Rb-Sr and Ar-Ar systematics of Malani volcanic rocks of southwest Rajasthan: Evidence for a younger post-crystallization thermal event

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Abstract. A new Rb-Sr age of 779 ± 10 Ma has been obtained for a suite of andesite-dacite-rhyolite from the Malani Igneous Province of southwestern Rajasthan, dated earlier at 745 ± 10 Ma by Crawford and Compston (1970). The associated basalts may be slightly younger than the felsic volcanics and have a mantle source. The felsic volcanics on the other hand were most probably derived by fractional crystallization of a crustal magma (Srivastava *et al* 1989a,b). ⁴⁰Ar-³⁹Ar systematics of three samples viz., a basalt, a dacite and a rhyolite show disturbed age spectra indicating a thermal event around 500–550 Ma ago. This secondary thermal event is quite wide-spread and possibly related to the Pan-African thermo-tectonic episode observed in the Himalayas and south India.

Keywords. Rb-Sr age; Malani Igneous Province; ⁴⁰Ar-³⁹Ar dating.

1. Introduction

The Malani Igneous Province (MIP), covering an area of about 50,000 sq. km in western and southwestern Rajasthan to the west of the Aravalli mountain range, represents the youngest Proterozoic tectonomagmatic event in the western part of the Indian shield (figure 1). It consists dominantly of felsic volcanics and two types of granites – a subsolvus hornblende-biotite bearing Jalore type granite and a hypersolvus peralkaline Siwana type granite. The volcanics overlie Proterozoic metasediments of uncertain age (pre-Delhi or Delhi Supergroup) at many places in the Pali and Sirohi districts of Rajasthan and underlie the Trans-Aravalli Vindhyan (Srivastava 1988). Besides the felsic volcanics and the granites, the MIP also contains minor amounts of basic, alkaline and intermediate alkaline rocks.

It is generally assumed that the Jalore and Siwana type granites represent the parent stock of the Malani rhyolite and all felsic volcanics and granites of the province belong to a single Proterozoic event dated at 745 ± 10 Ma by Crawford and Compston (1970). This view has been supported by Pareek (1981), Kochhar (1984) and Bhusan (1985, 1989) in recent years. However, as the samples constituting the Rb-Sr isochron reported by Crawford and Compston are not cogenetic and from far flung localities, the reported age for the MIP should be taken cautiously.

The contention that the MIP represents a single Proterozoic magmatic event (Pareek 1981, Kochhar 1984 and Bhusan 1985, 1989) is not supported by the detailed petrographic and geochemical work of Srivastava (1988) which suggests that the rocks of the MIP belong to four different associations viz., (■) basalt-andesite-dacite-rhyolite

Figure 1. Geological map of Malani Igneous Province of southwest Rajasthan, India (after Bhusan 1985).

association; (■) peralkaline and peraluminous granites and rhyolite; (■) intermediate alkaline rocks belonging to trachybasalt-trachyandesite-trachyte and rhyolite association and (■) alkaline and hyperalkaline rocks; representing separate magmatic events, separated in time. This has been corroborated recently by Rathore (1995) and Rathore *et al* (1995).

Figure 2. Geological map of felsic volcanics of Dir and Gurapratap Singh, Pali District, Rajasthan (after Maheshwari 1983).

2. Study area

The volcanics of Dir and Gurapratap Singh, Pali district, belonging to basalt-andesite-dacite-rhyolite association, were selected for the present study. The distribution of various rock types in the area is shown in figure 2. The main rock types include dacite, rhyodacite and rhyolite with minor occurrences of basalt and andesite. The volcanics have been extruded on a basement of mica schist and shale/slate of the Aravalli or Delhi Supergroup (Maheshwari 1983). Most of the rocks are aphyric to sparsely phyric with an obsidian-like appearance. Geological setting, petrography and major and trace element geochemistry of these volcanics have been described by Srivastava *et al* (1989a and b) who concluded that all the felsic volcanics of the area except the ultrapotassic rhyolite are cogenetic and have formed by fractional crystallization from a crustally derived magma.

3. Analytical methods

Strontium isotopic analysis was carried out on a VG-354 thermal ionization mass spectrometer in peak jumping mode at the KDM Institute of Petroleum Exploration, Dehradun with computer control of data acquisition and reduction. The mean value of the NBS 987 Sr standard during this work was 0.710219 ± 0.000058 . Measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$.

Argon isotopic measurements were done on a MS 10S mass spectrometer at the Physical Research Laboratory, Ahmedabad. The experimental procedures used for ^{40}Ar - ^{39}Ar analyses generally followed those described in detail by Venkatesan *et al* (1993) and Rathore *et al* (1995). Samples were irradiated in D4 (core) position of the APSARA reactor of the Bhabha Atomic Research Center (BARC), Bombay. This position gives the maximum neutron flux with minimum variation. Irradiation was in two batches at 1 MW power level in 12 and 15 discrete steps spread over 20 and 25 days, respectively. The horizontal fluence variations for the two irradiations as measured by

Table 1. Rb-Sr isotopic data of Malani volcanics from Diri and Gurapratap Singh, Pali District, Rajasthan.

Sample no.	Rock type	^{87}Rb (ppm)	^{86}Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}^{\dagger}$ (atomic)	$^{87}\text{Sr}/^{86}\text{Sr}^{\ddagger}$ (atomic)
D/88	Basalt	13.184	33.996	0.383	0.70804 ± 0.00084
D/10	Dacite	41.320	26.329	1.55	0.72336 ± 0.00012
D/117	Rhyolite	70.509	7.607	9.16	0.80929 ± 0.00011
D/5	Rhyolite	84.519	7.068	11.8	0.83694 ± 0.00018
GM/219	Rhyolite	70.691	3.463	20.2	0.92887 ± 0.00035

[†]A blanket error of $\pm 2\%$.[‡]Error is 2σ mean.

^{58}Co activity of pure Ni wire enclosed with the samples were found to be 5.5% and 3.4%, respectively.

Samples were heated incrementally from 500°C to fusion at 1500°C in an UHV furnace heated electrically. K_2SO_4 and CaF_2 salts were irradiated along with samples, to correct for interfering isotopes produced during irradiation. The measured isotopic ratios were also corrected for mass discrimination in the mass spectrometer. Apparent $^{40}\text{Ar}/^{39}\text{Ar}$ ages were calculated from the corrected isotopic ratios using the decay constants and isotopic ratios given by Steiger and Jaeger (1977). Total ages were computed for each sample by weighting with inverse variance of each temperature increment. A plateau is considered defined if the apparent ages of 4 or more contiguous temperature fractions, each with $> 5\%$ and together constituting $> 50\%$ of the total ^{39}Ar evolved, agree within their 2σ errors. If the disagreement exceeds 2σ errors or the portion of the ^{39}Ar constituting the plateau is less than 50% of the total, it is called a pseudo plateau.

4. Results and discussion

4.1 Rb-Sr studies

Five samples ranging in composition from basalt to rhyolite were analyzed (table 1). The samples showed good spread in their Rb/Sr ratios (0.1 to 7). In the conventional Sr evolution diagram (figure 3), the four samples (excluding basalt) show a good linear relationship. This line interpreted as an isochron corresponds to an age of 779 ± 10 Ma and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.70612 ± 0.00046 . The MSWD of the fit is 0.29 indicating that they meet the isochron conditions very closely. The initial Sr ratio implies a crustal source for the magma of these rocks (Faure and Hurley 1963). When the sample D/88 (basalt) is also included in the calculations, the five samples define an isochron age of 786 ± 11 Ma and an initial Sr isotopic ratio of 0.70559 ± 0.00043 (MSWD = 2.26). Based on the proximity of the ages and initial ratios obtained in both the cases, the poorly radiogenic basalt seems to fit into the isochron defined by more radiogenic felsic rocks.

Figure 4 shows the plot of all the five data points as proposed by Provost (1990). This plot allows one to simultaneously visualize the experimental data and their analytical precision, to judge the quality of the linear fit, to appraise the accuracy of the age and

Figure 3. Rb-Sr conventional isochron diagram of andesite-dacite-rhyolite association of Malani Igneous Province, Rajasthan.

initial ratio results, and to quantitatively appreciate the influence of each data point. It can be seen that basalt (D/88) falls distinctly away (below) from dacite and rhyolites on the best isochron diagram indicating that the basalt may be slightly younger and derived from a less radiogenic source. Srivastava *et al* (1989a) have also reported that the relationship between basalts and felsic volcanics is not clear in the field.

4.2 ^{40}Ar - ^{39}Ar studies

Three samples including a basalt (D/88), dacite (D/25) and a rhyolite (D/174) were taken for $^{40}\text{Ar}/^{39}\text{Ar}$ studies. The analytical results are given in table 2. Minnesota hornblende (MMhb-1), with an age of $520.4 \pm 1.7 \text{ Ma}$ (Samson and Alexander 1987), was used as monitor for all the samples. The errors quoted are at 2σ level and were computed by quadratically propagating the errors in the measured ratios, blanks and interfering isotopes. The errors quoted for the apparent and integrated ages include the error in the irradiation parameter 'J' but the error boxes in age spectra plots do not include the latter.

The age spectra plotted in figure 5 exhibit a step-wise increase in age for all the samples with increasing temperature. Similar patterns, normally interpreted as resulting from argon loss by diffusion, have been obtained for slowly cooled rocks and for rocks that have been reheated subsequent to the time of their formation (Hanson *et al* 1975; Berger and York 1981; Harrison and McDougall 1981 and Zeitler 1987).

For sample D/88 (basalt), four temperature steps (550 to 700°C ; 28.4% ^{39}Ar release) give a pseudo plateau corresponding to an age of $492.0 \pm 4.7 \text{ Ma}$ (figure 5a). The higher

Figure 4. Rb-Sr isochron diagram of basalt-andesite-dacite-rhyolite association of Malani Igneous Province, Rajasthan.

temperature steps give successively higher ages, but the total or integrated age of all the steps is 530.9 ± 4.4 Ma. In sample D/25 (dacite) five intermediate temperature steps (600 to 800°C, 51.7% ^{39}Ar release) define a pseudo plateau age of 507.8 ± 8.2 Ma (figure 5b). In the third sample D/174 (rhyolite) only three temperature steps (550 to 650°C, 25.7%, ^{39}Ar release) constitute a pseudo plateau at 520.5 ± 9.6 Ma (figure 5c). The high temperature fractions of the dacite and rhyolite samples give apparent ages higher than their Rb-Sr age of 779 ± 10 Ma, presumably due to the presence of excess argon. The integrated ages for these samples are 600.7 ± 8.0 Ma and 662.2 ± 8.4 Ma, respectively, which are significantly higher than that of the basalt.

The above pattern is similar to those of rocks subjected to secondary thermal episodes like metamorphism. The age spectra in this case either rise steeply to a relatively flat plateau over most of the ^{39}Ar release or show step-wise age increase with increasing temperature, with apparent ages well in excess of the metamorphic and/or formation age and in some cases, even older than the age of the earth. This type of pattern has been demonstrated for biotites from Greenland by Pankhurst *et al* (1973), Alpine biotites by Roddick *et al* (1980) and for phlogopites from the South African Kimberlites by Phillips and Onstotte (1986).

The age spectra of samples D/25 and D/174 therefore suggest that part of the radiogenic argon was lost by diffusion during a thermal event around 500–550 Ma ago, much later than their time of formation. This conclusion is supported by well-constrained Rb-Sr mineral ages of 500–550 Ma of the different granitic bodies from south Delhi Fold Belt e.g., Sendra, Sadri-Ranakpur and Sai (Choudhary 1984). These granites otherwise give whole rock Rb-Sr ages of 800 ± 50 Ma. Our $^{40}\text{Ar}/^{39}\text{Ar}$ results

Table 2. Step heating argon isotopic compositions and apparent ages of whole rock samples of Malani volcanics, Rajasthan.

Temp (°C)	$^{36}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{40}\text{Ar}/^{39}\text{Ar}$	^{39}Ar (% of total)	$^{40}\text{Ar}^*$ (%)	Age(Ma) ($\pm 2\sigma$)
Sample D/88 (Diri Basalt) $J = 0.00224 \pm 0.00002$						
400	0.1347	3.3566	183.8	1.1	78.3	503 $\pm$ 11
450	0.0405	3.1229	130.44	4.2	90.8	424 $\pm$ 6
500	0.0154	2.6167	135.24	4.9	96.6	463 $\pm$ 7
550	0.01575	3.9964	142.72	6.4	96.7	485 $\pm$ 6
600	0.01427	3.7099	144.64	6.1	97.1	493 $\pm$ 6
650	0.01216	2.6369	145.02	8.5	97.5	496 $\pm$ 6
700	0.0069	1.9187	143.06	7.4	98.6	494 $\pm$ 6
750	0.0079	2.1446	149.53	8.9	98.4	513 $\pm$ 6
800	0.00569	3.0859	160.84	18.6	98.9	549 $\pm$ 6
850	0.00659	3.162	152.98	16.6	98.7	525 $\pm$ 6
900	0.01778	4.7422	168.17	8.3	98.9	560 $\pm$ 7
1000	0.05225	20.672	21.5	4.5	93.6	684 $\pm$ 8
1100	0.0702	42.79	236.1	3.5	91.2	709 $\pm$ 9
1250	0.1211	21.93	240.3	1.1	85.1	679 $\pm$ 17
Total	0.01779	5.5509	158.3	100.0	96.7	531 $\pm$ 4
Sample D/25 (Diri Dacite) $J = 0.00275 \pm 0.00001$						
500	0.0799	1.1334	134.31	1.4	82.4	479 $\pm$ 11
550	0.0408	0.66506	122.75	3.1	90.2	479 $\pm$ 8
600	0.03895	0.36889	132.27	5.1	91.3	517 $\pm$ 8
650	0.01662	0.26803	125.1	8.9	96.1	515 $\pm$ 8
700	0.00595	0.22393	120.62	12.0	98.5	510 $\pm$ 8
750	0.00443	0.42165	116.07	10.8	98.9	495 $\pm$ 8
800	0.00428	0.63515	118.4	14.9	98.9	504 $\pm$ 8
850	0.00738	1.7925	127.0	20.9	98.3	532 $\pm$ 10
900	0.00655	1.8422	144.86	12.6	98.7	598 $\pm$ 9
950	0.023	4.717	234.2	5.0	97.1	876 $\pm$ 13
1000	0.0336	7.7124	376.6	1.6	97.4	1258 $\pm$ 17
1050	0.0493	10.65	458.4	1.0	97.0	1439 $\pm$ 20
1200	0.08095	10.182	468.0	1.0	95.0	1440 $\pm$ 32
1500	0.144	9.4665	473.3	2.0	91.0	1410 $\pm$ 58
Total	0.0158	1.5885	148.3	100.0	96.9	601 $\pm$ 8
Sample D/174 (Diri Rhyolite) $J = 0.00269 \pm 0.00003$						
500	0.02469	—	143.22	2.1	94.9	562 $\pm$ 9
550	0.00472	0.07582	124.8	3.5	98.9	517 $\pm$ 8
600	0.00241	—	126.41	10.7	99.4	525 $\pm$ 8
650	0.00103	—	124.65	11.5	99.8	520 $\pm$ 8
700	0.00069	—	132.4	12.2	99.8	549 $\pm$ 8
750	0.00193	—	146.95	13.7	99.6	598 $\pm$ 9
800	0.00351	—	183.8	14.8	99.4	721 $\pm$ 10
850	0.0029	0.08438	161.25	14.4	99.5	646 $\pm$ 10
900	0.00318	—	200.5	7.6	99.5	774 $\pm$ 11
950	0.00502	0.14589	240.4	3.5	99.4	895 $\pm$ 13
1200	0.01307	—	319.3	3.7	98.8	1107 $\pm$ 15
1500	0.0145	—	362.8	2.0	99.0	1217 $\pm$ 22
Total	0.02156	0.0198	166.13	100.0	99.4	662 $\pm$ 8

Figure 5. $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra of felsic volcanics of Dir and Gurapratap Singh, Pali District, Rajasthan: (a) Basalt, (b) Dacite and, (c) Rhyolite.

extend the imprint of this later thermal event in rocks exposed further west of the Aravalli range in Rajasthan.

While this thermal overprinting is most probably related to some large scale tectonic episode, none of the rocks dated so far in Rajasthan have yielded the primary crystallization age of 500–550 Ma. However, formation ages in this time band have been recorded for several granitoid plutons from a long linear belt in the north, running parallel to the Himalayan strike (Jager *et al* 1971; Mehta 1977; Le Fort *et al* 1983; Trivedi *et al* 1984 and Trivedi 1990) and from the southwest coast of Kerala in south India (Nair *et al* 1985; Santosh *et al* 1994). Mehta (1977), Bhargava (1980) and Mitchell *et al* (1983) have considered the large scale granitic activity in the Himalaya as a strong evidence for Late Cambrian orogeny. Valdiya (1993) suggested extensive emplacement of Cambrio-Ordovician granites (ca. 500 ± 25 Ma) as evidence for Pan-African orogeny in the Himalaya. Garzanti *et al* (1986), Bagati (1991), Bhargava *et al* (1991) and Shah (1991) attributed the break in sedimentation in the Himalaya to the last

epirogenic pulse of Pan-African orogeny. The emplacement of younger granites in south India has also been correlated with the Pan-African thermo-tectonic episode (Santosh *et al* 1994).

5. Conclusions

The felsic volcanics from Dirri and Gurapratap Singh in Pali district of Rajasthan give a whole rock Rb-Sr isochron age of 779 ± 10 Ma distinctly older than the 745 ± 10 Ma age assigned to an assorted collection of rhyolite and granites from the MIP by Crawford and Compston (1970). They are also older than the Jalore and Siwana type granites dated at 727 ± 8 Ma and 697 ± 10 Ma, respectively (Rathore 1995). These findings support the proposal of Srivastava (1988) that the Malani felsic volcanics are coeval with the Erinpura type of granites (800 ± 50 Ma) and were intruded so much later by the Jalore and Siwana type of granites that the latter cannot be genetically related to the former.

While the initial Sr isotopic ratio of the felsic volcanic rocks suggests a crustal source for their magma, that of the associated basalt implies an upper mantle source. ^{40}Ar - ^{39}Ar spectra of these rocks reflect a thermal event around 500–550 Ma ago, as did Rb-Sr mineral ages of granites of the south Delhi Fold Belt along the axial zone of the Aravalli mountain range (Choudhary 1984). The timing of this thermal overprinting on the Malani volcanic rocks and Erinpura type granites shows that it is related to the widespread Pan-African orogeny which is magmatically manifested in the Indian subcontinent along both the axial zone of the Himalayas and the western coast of south India.

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