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^{40}Ar–^{39}Ar ages of Anjar Traps, Western Deccan Province (India) and its relation to the Cretaceous–Tertiary Boundary events

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^{40}Ar–^{39}Ar ages of whole rock basalt samples from the lava flows sandwiching the Ir-rich intertrappean at Anjar are indistinguishable from the Cretaceous/Tertiary Boundary (KTB) age. These results imply that the Ir-rich layer represents the KTB boundary layer. The presence of several flows below the lower dated flow supports our earlier observation[1], based on the geochronological studies of Western Ghat lava flow sequence, that the initiation of the Deccan volcanism predated KTB.

THE discovery of an Ir-rich layer in an intertrappean bed at Anjar, Western India[2], seeks to establish a relationship, if there is, between the KTB events and the Deccan volcanism. The Deccan volcanism is cited as the internal cause for the KTB events[3–5], although there is mounting evidence that the iridium anomaly in the KTB layer is due to an impact of a bolide on earth[6]. A majority of physico-chemical evidences available today (such as shocked quartz, meteoritic spinels, geochemical anomalies and identification of the Chicxulub crater as the probable impact site) favour the impact scenario for the KTB event[7–9]. A third view is that the impact and volcanic events at the KTB are independent that occurred by chance at the same time[10]. Thus, the debate continues as to the cause of the KTB transition being internal or external. Therefore, it is important to get some high resolution event sequence from intertrappeans of the Deccan Province.

The geochemical observations on both the Deccan Traps (DT) and intertrappean sequences considered with the $^{40}Ar/^{39}Ar$ ages on the DT rule out a link between the KTB and DT[1,11,12]. The interpretation of the geochronological data, however, is not conclusive. For example, some workers[13–17] suggest that the available 'good' quality ^{40}Ar–^{39}Ar ages coupled with palaeomagnetic data imply a rapid eruption of Deccan lavas coincident with the KTB. On the other hand, Venkatesan *et al.*[1] argue that the initial, most intense, pulse of Deccan eruption predated the KTB by at least 1 Ma and the total duration of the volcanism is not less than 3 Ma. The conflicting interpretations of a similar data set stems primarily from the uncertainties in the geomagnetic time scales (GMTS) and the age(s) of the monitor sample(s) used for the ^{49}Ar–^{39}Ar dating of the KTB and the DT. These problems could be resolved if the KTB layer within the Deccan province be identified and the ages of the lava flows with respect to the KTB be obtained. Though the KTB seems to exist within the deep drill core samples of eastern Deccan trap sequence in Cauvery and Krishna–Godavari basins[18–20] and an estimate of the duration and timing of the DT-based on palaeontological evidences have been obtained, chemical studies have not been made. This makes the discovery of an Ir-rich layer in the Anjar intertrappean[2] important. The presence of lava flows above and below the Ir-rich layer offers an opportunity to find the relative timing and duration of the Deccan volcanism *vis-à-vis* the KTB. We report here ^{40}Ar–^{39}Ar ages of whole rock samples of the lava flows from Anjar.

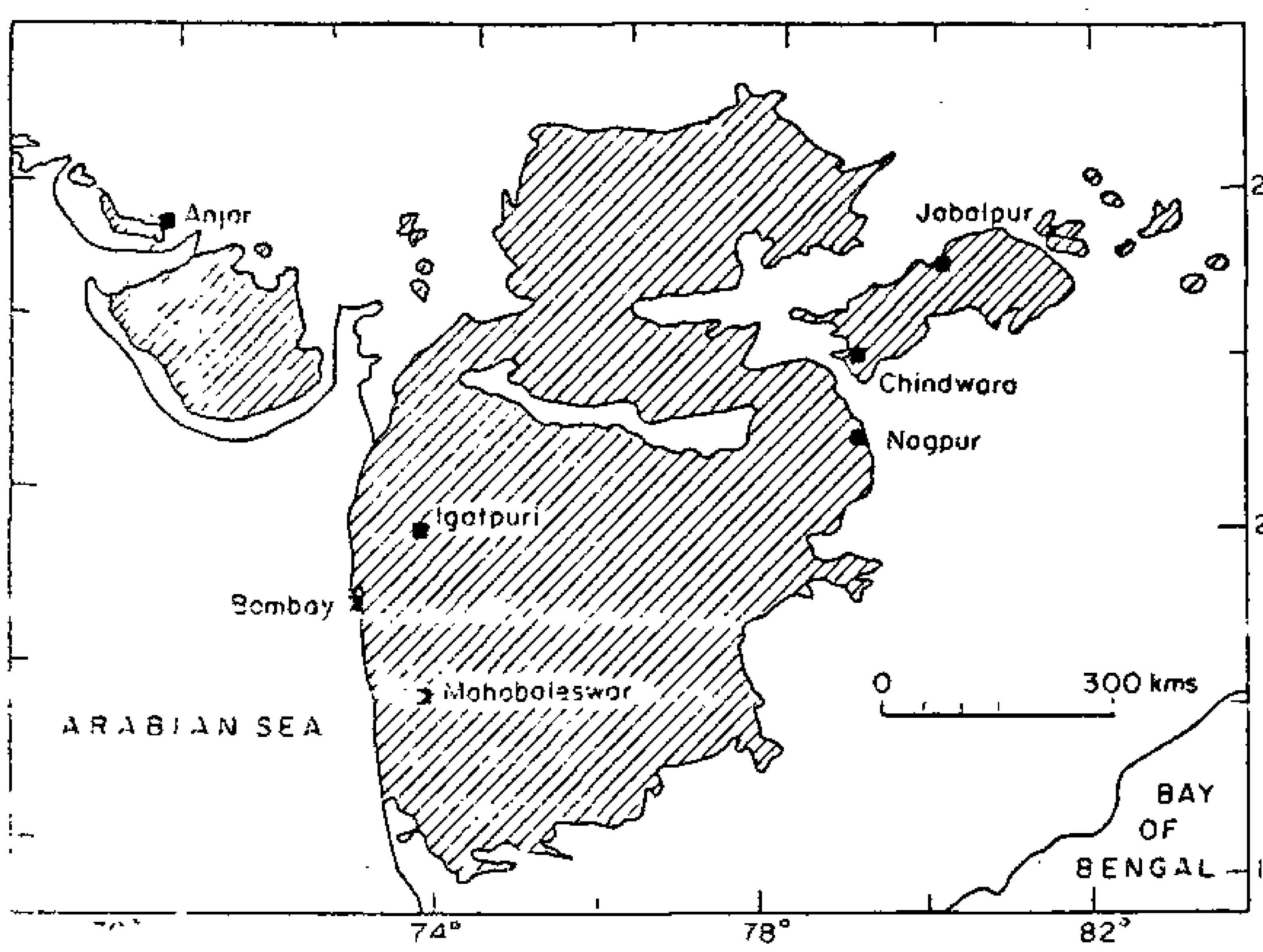

Figure 1. Map of western India showing the Deccan volcanic province and the location of Anjar.

Sample and experimental details

The Anjar trap sequence in Kutch (Figure 1), Western Deccan province (India), consists of several basalt flows with a well-developed intertrappean sedimentary sequence. Bhandari *et al.*[2] have reported an iridium-rich KTB layer in this intertrappean. Two samples from each of the lower and the upper flows were sampled and analysed at difrerent times. Alteration is ubiquitous in these basalts though care was taken to select the least altered samples. In thin section, the samples vary from aphyric to porphyritic and all show low temperature alteration. The details of sample preparation, argon extraction and analysis are reported elsewhere[1]. Briefly, about 700 mg of cleaned whole rock samples and the flux monitor Minnesota hornblende (MMhb-1) were sealed in quartz vials.

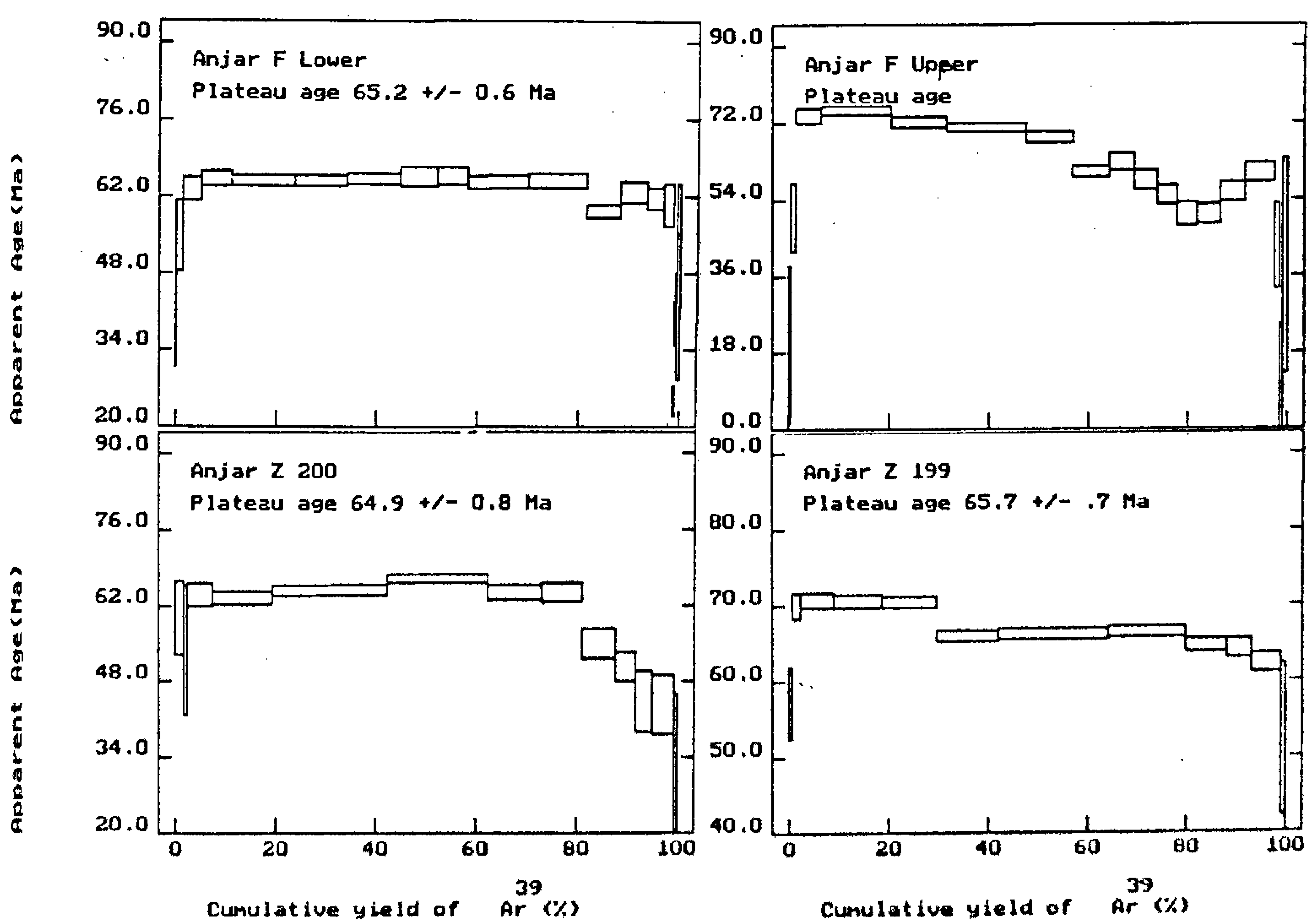

Figure 2. Age spectrum for the two samples from each of the lower and upper flows. Error boxes are 2σ and do not include σ_j.

Table 1. ^{40}Ar–^{39}Ar data for duplicate samples from the two flows sandwiching the Ir-rich intertrappean. Errors are 2σ and includes σ_J

Sample	Integrated age (Ma)	Inverse isochron Age (Ma) (MSWD)	Inverse isochron $^{40}Ar/^{36}Ar$ (Trapped)	Plateau Age (Ma)	Plateau ^{39}Ar (%)
F Upper	65.1 ± 1.5	–	–	–	–
Z 199	66.8 ± 1.2	–	–	65.7 ± 0.7*	63
F Lower	64.3 ± 1.5	65.3 ± 6.8 (0.15)	289 ± 8	65.2 ± 0.6	76
Z 200	61.9 ± 1.2	66.2 ± 4.5 (0.83)	278 ± 12	64.9 ± 0.8	79

*Plateau-like.

Table 2. Argon isotopic composition (corrected for blank, mass discrimination and interference), age and percentage of nucleogenic and radiogenic argon for Z 199 of Anjar-traps. Errors on age are without and with error on J respectively. Errors quoted are 1σ
$J = 0.0024718 \pm 0.0000230$

Temp. (°C)	$^{36}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$	Age (Ma)			^{39}Ar (%)	Rad. (%)	$^{37}Ar/^{39}Ar$	$^{40}Ar/^{36}Ar$
550	0.0649 ± 0.0015	32.24 ± 0.33	57.3	± 2.4	± 2.4	0.74	40.4	3.423 ± 0.031	496.4 ± 12.7
600	0.01680 ± 0.00035	20.99 ± 0.17	70.06	± 0.80	± 1.0	1.74	76.3	1.9707 ± 0.0046	1249.5 ± 27.9
650	± 0.006613 ± 0.000098	18.13 ± 0.11	70.71	± 0.43	± 0.78	6.49	89.2	1.2308 ± 0.0057	2741.5 ± 43.1
700	0.004807 ± 0.000079	17.550 ± 0.100	70.51	± 0.40	± 0.76	9.59	91.9	1.0245 ± 0.0021	3650.3 ± 63.1
750	0.001952 ± 0.000057	16.677 ± 0.098	70.39	± 0.37	± 0.74	11.22	96.5	0.9265 ± 0.0019	8543.3 ± 251.4
800	0.001017 ± 0.000067	15.397 ± 0.091	66.08	± 0.35	± 0.70	12.15	98.0	0.9285 ± 0.0019	15138.3 ± 1003.0
850	0.001159 ± 0.000043	15.460 ± 0.090	66.17	± 0.34	± 0.69	21.95	97.7	0.9474 ± 0.0019	13337.1 ± 496.7
900	0.001406 ± 0.000076	15.595 ± 0.092	66.44	± 0.36	± 0.71	15.75	97.3	0.9094 ± 0.0051	11095.4 ± 602.4
950	0.00125 0.00019	15.157 ± 0.097	64.76	± 0.45	± 0.74	8.38	97.5	1.0606 ± 0.0023	12146.6 ± 1852.2
1000	0.00257 ± 0.00032	15.45 ± 0.12	64.33	± 0.64	± 0.87	4.85	95.0	2.1960 ± 0.0091	6009.3 ± 745.5
1100	0.00397 ± 0.00038	15.41 ± 0.12	62.37	± 0.68	± 0.89	6.25	92.3	19.38 ± 0.44	3884.0 ± 376.4
1400	0.00425 ± 0.00058	13.1 ± 1.1	52.3	± 5.0	± 5.0	0.89	90.4	15.045 ± 0.034	3094.4 ± 501.5
Total	0.002994 ± 0.000041	16.154 ± 0.036	66.82	± 0.15	± 0.63	100.00	94.5	2.345 0.028	5394.6 ± 75.0

irradiated in the central core of the light ated APSARA reactor (rated power 1 MW) 0 h at the Bhabha Atomic Research Centre, Bombay. The reactor was not operated con therefore, appropriate correction for ^{37}Ar deca mented irradiations was used. Pure nickel wires

with the samples and the monitor vials, were used to correct for any variation (less than ~ 2%) in the neutron fluence. Interference corrections were based on analysis of pure CaF_2 and K_2SO_4 salts irradiated with the samples. For each sample the argon was extracted in a series of twelve or more steps of increasing temperatures up to 1400°C in an electrically heated ultra-high vaccum furnace. The argon gas released in each step, after a two-stage purification, was measured for isotopic composition using an AEI MS10 mass spectrometer in static mode. Generally the ^{40}Ar blanks are less than 3 ›
ccSTP (about 2–5% of sample gas) for the lower
perature steps (up to 1000°C) and increase gradual
about 1.8×10^{-8} ccSTP at 1400°C.

Discussion

The ^{40}Ar–^{39}Ar age data for two samples of each c
flows are presented in Table 1. Detailed data for
samples are given in Tables 2–5. The age spectr

Table 3. Argon isotopic composition (corrected for blank, mass discrimination and interference), age and percentage of nucleogenic and radiogenic argon for F Upper of Anjar-traps. Errors on age are without and with error on J respectively. Errors quoted are 1σ

$J = 0.0021427 \pm 0.0000240$

Temp. (°C)	$^{36}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$		Age (Ma)		^{39}Ar (%)	Rad. (%)	$^{37}Ar/^{39}Ar$	$^{40}Ar/^{36}Ar$
400	0.0961 ± 0.0038	33.6 ± 2.1	± 9.2	20.0	± 9.2	0.41	15.5	0.9237 ± 0.0018	349.7 ± 26.2
450	0.0382 ± 0.0016	24.45 ± 0.97	± 4.1	50.1	± 4.1	0.91	53.8	0.4909 ± 0.0011	639.6 ± 37.2
500	0.01379 ± 0.00039	23.53 ± 0.23	± 0.91	73.68	± 1.2	5.00	82.6	0.6611 ± 0.0016	1706.2 ± 50.9
550	0.00878 ± 0.00015	22.38 ± 0.14	± 0.50	74.89	± 0.96	13.89	88.4	1.0658 ± 0.0076	2548.9 ± 45.6
600	0.00772 ± 0.00015	21.39 ± 0.15	± 0.52	72.39	± 0.95	11.02	89.3	1.5009 ± 0.0036	2770.7 ± 55.1
650	0.02171 ± 0.00012	25.24 ± 0.16	± 0.52	71.31	± 0.94	16.13	74.5	1.8695 ± 0.0037	1162.6 ± 9.0
700	0.00724 ± 0.00017	20.32 ± 0.15	± 0.56	68.93	± 0.94	9.17	89.4	2.0964 ± 0.0096	2805.6 ± 69.6
750	0.01135 ± 0.00022	19.44 ± 0.20	± 0.66	61.12	± 0.94	7.52	82.7	2.475 ± 0.014	1712.8 ± 36.5
800	0.01072 ± 0.00061	19.82 ± 0.21	± 1.0	63.3	± 1.2	4.91	84.0	2.451 ± 0.021	1849.3 ± 106.2
850	0.01395 ± 0.00065	19.63 ± 0.23	± 1.1	59.0	± 1.3	4.60	79.0	2.6100 ± 0.0100	1407.9 ± 67.2
900	0.01392 ± 0.00070	18.67 ± 0.25	± 1.1	55.4	± 1.3	4.26	77.9	2.696 ± 0.028	1341.0 ± 69.4
950	0.02040 ± 0.00081	19.43 ± 0.27	± 1.3	51.1	± 1.4	3.72	68.9	3.605 ± 0.043	952.4 ± 39.9
1000	0.01508 ± 0.00060	17.90 ± 0.22	± 1.0	51.2	± 1.2	4.95	75.1	4.0311 ± 0.0081	1186.6 ± 49.4
1050	0.01454 ± 0.00075	19.28 ± 0.22	± 1.2	57.0	± 1.3	4.97	77.7	9.972 ± 0.020	1326.3 ± 69.7
1100	0.01372 ± 0.00074	20.49 ± 0.22	± 1.1	62.4	± 1.3	6.03	80.2	19.701 ± 0.039	1492.8 ± 81.9
1150	0.0070 ± 0.0038	14.13 ± 0.67	± 4.9	46.0	± 4.9	0.98	85.3	26.664 ± 0.058	2014.7 ± 1093.9
1200	0.0712 ± 0.0062	23.8 ± 1.1	± 8.2	10.9	± 8.2	0.60	11.8	24.118 ± 0.061	335.1 ± 33.2
1400	0.0155 ± 0.0080	15.0 ± 2.4	± 12.6	40.1	± 12.6	0.93	69.6	17.386 ± 0.035	973.3 ± 526.2
Total	0.01398 ± 0.00014	21.294 ± 0.058	± 0.25	65.14	± 0.76	100.00	80.6	3.9743 ± 0.0040	1523.2 ± 15.3

these samples, assuming an atmospheric composition ($^{40}Ar/^{36}Ar = 295.5$) for the trapped argon in each step, are shown in Figure 2. The error limits of each step age in Figure 2 do not include the uncertainty in the J value, the irradiation parameter. The plateau ages given in Table 1 and Figure 2 are weighted means of ages of adjacent temperature steps that agree with each other within 2σ levels and contain cumulatively more than 40% of the total ^{39}Ar released. The plateau age error quoted is 2σ level and includes the error in J.

We noticed that the samples from the lower flow yield good plateaus comprising more than 75% of ^{39}Ar. The sample from the upper flow had no plateau. One of the samples gave a plateau-like feature for the higher temperature steps.

We also calculated the inverse isochron ages of the samples listed in Table 1 along with inferred trapped argon composition. All the samples have atmospheric value for the trapped argon composition within the limits of uncertainty, implying that the plateau ages are true ages. The integrated ages listed in Table 1 correspond to total fusion ages calculated by summing up the isotopic abundances of all fractions for each sample. All the three (viz. isochron, plateau and integrated) ages for a sample were calculated relative to the monitor MMhb-1 age of 520.4 ± 1.7 Ma (ref. 23).

It is evident that for the lower flow, the plateau, isochron and integrated ages for replicated samples are in excellent agreement, within errors, indicating negligible argon loss. Also, the isochron and integrate ages have relatively larger errors compared to the plateau age of the samples. We prefer to use the plateau ages for discussion because of their higher reliability[24].

The plateau age of 65.2 ± 0.6 and 64.9 ± 0.8 Ma for samples from the flow which underlies the intertrappean wherein the Ir-rich KTB layer has been identified by Bhandari *et al.*[2] are in agreement and are indistinguishable from an age of 65.2 ± 0.1 Ma for the KTB as determined

Table 4. Argon isotopic composition (corrected for blank, mass discrimination and interference), age and percentage of nucleogenic and radiogenic argon for Z 200 of Anjar-traps. Errors on age are without and with error on J respectively. Errors quoted are 1σ
$J = 0.0024342 \pm 0.0000230$

Temp. (°C)	$^{36}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$	Age (Ma)			^{39}Ar (%)	Rad. (%)	$^{37}Ar/^{39}Ar$	$^{40}Ar/^{36}Ar$
500	0.1470 ± 0.0027	57.32 ± 0.91	59.9	± 3.3	± 3.4	1.50	24.2	3.885 ± 0.040	389.8 ± 8.0
550	0.0568 ± 0.0037	29.23 ± 0.89	53.8	± 6.0	± 6.0	0.80	42.5	4.07 ± 0.11	514.6 ± 36.7
600	0.03532 ± 0.00061	25.31 ± 0.20	64.1	± 1.1	± 1.3	4.98	58.7	2.3159 ± 0.0084	716.6 ± 13.5
650	0.01959 ± 0.00013	20.53 ± 0.13	63.58	± 0.52	± 0.79	12.21	71.8	2.0400 ± 0.0057	1047.8 ± 9.4
700	0.014468 ± 0.000084	19.31 ± 0.12	64.84	± 0.45	± 0.75	22.71	77.8	2.4253 ± 0.0049	1334.8 ± 10.6
750	0.00948 ± 0.00017	18.36 ± 0.11	67.05	± 0.47	± 0.78	20.05	84.7	2.9227 ± 0.0058	1937.6 ± 35.9
800	0.01223 ± 0.00035	18.59 ± 0.13	64.57	± 0.68	± 0.90	10.81	80.5	2.5039 ± 0.0050	1519.4 ± 45.1
850	0.00954 ± 0.00054	17.76 ± 0.15	64.42	± 0.88	± 1.1	8.07	84.1	2.6441 ± 0.0088	1860.7 ± 105.6
900	0.01185 ± 0.00086	16.25 ± 0.20	55.1	± 1.3	± 1.4	6.43	78.4	3.273 ± 0.016	1370.7 ± 105.5
950	0.0111 ± 0.0011	14.987 ± 0.094	50.6	± 1.4	± 1.5	4.06	78.0	4.7493 ± 0.0095	1344.7 ± 127.9
1000	0.0091 ± 0.0015	12.92 ± 0.48	44.4	± 2.8	± 2.9	3.22	79.1	9.028 ± 0.018	1420.3 ± 247.0
1100	0.0145 ± 0.0014	14.39 ± 0.49	43.8	± 2.8	± 2.8	4.61	70.1	57.31 ± 0.11	989.3 ± 101.8
1400	0.0154 ± 0.0025	12.2 ± 1.3	33.1	± 6.3	± 6.3	0.56	62.5	42.02 ± 0.27	789.8 ± 152.2
Total	0.01635 ± 0.00014	19.166 ± 0.055	61.87	± 0.28	± 0.64	100.00	74.8	5.6466 ± 0.0061	1172.6 ± 10.5

Table 5. Argon isotopic composition (corrected for blank, mass discrimination and interference), age and percentage of nucleogenic and radiogenic argon for F Lower of Anjar-traps. Errors on age are without and with error on J respectively. Errors quoted are 1σ
$J = 0.0021588 \pm 0.0000240$

Temp. (°C)	$^{36}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$		Age (Ma)		^{39}Ar (%)	Rad. (%)	$^{37}Ar/^{39}Ar$	$^{40}Ar/^{36}Ar$
450	0.2151 ± 0.0042	74.4 ± 1.2	± 5.2	41.7	± 5.3	0.07	14.5	4.61 ± 0.11	345.9 ± 8.0
500	0.0541 ± 0.0022	30.36 ± 0.56	± 3.2	55.1	± 3.3	1.11	47.3	3.0646 ± 0.0061	561.1 ± 25.2
550	0.01927 ± 0.00066	22.30 ± 0.20	± 1.0	63.5	± 1.2	3.71	74.4	2.5426 ± 0.0051	1157.6 ± 41.1
600	0.01083 ± 0.00040	20.36 ± 0.15	± 0.69	65.61	± 1.0	6.05	84.2	2.2429 ± 0.0045	1880.3 ± 71.4
650	0.01808 ± 0.00020	22.41 ± 0.14	± 0.51	65.26	± 0.87	12.83	76.1	1.8512 ± 0.0042	1239.4 ± 15.5
700	0.00441 ± 0.00024	18.36 ± 0.12	± 0.49	65.24	± 0.86	10.16	92.9	1.4524 ± 0.0029	4164.1 ± 228.4
750	0.00442 ± 0.00023	18.42 ± 0.12	± 0.48	65.43	± 0.86	10.73	92.9	1.2849 ± 0.0026	4171.2 ± 219.2
800	0.00375 ± 0.00068	18.31 ± 0.13	± 0.89	65.76	± 1.1	7.25	93.9	1.1566 ± 0.0023	4887.2 ± 890.5
850	0.00850 ± 0.00046	19.78 ± 0.22	± 0.73	66.03	± 1.0	6.03	87.3	1.1660 ± 0.0031	2327.1 ± 127.2
900	0.00543 ± 0.00040	18.60 ± 0.13	± 0.60	65.00	± 0.93	12.22	91.3	1.1776 ± 0.0029	3426.1 ± 254.8
950	0.00061 ± 0.00044	17.91 ± 0.11	± 0.62	65.05	± 0.94	11.13	98.9	1.1604 ± 0.0023	27969.4 ± 19925.7
1000	0.00329 ± 0.00037	16.49 ± 0.13	± 0.62	59.45	± 0.90	6.55	94.1	1.2448 ± 0.0045	5019.8 ± 572.0
1050	0.00086 ± 0.00067	16.72 ± 0.15	± 0.92	62.99	± 1.1	5.45	98.4	1.9638 ± 0.0039	19497.8 ± 15251.0
1100	0.00105 ± 0.00043	16.66 ± 0.23	± 0.96	62.56	± 1.2	3.44	98.1	8.968 ± 0.018	15826.3 ± 6401.1
1150	0.00180 ± 0.00098	17.66 ± 0.44	± 1.9	65.5	± 2.1	2.03	96.9	45.49 ± 0.16	9831.6 ± 5346.5
1200	0.00301 ± 0.00065	8.86 ± 0.31	± 1.3	30.8	± 1.4	0.40	89.9	55.50 ± 0.33	2944.7 ± 646.3
1250	0.0106 ± 0.0021	16.08 ± 0.63	± 3.3	49.7	± 3.4	0.23	80.4	73.97 ± 0.15	1510.8 ± 303.3
1400	0.0075 ± 0.0041	16.1 ± 2.0	± 8.8	53.4	± 8.9	0.59	86.3	62.31 ± 0.12	2164.8 ± 1220.1
Total	0.00730 ± 0.00012	18.966 ± 0.044	± 0.20	64.30	± 0.73	100.00	88.6	3.4034 ± 0.0038	2599.3 ± 43.8

by ^{40}Ar–^{39}Ar plateau ages of microtektites in the KTB marine sediments[25] and melt glasses from Chicxulub crater[9] related to an age of 520.4 ± 1.7 for MMhb-1. For one of the samples, of the upper flow the plateau-like feature for higher temperature steps yields an age of 65.7 ± 0.7 Ma representing 63% of ^{39}Ar released.

The most significant conclusions emerging from the present data are (i) the Ir-rich layer occurring in the intratrappeans sandwiched by the two flows represents the KTB layer, (ii) the presence of several flows below the lower flow indicates the initiation of Deccan volcanism much before the KTB precluding any causal link between KTB and Deccan Traps.

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