top)	WR
	B: recoil	66.5 ± 0.8		WR
	B: saddle shape	67.5 ± 0.6		WR
	B: recoil	66.8 ± 0.6		WR
	A	67.0 ± 0.8		WR
	B: recoil	67.5 ± 0.8		WR
	B: recoil	66.1 ± 0.8		WR
	A: 3 steps	64.1 ± 1.0		WR
	A	62.1 ± 1.0		WR
	A	62.4 ± 0.8		WR
This work	A	**65.2 ± 0.4**	Dyke, south Bombay	AMPH
	A	**63.8 ± 3.7**	Mahabaleshwar, top 400 m section at the	PL
	A	**65.4 ± 1.3**	bottom of the series	PL
	A	**65.0 ± 1.5**	as above	PL
	A	**65.4 ± 1.6**	as above	PL
	A	**65.7 ± 1.3**	as above	PL
	A	**65.8 ± 2.0**	as above	PL
Northwest and east				
Courtillot et al. [5]	B (standard)	**66.4 ± 1.9**	East (Dongargaon)	PL
	A	**63.6 ± 0.5**	Narmada Valley (dyke)	PL
	A	63.8 ± 0.2	Narmada Valley	WR
	A	**67.8 ± 1.8**	Narmada Valley (bottom)	PL
	A	**65.3 ± 0.6**	Narmada Valley (bottom)	PL
Basu et al. [24]	A	**65.0 ± 0.2**	Narmada Valley	BIO
Northwest, Kutch				
Kaneoka [2]	B (standard)	68.6 ± 4.8	Mount Girnar	WR
Venkatesan [25]	A	64.9 ± 0.8	Anjar area	WR
	A	65.2 ± 0.6		WR

Uncertainties are given at the 2σ level. Quality A corresponds to a plateau satisfying the criteria recalled in the text. B is for less reliable results: plateau ages affected by Ar recoil (based on published spectra) or ages with an unknown, internal or not comparable monitor. A-quality ages based on mineral separates are shown in bold type. For A samples, the MMhb-1 monitor age is taken as 520.4 Ma. WR = whole rock, KF = analysis on K-feldspar bulk sample, PL = analysis on plagioclase bulk sample, BIO = analysis on a biotite single grain. 'Standard' means that the used monitor is unknown, internal or cannot be related to the others.

cordant results from two different laboratories: four lava flows and one dyke yield plateau ages that satisfy our criteria.

Venkatesan et al. [7] have proposed a list of 10 ages which have been subject to some controversy [8,9]. The authors propose that ages for the lowermost 2000 m of the Western Ghats are concentrated near 67 Ma, with the above 800 m being time transgressive, from 67 to 60 Ma. Féraud and Courtillot [9] argue that this span would be much reduced if plateau ages featuring steps clearly affected by ^{39}Ar recoil were reassessed. This in our opinion leads to artificial overestimation of these ages: the intermediate to high temperature steps in the age spectra cluster near 65 Ma. Only two of the youngest ages do not show decreasing apparent ages. Still, these ages are all listed in Table 3.

Baksi [23] undertook both K/Ar and $^{40}Ar/^{39}Ar$ determination on whole rock samples. Any Ar loss due to recoil can be detected by comparing the two age estimates for the same sample. In the nine out of 15 spectra that pertain to the Western Ghats, most show strong effects of recoil and/or alteration. Only two which span intermediate time steps satisfy our criteria, and have been recalculated with our monitor value (Table 3): these are concordant near 66.5 Ma.

Basu et al. [24] analyzed pre- and post-trap emplacement alkaline lavas. One determination comes from alkaline rock in the Narmada Valley intruding basaltic trap flows. The age is 65.0 ± 0.2 Ma, based on plateau ages for two biotite single grains.

Venkatesan et al. [25] have published plateau ages from flows surrounding an iridium-bearing intertrappean layer [26]. These sections were the subject of joint Indo–French work that will be presented elsewhere (Courtillot et al., in preparation) and we do not discuss these in detail here. Two plateau ages published by Venkatesan et al. [25] pass our criteria and are listed in Table 3.

Altogether, there are 33 data listed in Table 3. The frequency distribution of these 33 data is shown in Fig. 6, curve a. Taken at face value, it would indicate a prolonged history of volcanism, with a first peak phase near 67 Ma, a second even larger one at 65 Ma and a third pulse at 64 Ma. However, for three of the data, the monitor age is unknown, internal or cannot be related to the others. Out of the 10 data published by Venkatesan et al. [7], six are considered dubious (see above and [9,11]). The remaining (A-quality) 24 corrected $^{40}Ar/^{39}Ar$ plateau ages are shown in Fig. 5, together with the Cande–Kent reference time scale [17]. The frequency distribution for these 24 data (Fig. 6, curve b) has a much reduced secondary maximum (almost an inflexion) near

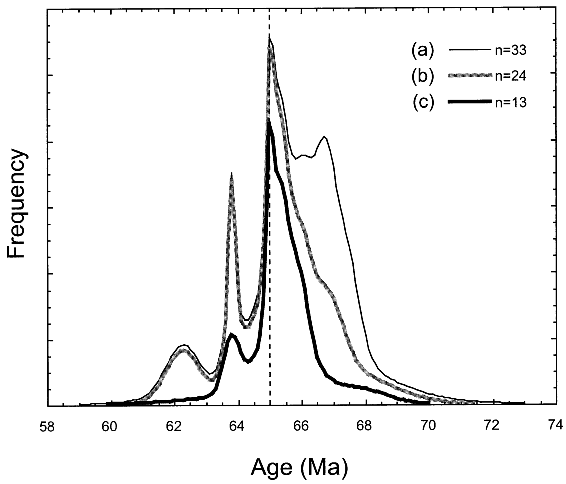

Fig. 6. Frequency distributions of (a) 33 $^{40}Ar/^{39}Ar$ plateau ages from the Deccan traps compiled in this paper and listed in Table 3; (b) a restriction to 24 A-quality results obtained on whole rock samples and mineral separates; (c) a further restriction to 13 A-quality results obtained on mineral separates only (see text). Each datum is represented as a unit surface normal gaussian distribution with variance equal to the analytical uncertainty. The total integral under each curve is therefore equal to the total number of samples. Vertical axis is frequency (in Ma^{-1}, with a half unit per tick mark) and horizontal axis is age (in Ma).

67 Ma. The width of the frequency distribution peak near 65 Ma at mid-height is reduced from 2.5 to 1.3 Ma. The standard deviation of the best fitting gaussian curve is 1.5 Ma, compared to 2.5 Ma in the similar frequency distribution of Vandamme et al. [1].

If we restrict our selection to A-quality results obtained on pure, separate minerals (nine plagioclase, two K-feldspars, one amphibole and one biotite), which are far less affected by alteration and recoil, most (10) of the plateau ages range from 65.0 to 66.0 Ma. Two plagioclases from the Narmada Valley (a flow near the bottom and a dyke) give values of 67.8 ± 1.8 Ma and 63.6 ± 0.5 Ma. The dyke may of course correspond to a younger event. The apparently older flow from the base of the Narmada section is actually close to another flow dated by the same group at 65.3 ± 0.6 Ma, which is in the main data population. The plagioclase from the top flow in Mahabaleshwar is also at 63.8 ± 3.7 Ma. The frequency distribution restricted to A-quality results on separate minerals is much better clustered than when whole rock plateau ages are included (Fig. 6, curve c). There is a very significant peak remaining (with a width at mid-height ranging from 64.8 to 65.9 Ma); one of the other two which were prominent on the 33 data frequency distribution has been considerably reduced or even suppressed. The other remains with much reduced, yet significant, amplitude at about 64 Ma, it represents two plateau ages obtained on one plagioclase and one whole rock from the Narmada valley [5]. Note that the main peak in the frequency distribution is asymmetrical, with a steeper slope on the younger side at 65 Ma. This could be due to a remaining as yet undetected disturbance of the K/Ar system or an experimental artifact, which may not be a reflection of the actual history of volcanism. Hence, volcanism could have lasted even shorter than suggested here. This quick analysis confirms that an increase in data selection reduces the width of the frequency distribution, which therefore (at least to that extent) reflects some form of alteration process and ^{39}Ar recoil rather than the actual duration of volcanism.

This means that even when usual plateau age criteria are used, whole rock data are probably affected by undetectable alteration and/or by ^{39}Ar recoil, which may be at least partly visible on age spectra; both can have opposite effects on apparent ages. A good illustration of this point is given by a comparison of our results on the Igatpuri section with those obtained in the same formations/area by other authors: 66.4 ± 1.2 Ma for Baksi [21], 68.6 ± 2.4 Ma for Duncan and Pyle [4] and 66.8 ± 0.6 Ma for Venkatesan et al. [7]. Note that these ages agree with each other (at the 2σ level). On the other hand, our mean value for five determinations (65.4 ± 0.7 Ma) agrees at the same level only with the Baksi determination, and barely touches the two others. This systematic difference between plagioclase and whole rock data may originate from ^{39}Ar loss on whole rocks during irradiation. The differences between the whole rock and single mineral ages obtained by Duncan and co-authors provides further support for this view.

The mean (and standard deviation) of this selected population of plateau ages obtained on mineral separates (Figs. 5 and 6) fails to encompass reversed chrons 28R or 30R and is compatible only with 29R (and of course the two encompassing normal chrons for the normal flows).

6. Conclusion

Five new ^{40}Ar/^{39}Ar plateau ages from the base of the Deccan traps at the Igatpuri section agree with one from a dyke crossing some of the upper (but not uppermost) formations and are consistent with an absolute age for most of the lava pile (at least its lower two-thirds) near 65.5 Ma, encompassing reversed chron 29R and unlikely to exceed 1 Ma in duration. New information from the uppermost, normal polarity Mahabaleshwar flows is consistent with this, though its large uncertainty does not preclude a significantly younger age (though no lower than 62 Ma).

A critical review of the available data base, and a comparison between mineral separates and whole rock analyses, is also consistent with a single main peak of volcanic activity near 65.5 Ma. A smaller peak remains in the frequency distribution, indicating possible minor late volcanism at about 64 Ma. The spread in ages is much reduced compared to a previous compilation [1] confirming that much of that spread does not reflect actual age differences. We consider that older ages reported in the Deccan tend to correspond to age spectra with evidence for alteration and/or ^{39}Ar recoil; whole rock apparent ages can be up to 1 Ma older (and even more) than what we consider to be probable actual ages. The results from the lowermost Igatpuri sections reported in this paper are particularly critical in supporting this conclusion. However, one message from this short review of the still scant data base of absolute ages from the Deccan traps reflects the low potassium content of these lavas, their poor state of preservation and the difficulty of the task. There is still ample room for improvement, coordinated sampling and dating campaigns from several laboratories with added emphasis on field analysis, selection of samples and systematic analyses of mineral separates.

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