New ^{39}Ar–^{40}Ar ages of dykes from Madhya Pradesh and Chhattisgarh: evidence for polyphase dyke intrusion in eastern Deccan Volcanic Province

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Mafic dykes constitute an important component of the Deccan Volcanic Province. The duration of Deccan volcanism was from 69 to 63 Ma with a peak at 65 ± 1 Ma. The thickness of the lava flows is much reduced and intensity of dyke occurrence is much less in the eastern part of the province compared to the western part. Here we report new ^{39}Ar–^{40}Ar plateau ages of 60.1 ± 0.3 Ma (2σ) and 82.3 ± 0.7 Ma (2σ) of two mafic dykes from Shahdol (Madhya Pradesh) and Chirimiri (Chhattisgarh), which indicate polyphase dyke intrusion in the eastern Deccan Volcanic Province.

Keywords: Argon dating, lava flows, mafic dykes, volcanic burst.

DYKES occur in a wide variety of geological and tectonic settings. They also help identify Large Igneous Provinces (LIPs)[1]. Like most LIPs, mafic dykes are an integral part of Deccan Volcanic Province (DVP), where a huge volume[2], 0.2–3.5 million km^3, of predominantly tholeiitic basalt erupted over an area of about 500,000 sq. km. It is generally believed that this immense volcanic outburst is the result of the interaction between Indian lithosphere and the Réunion hotspot during the northerly drifting Indian subcontinent in the Late Cretaceous. Age and duration of the Deccan volcanic episode is a most debated topic[3,4]. It has been argued[5–10] that the peak Deccan volcanism occurred at ~65.5 ± 1 Ma, straddling the Cretaceous–Palaeogene (K–Pg) boundary mass extinction[11,12], while an alternate view suggested that the Deccan volcanism was episodic with an extended duration from 69 to 63 Ma (ref. 4). This period experienced maximum outpouring of flood lavas. A recent study[13] on the alkaline magmatic body of western Pakistan yielded ages of 69.1–70.6 Ma, believed to be the product of interaction of Réunion plume and the Indian lithosphere as a precursor to the peak phase of Deccan flood basalt volcanism. Mafic dykes have been considered to be the feeder to the mafic flows in parts of the DVP[14]. Dykes occur along well-defined faults. In the western sector of Deccan exposure dyke and dyke swarms have been dated[5,15]. In eastern India, Rajmahal–Bengal Basin–Sylhet basalts have yielded an older age of ~115a (refs 16–18).

There are several mafic and ultramafic dykes in the vicinity of the Rajmahal basalt in the coal-bearing Raniganj and Jharia Gondwana basins. Geochronological data on the dykes from this area are lacking. However, Salma dyke, a ferrodolerite from Raniganj basin occurring in close proximity of the ~115 Ma Rajmahal volcanic province yielded ^{39}Ar–^{40}Ar age of 64.4 ± 0.3 Ma (ref. 16).

The present study reports precise ^{39}Ar–^{40}Ar dates of the mafic dykes from the eastern fringe of the DVP in an attempt to establish the duration of magmatic activity in this part and to explore if any linkage exists between the dyke in the Raniganj basin and the eastern Deccan dykes.

Two mafic dykes were mapped during field studies around Shahdol and Chirimiri, in the easternmost fringes of the DVP[19] (Figure 1). Very thin flows varying between 2 and 5 m in thickness are exposed over the Gondwana formations. Due to extensive weathering, the thin Deccan flows have been eroded away exposing the Gondwana basement sediments and the mafic flows form irregular outcrops.

The mafic dyke (RB-13) at Shahdol, trending NE–SW, is exposed along the Son River intruding the Permo-Triassic Barakar Formation of Gondwana Group (Figure 1). This dyke, 120 m long and 6 m wide, has developed a chilled margin characterized by fine grain size. Smaller NE–SW-trending dykes cut across the main dyke and show thin ramifications into the country rock of Gondwana sandstone. The nearest flow occurs at 1.2 km from the present dyke exposure.

The absolute ages of these flows are not known. Another mafic dyke trending in E–W direction intrudes the sedimentary Barakar Formation at Chirimiri (RB-68B; Figure 1). The dyke is 60 m long with a width of 5 m. Chirimiri is about 2 km east of Shahdol. Widdowson *et al.*[14] related the mafic dykes which crop out at the coastal belt of Goa to the Deccan continental flood basalts, though they are separated by a distance of 50–80 km.

The dyke samples are medium to coarse-grained and composed of plagioclase feldspar, clinopyroxene, olivine and opaque grains (Figure 2). Plagioclase grains mostly occur as laths and in the groundmass. Plagioclase composition in dyke samples falls in the range between bytownite and labradorite (An_{42}–$An_{71.6}$) as in Deccan trap plagioclases. Clinopyroxene grains are augitic with a compositional range between $Wo_{38.3}Fs_{23.9}En_{37.8}$ and $Wo_{34.5}Fs_{41}En_{24.5}$, and similar to pyroxenes of other Deccan traps[20]. Magnetite and ilmenite, disseminated in the groundmass, constitute the opaque minerals. The plagioclase grains are clear and without any cloudy appearance or alteration. The olivine grains mostly occur as phenocryst and sometimes occur as inclusions within large clinopyroxene phenocrysts. Two samples (RB-13, RB-68B) were selected for age determination on the basis of petrographic freshness.

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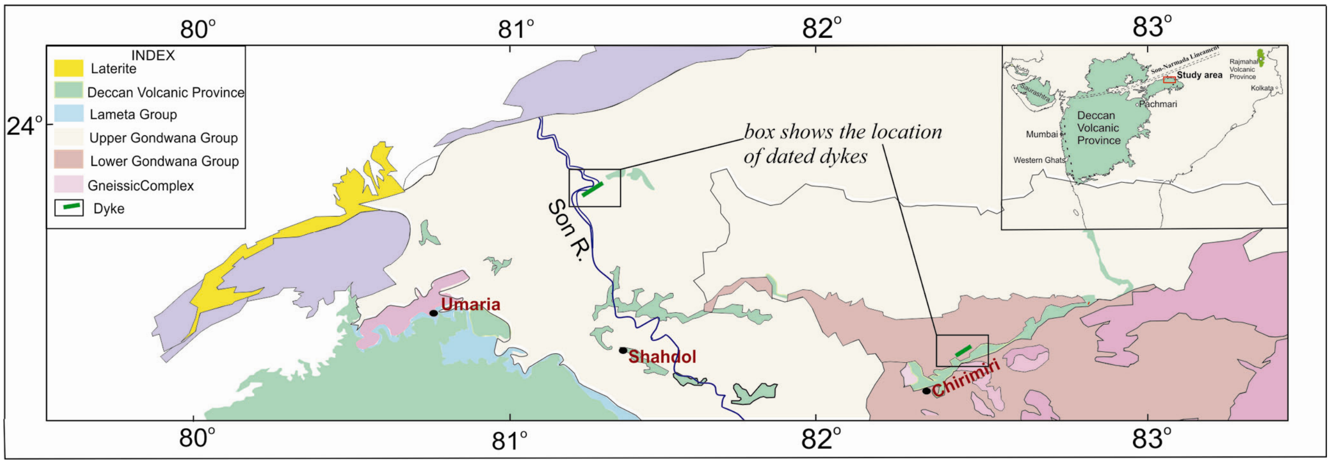

Figure 1. Geological map of the area around Shahdol, Amarkantak, Umaria and Chirimiri based on the published quadrangle geological map of the Geological Survey of India (2004). Two mafic dykes are shown in the box.

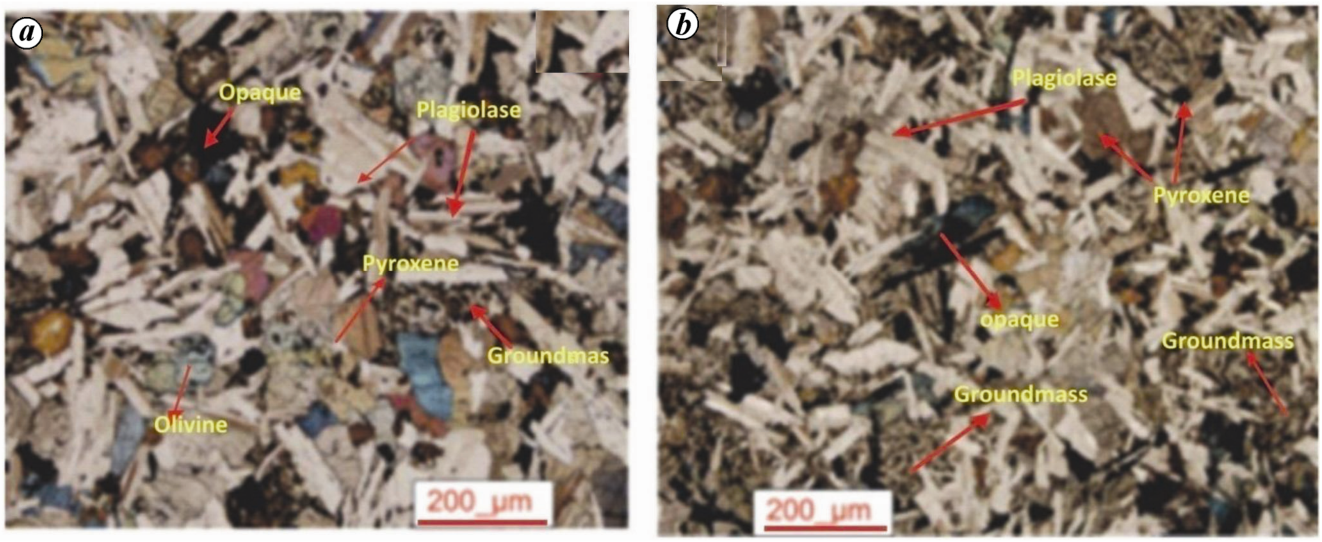

Figure 2. Photomicrographs of dyke samples: (***a***) Shahdol (RB-13) and (***b***) Chirimiri (RB-68B) dykes. The freshness of the plagioclase grains is noteworthy.

Fresh rock chips of the two dyke samples were crushed and sieved. About 0.2 g of the 120–180 μm sized fractions of each was packed in aluminum foil and irradiated in the DHRUVA reactor at the Bhaba Atomic Research Centre (BARC), Mumbai, for about 100 h along with the 523.1 ± 2.6 Ma Minnesota hornblende (MMhb-1) monitor[21] and high-purity CaF_2 and K_2SO_4 salts. High-purity nickel wires irradiated with the samples were used to monitor the neutron fluence variation, which was typically about 5%. The irradiated samples were repacked in aluminum foil and loaded on the extraction unit of a Thermo-Fisher Scientific noble gas preparation system. Argon was extracted in a series of steps up to 1400°C in an electrically heated ultra-high vacuum furnace.

After purification using Ti–Zr getters, the argon released in each step was measured with a Thermo-Fisher ARGUS VI mass spectrometer located at the IITB–DST National Facility for ^{40}Ar–^{39}Ar Geothermochronology in the Department of Earth Sciences, IIT Bombay. Interference corrections for Ca- and K-produced Ar were (^{36}Ar/^{37}Ar)Ca, (^{39}Ar/^{37}Ar)Ca and (^{40}Ar/^{39}Ar)K = 0.000334, 0.000762, 0.00081 and 0.001434, 0.001081, 0.00065 for RB-13 and RB-68B respectively.

The irradiation parameter J, corrected for neutron flux variation, is 0.002363 ± 0.000008 for RB-13, and 0.001010 ± 0.000005 for RB-68B. The program[22] ISOPLOT v. 3.75 was used to plot the ^{40}Ar/^{39}Ar step-heating data given in Tables 1 and 2.

A plateau in an argon release spectrum consists of four or more successive degassing steps with mean ages overlapping at the 2σ level, including the error contribution from the J value and comprising minimum of 60% of the total ^{39}Ar released. Whole-rock step-heating age spectra are given in Figure 3 *a* and *b*. Sample RB-13 yielded an

Table 1. Argon isotopic composition (corrected for blank, mass discrimination and interference), apparent age and percentage of nucleogenic and radiogenic argon for sample RB-13

Temperature (°C)	$^{36}Ar/^{39}Ar$ ($\pm 2\sigma$)	$^{40}Ar/^{39}Ar$ ($\pm 2\sigma$)	Apparent age (Ma; $\pm 2\sigma$)	^{39}Ar%	$^{40}Ar^*$%	$^{37}Ar/^{39}Ar$ ($\pm 2\sigma$)	$^{40}Ar/^{36}Ar$ ($\pm 2\sigma$)
550	2.966	879.371	12.53	1.52	0.34	0.7138	296.5
	0.020	4.398	30.9 (30.9)			0.0041	4.0
600	1.765	524.407	10.95	1.58	0.49	1.1579	297.0
	0.014	2.621	20.9 (20.9)			0.0093	3.8
650	0.855	253.028	2.35	1.81	0.22	0.6785	296.2
	0.006	1.266	9.63 (9.63)			0.0040	4.3
700	0.285	84.968	2.94	3.33	0.81	0.6110	297.9
	0.002	0.426	3.11 (3.11)			0.0030	4.1
750	0.071	22.005	4.11	4.47	4.38	0.5350	309.0
	0.001	0.110	0.86 (0.86)			0.0044	4.5
800	0.112	35.086	8.77	3.3	5.87	1.0943	313.9
	0.000	0.177	0.86 (0.86)			0.0063	2.1
850	0.075	24.247	9.34	2.97	9.05	1.9101	324.9
	0.000	0.122	0.78 (0.78)			0.0175	3.2
900	0.031	23.009	59.77	4.48	61.85	2.5760	774.6
	0.000	0.207	0.89 (0.92)			0.0192	9.4
950	0.022	20.476	60.01	7.06	69.78	2.6859	977.8
	0.000	0.103	0.45 (0.50)			0.0054	7.6
1000	0.013	17.968	60.30	9.73	79.86	3.5547	1466.9
	0.000	0.090	0.40 (0.46)			0.0071	17.3
1050	0.014	17.856	60.12	11.18	80.02	5.0102	1479.2
	0.000	0.090	0.38 (0.44)			0.0100	12.2
1100	0.024	20.708	60.08	13.45	68.92	5.7097	950.9
	0.000	0.104	0.44 (0.49)			0.0114	6.6
1150	0.018	18.908	60.01	9.33	75.31	7.2600	1196.7
	0.000	0.095	0.41 (0.47)			0.0145	10.7
1200	0.020	19.379	59.91	8.85	73.41	6.1845	1111.4
	0.000	0.097	0.42 (0.47)			0.0124	12.2
1250	0.030	22.297	59.96	5.75	63.82	6.8950	816.7
	0.000	0.112	0.52 (0.56)			0.0138	7.5
1300	0.059	29.521	60.09	5.48	47.83	19.8491	566.4
	0.000	0.148	0.65 (0.69)			0.0514	4.5
1350	0.120	43.490	60.03	4	31.51	56.6300	431.5
	0.000	0.218	1.02 (1.05)			0.1132	3.1
1380	0.235	77.816	60.31	1.71	17.71	55.2503	359.1
	0.001	0.392	2.08 (2.09)			0.2129	4.9
Total	0.133	50.316	50.03	100	23.51	8.1986	386.3
	0.000	0.088	0.61 (0.64)			0.0073	1.5

Errors on age are without and (with) error on J respectively. Errors quoted are 2σ. $J = 0.002362 \pm 0.000009$.

11-step plateau age of 60.1 ± 0.3 Ma (2σ), with the age spectrum comprising 81.0% of total ^{39}Ar released (Figure 3 *c*). Its isochron age of 60.1 ± 0.5 Ma (2σ) and inverse isochron age of 60.1 ± 0.3 Ma (2σ) are statistically concordant with its plateau age (Figure 3 *e*). Sample RB-68B yielded a 10-step plateau age of 82.3 ± 0.7 Ma (2σ), with the age spectrum comprising 60.6% of total ^{39}Ar released (Figure 3 *d*). The age spectrum of this sample shows that the higher temperature steps (more than 1050°C) yielded progressively higher apparent ages indicating excess inherited argon, most probably residing in fluid inclusions in minerals[23].

Its isochron age of 82.3 ± 2.8 Ma (2σ) and inverse isochron age of 82.3 ± 1.8 Ma (2σ) are statistically indistinguishable from the plateau age (Figure 3 *f*). These results have been summarized in Table 3. For both samples, the concordant plateau, isochron and inverse isochron ages, the large amount of total released ^{39}Ar for the plateau steps, and the atmospheric value of the $^{40}Ar/^{36}Ar$ ratio of trapped argon given by their intercepts, imply that these represent crystallization ages.

The 60.1 ± 0.5 Ma (2σ) age of the dyke at Shahdol indicates that this dyke postdates Deccan volcanic eruption. Earlier studies on two samples of mafic dykes intrusive into the sedimentary rocks of the Mesoproterozoic Chhattisgarh basin, Bastar craton have reported $^{40}Ar/^{39}Ar$ whole-rock ages of 63.7 ± 2.7 and 66.6 ± 2.2 Ma (ref. 24). Surprisingly, the Salma dyke from Raniganj basin occurring in close proximity of the ~ 115 Ma (ref. 25) Rajmahal volcanic province yielded ^{39}Ar–^{40}Ar age of

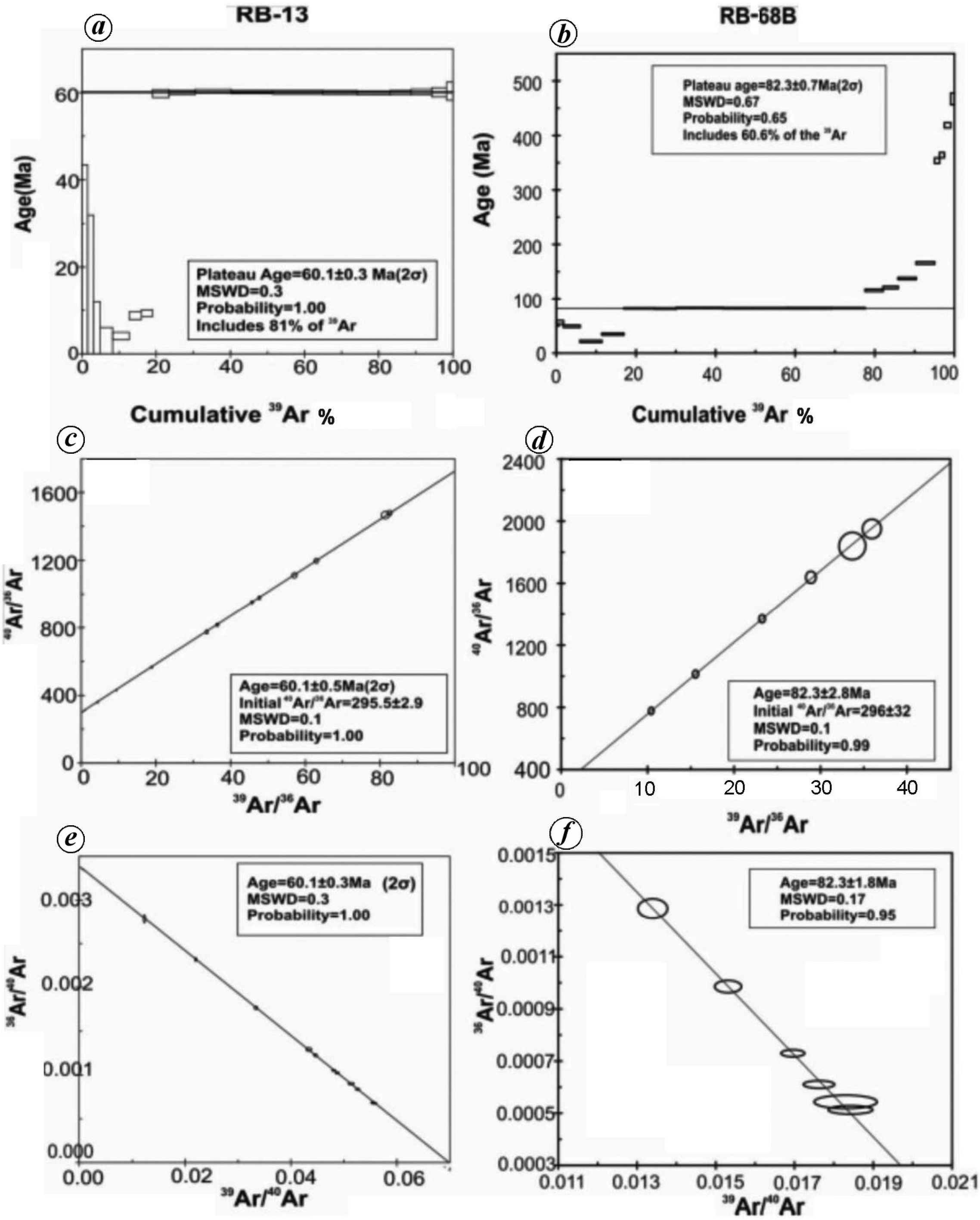

Figure 3 *a*, *b*. Whole-rock step-heating age spectra showing apparent age as a function of cumulative fraction of ^{39}Ar released. ***c***, ***d***, Plateau ages with the corresponding 2σ uncertainty, calculated using the isochron-defined initial ^{40}Ar–^{39}Ar. Isotope correlation diagrams (^{36}Ar/^{40}Ar versus ^{39}Ar/^{40}Ar) for the plateau steps showing 2σ error envelopes and the best fit regression line for each are also shown. ***e***, ***f***, Inverse isochron ages ($\pm 2\sigma$), intercept values (trapped ^{40}Ar–^{39}Ar, $\pm 2\sigma$) and MSWD (mean square weighted deviate).

64.4 ± 0.3 Ma (ref. 16). The Tertiary dyke at Salma (Raniganj basin), the Shahdol dyke (RB 13, the present study) and the lava flows of Shahdol are petrologically and geochemically similar[25]. Interestingly, the 82.3 ± 1.8 Ma (2σ) Chirimiri dyke intruding the Gondwana Formation east of the Deccan volcanic outcrops is significantly older than the Deccan lava flows. The ^{39}Ar–^{40}Ar ages reported here indicate polyphase dyke

Table 2. Argon isotopic composition (corrected for blank, mass discrimination and interference), apparent age and percentage of nucleogenic and radiogenic argon for sample RB-68B

Temperature (°C)	$^{36}Ar/^{39}Ar$ (± 2σ)	$^{40}Ar/^{39}Ar$ (± 2σ)	Apparent age (Ma; ± 2σ)	^{39}Ar%	$^{40}Ar^*$%	$^{37}Ar/^{39}Ar$ (± 2σ)	$^{40}Ar/^{36}Ar$ (± 2σ)
550	0.616	213.448	56.63	1.80	14.79	0.4017	346.8
	0.001	1.802	3.26 (3.27)			0.0023	35.6
600	0.061	45.140	49.13	4.13	60.54	0.6097	748.9
	0.001	1.022	1.89 (1.91)			0.0022	39.8
650	0.032	20.718	21.52	5.48	57.30	1.2202	692.0
	0.000	0.971	1.75 (1.76)			0.0024	40.5
700	0.041	31.152	34.77	5.54	61.84	0.7321	774.4
	0.000	0.999	1.79 (1.80)			0.0022	36.2
750	0.029	54.246	81.99	7.80	84.85	0.6687	1950.2
	0.000	0.442	0.77 (0.88)			0.0022	50.6
800	0.034	54.491	81.67	5.37	83.94	2.7402	1840.3
	0.000	0.562	0.99 (1.07)			0.0055	71.1
850	0.037	56.632	82.79	11.72	81.97	1.9445	1638.9
	0.000	0.535	0.94 (1.02)			0.0039	31.5
900	0.047	58.802	82.33	16.05	78.43	2.6477	1370.3
	0.000	0.517	0.90 (0.99)			0.0433	20.8
950	0.070	65.027	82.39	11.36	70.88	3.9679	1014.7
	0.000	0.540	0.95 (1.03)			0.2172	19.8
1000	0.101	74.357	82.37	8.33	62.00	3.5405	777.6
	0.000	0.486	0.86 (0.95)			0.2180	18.5
1050	0.184	117.387	115.79	4.49	55.60	5.5608	665.5
	0.001	1.140	2.03 (2.11)			0.2203	28.8
1100	0.176	113.646	121.06	3.77	59.57	14.1880	730.8
	0.001	1.192	2.13 (2.22)			0.2214	38.7
1150	0.181	111.250	137.55	4.53	67.44	40.6338	907.7
	0.001	1.126	2.06 (2.17)			0.2202	47.4
1200	0.184	108.012	165.99	4.66	80.80	79.3694	1539.4
	0.001	1.108	2.17 (2.31)			2.1995	147.4
1250	0.810	426.397	353.73	1.24	48.05	41.8600	568.8
	0.002	2.930	5.09 (5.35)			2.3431	18.7
1300	0.854	460.260	363.93	1.23	47.05	20.2676	558.1
	0.002	3.100	4.80 (5.09)			0.2179	82.9
1350	1.048	550.982	418.72	1.58	45.70	24.8834	544.2
	0.002	3.191	4.85 (5.22)			0.4591	63.0
1350	1.301	669.036	467	0.92	43.23	11.0373	520.5
	0.020	4.362	10.6 (10.8)			0.2186	13.7
Total	0.132	91.484	101.25	100.00	61.85	9.7093	774.6
	0.000	2.105	0.38 (0.64)			0.1204	6.5

Errors on age are without and (with) error on J respectively. Errors quoted are 2σ. $J = 0.001010 \pm 0.000005$.

Table 3. Summary of results of ^{40}Ar–^{39}Ar dating of dyke samples

Sample ID	Plateau age (Ma)	Isochron age (Ma)	Intercept	Inverse isochors age (Ma)
RB-13	60.1 ± 0.3 81% of ^{39}Ar	60.1 ± 0.5	295.5 ± 2.9	60.1 ± 0.3
RB-68B	82.3 ± 0.7 60.6% of ^{39}Ar	82.3 ± 2.8	296 ± 32	82.3 ± 1.8

intrusions both pre-dating and post-dating peak Deccan volcanic episode at 65 ± 1 Ma. Furthermore, the 60.1 ± 0.3 Ma age for the Shahdol dyke, the only Ar–Ar age available from the eastern DVP, suggests that this dyke could not be the feeder to the presently exposed lava flows of the region.

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Late Cretaceous diurnal tidal system: a study from Nimar Sandstone, Bagh Group, Narmada Valley, Central India

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Tidalites from the Cenomanian Nimar Sandstone, Bagh Group, Central India, are represented by (i) laterally accreted tidal bundles, (ii) herringbone cross-strata, (iii) sigmoidal cross-strata and (iv) tidal rhythmites with lenticular/wavy bedding. These indicate sedimentation in an upper subtidal to lower intertidal setting within fluvio marine interactive system. Time-series analysis of continuous rhythmic foreset bundles (sub-annual scale) manifests neap–spring tidal cycles within a diurnal tidal system with synodic and sidereal month lengths of ~28.4 lunar days and ~26.28 solar days respectively. Estimated Earth–Moon system parameters of the Late Cretaceous reveal no significant changes during the last ~100 Ma.

Keywords: Cenomanian, Cross-strata, lamina thickness, lunar orbital cyclicity, tidal bundles.

TIDALITES, represented by vertically accreted planar deposits (tidal rhythmites) and laterally accreted foreset bed forms (tidal bundles), within sandstone–mudstone heterolithic units preserve the records of past tidal activities. Analysis of the laterally and vertically continuous cyclic tidal successions provides an opportunity for precise estimation of lunar orbital periodicities and Earth–Moon parameters through geological ages[1–3]. Biological chronometers, such as growth lines on corals and bivalves, have failed to come up as an alternative method for their lack of precision due to complex environmental and biogenetic factors[4]. Report of tidalites and interpretation of the corresponding Earth–Moon parameters is

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