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^{40}Ar–^{39}Ar age of the St. Mary's Islands volcanics, southern India: record of India–Madagascar break-up on the Indian subcontinent

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Abstract

The felsic volcanics (rhyolites and rhyodacites) of the St. Mary's Islands (SMI), southern India (~13°N), were originally interpreted as a distant outlier of the ~65 Ma Deccan volcanic province of west–central India, comprising dominantly flood basalts. Later the SMI volcanics were dated at ~93 Ma by the K–Ar technique. However, this K–Ar 'age' was dubious, being merely an average of five out of six widely varying dates and arbitrary data selectivity being involved in this averaging. Our first ^{40}Ar–^{39}Ar dating of the SMI volcanics yields excellent plateau and isochron ages, and their weighted mean isochron age is 85.6 ± 0.9 Ma (2σ). Interestingly, the southern Indian Precambrian terrain is intruded by numerous mafic–doleritic dyke swarms ranging in age from Proterozoic to the latest Cretaceous (69–65 Ma, Deccan-related), and indeed, two regional dykes (a leucograbbro and a felsite) from the Kerala region of southwestern India remain previously dated at ~85 Ma, but again with the K–Ar technique. However, this age for the SMI volcanics also corresponds excellently with ^{40}Ar–^{39}Ar ages of ~89–85 Ma (weighted mean isochron age 87.6 ± 1.2 Ma, 2σ: equivalent to 88.1 ± 1.2 Ma corresponding to MMhb-1 age of 523.1 ± 2.6 Ma) for the Madagascar flood basalt province. Together, therefore, the Madagascar flood basalt province, the SMI volcanics, and possibly the Kerala dykes could represent volcanic activity associated with the break-up of Greater India (India plus Seychelles) and Madagascar, thought to have occurred in the Upper Cretaceous at ~88 Ma.

Keywords: Ar-40/Ar-39; geochronology; volcanism; India; tectonics; rifting

1. Introduction

Several flood basalt provinces are found along rifted continental margins [1–4]. The western Indian continental margin is a typical passive rifted margin [5–9]. Its southern half (area south of 16°N) is mostly composed of Archaean and Proterozoic crystalline rocks of the Indian shield, while the northern half (16–22°N) is chiefly covered by the ~65 Ma Deccan flood basalt prov-

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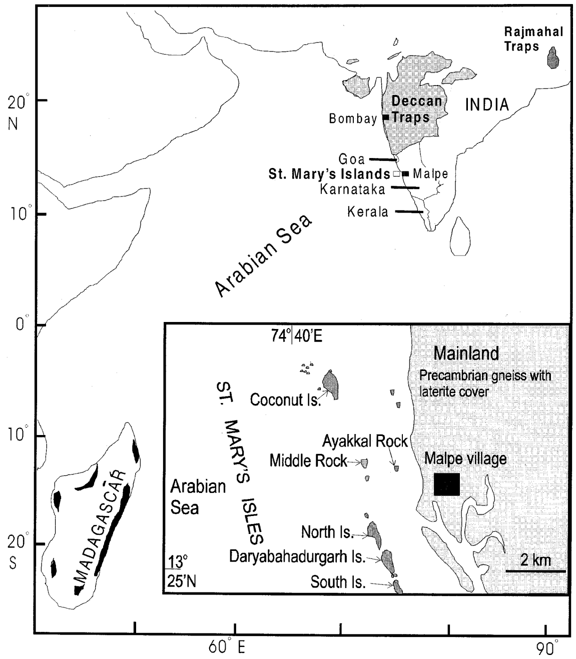

Fig. 1. The present position of Madagascar and India. Outcrop of Madagascar flood basalt province is shown in black (after [13]), and outcrops of the Deccan and Rajmahal Traps are shown shaded. The Goa, Karnataka and Kerala regions of India are also shown. The inset shows a detailed map of the SMI, India.

ince [5] (Fig. 1). The western continental margin has been the site of two major episodes of continental break-up during the Cretaceous: the break-up of Greater India (India plus Seychelles) from the African island of Madagascar in the Upper Cretaceous at about 88 Ma, and subsequently the break-up of Greater India into the present Indian subcontinent and the Seychelles microcontinent at ∼65 Ma, the latter contemporaneous with the later stages of the huge Deccan volcanic episode [10,11].

The Greater India–Madagascar break-up was accompanied by the formation of an extensive volcanic province in Madagascar, especially along its rifted eastern margin [11–14], comprising voluminous flood basalt flows and doleritic dykes with subordinate rhyolite flows. Counterpart volcanic activity on the Indian side has not been unambiguously identified so far, though Anil Kumar et al. [15] have suggested that the ENE–WSW striking mafic dykes in Karnataka, southern India, are perhaps related to this event. The southern Indian Precambrian terrain is traversed by a large number of mafic, mostly doleritic, dyke swarms emplaced at various times, some of which have been radioisotopically dated. Latest Cretaceous ^{40}Ar–^{39}Ar ages (69–65 Ma, [16]) for doleritic dykes of the central and north Kerala region (Fig. 1) link them unquestionably to the Deccan volcanic episode which had a far greater manifestation to the north. Doleritic dykes in Goa (Fig. 1) along the western Indian coast, some 50–80 km south of the southernmost limit of the Deccan lavas, have yielded ^{40}Ar–^{39}Ar ages of about 62 Ma (weighted mean age of four dykes 62.8 ± 0.2 Ma) [17]. In the far south there also exist numerous generations of mafic dykes emplaced in the Proterozoic, for example at 1980 ± 25 Ma, and also dykes giving ages of 144 ± 6 Ma [18]. The latter dykes have a restricted occurrence in southern Kerala, along the southernmost tip of India, and may be related to rifting preceding the separation of Australia, Antarctica and India [18]. The K–Ar ages of ∼85 Ma for both a major leucogabbro dyke from central Kerala [19] and for a major felsite dyke from north Kerala [18] and ^{40}Ar–^{39}Ar ages of ∼88–90 Ma for the ENE–WSW striking dykes in Karnataka [20] have been reported.

The rhyolites and rhyodacites of the St. Mary's Islands (SMI), located at 13°N off the western Indian coast 300 km south of the southernmost limit of the Deccan basalt lavas (Fig. 1), have long been known to be petrologically very similar to the Deccan felsic volcanics, e.g. of Bombay at 19°N [21–23], and were originally thought to represent a distant outlier of the Deccan Traps [21,22]. Valsangkar et al. [24] later carried out a K–Ar dating and paleomagnetic study of these and derived an average age of ∼93 Ma for them, based on which the SMI have been subsequently interpreted as an early episode of felsic volcanism preceding the break-up of Madagascar and Greater India. Sheth [25] pointed out, however, that the K–Ar date could be spurious and, especially in light of Deccan age dykes recently identified from southern India [16] and the long-appreciated petrological similarity of the SMI volcanics with the felsic volcanics of the Deccan [21–

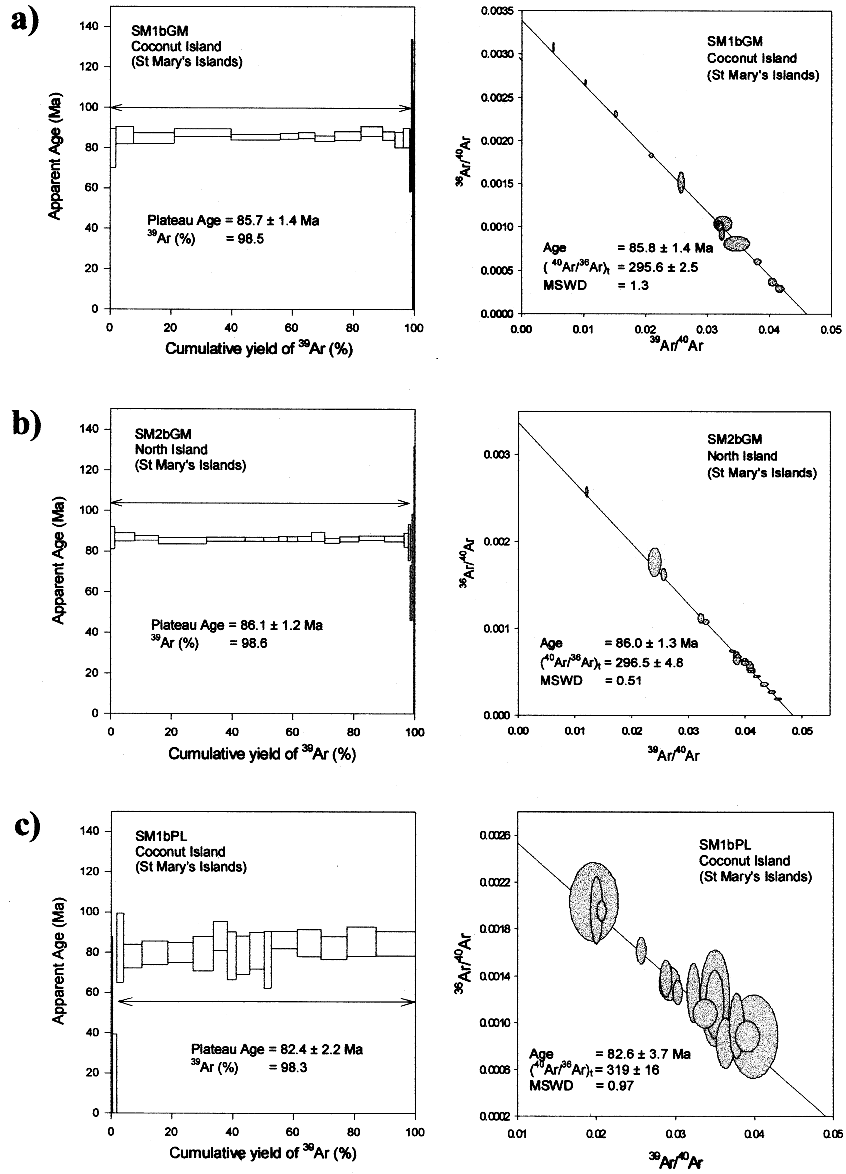

Fig. 2. (a–c) (Left) Step-heating age spectra showing apparent ages as a function of cumulative fraction of ^{39}Ar released. The vertical width of the individual steps indicates 2σ error calculated without propagating the error on J. Plateau age with the corresponding 2σ uncertainty is shown. (Right) Isotope correlation diagrams (^{36}Ar/^{40}Ar vs. ^{39}Ar/^{40}Ar) for the plateau steps, showing 2σ error envelopes and the best-fit regression line for each. Inverse isochron ages (±2σ), intercept values (trapped ^{40}Ar/^{36}Ar, ±2σ) and MSWD are given.

23], ^{40}Ar–^{39}Ar dating of the SMI was required to unambiguously establish whether the SMI were indeed a part of the Deccan episode, or older. Our results establish beyond doubt that the SMI are not related to the Deccan, but also that their K–Ar age of 93 Ma [24] is a serious overestimate by ~8 Myr, and the significant implications of this finding for the Upper Cretaceous tectonic and magmatic history of the Indian subcontinent are presented here.

2. Geology and petrography

The SMI comprise a group of four main islands, namely, Coconut Island, North Island, Daryabahadurgarh Island and South Island, and several small islets, forming a N–S-trending chain of about 6 km length, off Malpe, about 6 km west of Udupi town in coastal Karnataka state (Fig. 1). The mainland near Malpe consists of Precambrian gneisses weathered to thick laterite. The SMI volcanics consist of dacite, rhyodacite, rhyolite and granophyre which are fresh, light to dark gray in color, and devoid of vesicles. These petrographic types are present in all the large islands of the group, though not as separate physical bodies. They contain small (generally up to ∼1 cm in diameter), rounded, dark patches of basaltic composition, which probably represent earlier basaltic magmas still hidden at depth [21–24]. The Coconut Island outcrops show spectacular columnar jointing for which it has been designated a National Geological Monument by the Geological Survey of India. The columns are up to 15 m in height. These outcrops give the appearance of a lava flow but no vesicularity is observed (though its top is eroded and base is under water). Columnar jointing is absent on the other islands, but North Island and Daryabahadurgarh Island are full of rocky outcrops as high as 25 m, traversed by N–S striking and steeply dipping joints. The general appearance of these rocks is not flow-like [22]. The Coconut Island and North Island volcanics are fine-grained and porphyritic. Plagioclase forms mega- and microphenocrysts, while quartz, orthoclase and sanidine form the groundmass.

3. Previous (K–Ar) dating work

Valsangkar et al. [24] carried out K–Ar dating of six samples of the SMI volcanics. Their K–Ar dates range from ∼80 Ma to ∼97 Ma. One of the samples (C3) has a substantially younger date (80.3 ± 1.7 Ma) than the other five. They calculated a 'mean age' of 93.1 ± 2.4 Ma (2σ) for five samples excluding the sample with a younger age and designated it as the age of SMI volcanism. They also argued that there was no evidence for the presence of excess ^{40}Ar in any of these five samples, because there was no correlation between age and potassium content, and therefore, the mean age of 93.1 ± 2.4 Ma would be the younger limit for the age of volcanic activity.

Assuming that the 93.1 ± 2.4 Ma 'age' was an eruption age, Valsangkar et al. [24] stated that the SMI volcanic activity occurred about 20–25 Myr before the Deccan volcanism. They also argued that if all of the samples had lost ^{40}Ar, the real crystallization ages should have been higher than 93 Ma and the SMI could therefore be correlative with the Rajmahal Traps of eastern India. The real age of the SMI volcanics has, however, remained unclear until now.

4. ^{40}Ar–^{39}Ar dating: samples and analytical methods

We undertook the first ^{40}Ar–^{39}Ar dating of the SMI volcanics by conventional step-heating following the methods of Venkatesan et al. [26]. We chose three samples: SM1bGM (groundmass of the Coconut Island lava), SM2bGM (ground-

Table 1
Summary of results of ^{40}Ar–^{39}Ar dating of SMI samples

Sample	Plateau			Isochron			Inverse isochron		
	Steps	^{39}Ar (%)	Age (Ma)	Age (Ma)	Trap	MSWD	Age (Ma)	Trap	MSWD
SM1bGM	13	98.5	85.7 ± 1.4	85.6 ± 1.4	295.6 ± 2.5	1.4	85.8 ± 1.4	295.6 ± 2.5	1.3
SM2bGM	17	98.6	86.1 ± 1.2	86.0 ± 1.3	296.9 ± 4.4	0.92	86.0 ± 1.3	296.5 ± 4.8	0.51
SM1bPL	15	98.3	82.4 ± 2.2	82.1 ± 3.6	321 ± 16	1.03	82.6 ± 3.7	319 ± 16	0.97
Mean			85.4 ± 0.8	85.6 ± 0.9	296.4 ± 2.2		85.7 ± 0.9	296.2 ± 2.2	

Trap, trapped initial ^{40}Ar/^{36}Ar composition. Errors on ages are 2σ and obtained relative to flux monitor MMhb-1 (523.1 ± 2.6 Ma).

mass of the North Island lava) and SM1bPL (plagioclase separate from the same Coconut Island sample as sample SM1bGM). We separated plagioclase phenocrysts and groundmass to avoid the possibility of obtaining a spurious and geologically meaningless date in case the phenocrysts were actually older xenocrysts. Also, any mafic inclusions contained in these lavas were carefully removed. About 1 g each of ultrasonically cleaned sample powders were sealed in quartz capsules and irradiated for 100 h cumulative, along with the flux monitor standard Minnesota Hornblende MMhb-1 (523.1 ± 2.6 Ma, [27]), in the central core of the light–water-moderated APSARA reactor (rated power of 1 MW) at the Bhabha Atomic Research Centre, Bombay, India. Because the reactor was not operated continuously, appropriate correction for ^{37}Ar decay between segmented irradiations was made following McDougall and Harrison [28]. Pure nickel wires were enclosed in both sample and monitor capsules to measure and correct for the variation in neutron fluence. Interference corrections were applied based on measurements on pure CaF_2 and K_2SO_4 salts irradiated with the samples. The mean values for $(^{36}Ar/^{37}Ar)_{Ca}$, $(^{39}Ar/^{37}Ar)_{Ca}$ and $(^{40}Ar/^{39}Ar)_K$ are 0.0001640, 0.0007456, and 0.069205, respectively.

From each sample, argon was extracted in an electrically heated ultra-high-vacuum furnace, in a series of 18–20 steps of increasing temperature, starting at 450°C and going up to fusion (1400°C). The steps were arranged in 50°C temperature increments and the last step was repeated. The argon released in each step was subjected to a two-stage purification, and its isotopic composition measured using an AEI MS10 mass spectrometer in static mode. We define a plateau as comprising four or more contiguous steps in an apparent age spectrum with apparent ages that overlap with the mean at the 2σ level of error excluding the error contribution from the error in the J value, with a total $^{39}Ar_K$ release of 60% or more. The plateau age and the associated error, however, are calculated as advocated by Renne et al. [29]. A weighted mean value of $^{40}Ar^*/^{39}Ar_K$ (R_w) was calculated from the individual step value (R_i) of this ratio for plateau steps as:

$$R_w = \left(\sum R_i/\sigma^2_{R_i}\right)/\sum\left(1/\sigma^2_{R_i}\right)$$

and the uncertainty in this value was calculated as:

$$\sigma R_w = \left(\sum(\sigma_{R_i})^{-2}\right)^{-1/2}$$

The plateau age is calculated as:

$$t_w = \ln(R_w \cdot J + 1)/\lambda$$

The uncertainty on plateau age neglecting uncertainty in the decay constant λ is:

$$\sigma_{t_w} = \left(R^2_w \cdot \sigma^2_J + J^2 \cdot \sigma^2_{R_w}\right)^{1/2}/(R_w \cdot J + 1) \cdot \lambda$$

All ages presented herein are based on MMhb-1 at 523.1 ± 2.6 Ma. For comparison all the previously published ages discussed in this paper have been recalculated to this age of MMhb-1. The isochron and inverse isochron ages were determined using the regression method of York [30] through the selected step gas composition using the $^{40}Ar/^{36}Ar$ vs. $^{39}Ar/^{36}Ar$ and $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ isotope correlation diagrams, respectively. ^{40}Ar blanks were typically about 1–2% of sample ^{40}Ar for the lower temperatures up to 1000°C, and increased gradually to $< 20\%$ at 1400°C. The values of the irradiation parameter J for the samples are as follows: SM1bGM, 0.002235 ± 0.000017; SM2bGM, 0.002368 ± 0.000018; SM1bPL, 0.002452 ± 0.000018.

5. ^{40}Ar–^{39}Ar dating: results

Table 1 shows the analytical results with the errors quoted at 2σ level. The plateau age spectra and inverse isochron plots are presented in Fig. 2. All the three SMI samples yield very good plateaus and inverse isochrons. Sample SM1bGM (Fig. 2a) has a 13-step plateau age of 85.7 ± 1.4 Ma, with the age spectrum comprising 98.5% of total ^{39}Ar released. Its isochron age 85.6 ± 1.4 Ma is identical with its plateau age, and the isochron has a mean square weighted deviate (MSWD) of 1.4 along with a $^{40}Ar/^{36}Ar$ intercept of 295.6 ± 2.5 which is the same as the atmospheric value of

295.5. The inverse isochron age for this sample is 85.8 ± 1.4 Ma with an atmospheric value for trapped argon composition. Sample SM2bGM (Fig. 2b) has a 17-step plateau age of 86.1 ± 1.2 Ma, the age spectrum comprising 98.6% of total ^{39}Ar released. Its isochron age of 86.0 ± 1.3 Ma is concordant with its plateau age and the isochron has a MSWD of 0.92, while its trapped ^{40}Ar/^{36}Ar composition of 296.9 ± 4.4 is again atmospheric. Its inverse isochron age 86.0 ± 1.3 Ma is also with atmospheric trapped argon composition. Sample SM1bPL (Fig. 2c) has low amounts of argon and therefore the data reduction involved significant corrections for blanks and consequently the age has a higher uncertainty. It yielded a 15-step plateau comprising 98.3% of total ^{39}Ar released. Its isochron age is 82.1 ± 3.6 Ma with a MSWD of 1.03 and an ^{40}Ar/^{36}Ar intercept of 321 ± 16, marginally higher than the atmospheric value. Its inverse isochron age also is 82.6 ± 3.7 Ma with the trapped argon composition 319 ± 16, slightly higher than the atmospheric value. The age spectrum for this sample calculated using the isochron defined initial ^{40}Ar/^{36}Ar gives a 15-step plateau age of 82.4 ± 2.2 comprising 98.3% of ^{39}Ar released, indistinguishable from its isochron age.

6. Discussion and conclusions

The concordant plateau, isochron and inverse isochron ages for all the three samples, SM1bGM, SM2bGM and SM1bPL, the large amounts (98–99%) of total released ^{39}Ar for the plateau steps, the atmospheric values of the trapped ^{40}Ar/^{36}Ar component, and acceptable MSWD values for the isochrons (Table 1) imply that these ages represent true crystallization ages. The weighted mean plateau age of these samples is 85.4 ± 0.8 Ma, their weighted mean isochron age is 85.6 ± 0.9 Ma with weighted mean ^{40}Ar/^{36}Ar intercept value 296.4 ± 2.2, and their weighted mean inverse isochron age is 85.7 ± 0.9 Ma with weighted mean ^{40}Ar/^{36}Ar intercept value of 296.2 ± 2.2. The eruption/crystallization age of the SMI volcanics therefore can be taken as the weighted mean isochron age, 85.6 ± 0.9 Ma. This age conclusively shows that the SMI are not related to the Deccan Trap volcanism as originally conceived [21,22] but a substantially older event, but that the average K–Ar date of 93 Ma [24] was also a serious overestimate by ~8 Myr.

Tectonic activity associated with and presumably causative of SMI volcanism needs to be identified. Interestingly, the SMI ^{40}Ar–^{39}Ar age corresponds well with ^{40}Ar–^{39}Ar ages of ~89–85 Ma for the Madagascar flood basalt province [13], which formed contemporaneously with the break-up of Madagascar and Greater India in the Upper Cretaceous at ~88 Ma. Note that the SMI ages (present study) and those for the Madagascar volcanics [13] have been obtained relative to the same flux monitor MMhb-1, though the latter ages have been recalculated to a MMhb-1 age of 523.1 ± 2.6 Ma. The Madagascar province, originally of a considerable extent and volume, today stands mostly eroded [11–14]. Lavas from the 1500-km-long eastern rifted margin of Madagascar show virtually no statistically significant differences in age, the entire duration of Cretaceous volcanism on Madagascar was no more than 6 Myr, with the youngest ages being ~84 Ma, and the weighted mean of the isochron ages 88.1 ± 1.2 Ma (2σ) [13]. In this continental break-up scenario the SMI can therefore be designated as the counterpart volcanic activity on the Indian side.

Other contemporaneous volcanic activity in India needs to be unambiguously identified. Recently, Anil Kumar et al. [20] have reported ^{40}Ar–^{39}Ar ages of ~88–90 Ma for the ENE–WSW striking dykes in Karnataka. K–Ar ages of ~85 Ma existing on two major dykes in Kerala [18,19] need to be confirmed with ^{40}Ar–^{39}Ar dating. If confirmed, these dykes, the SMI and the Madagascar province might constitute a single large igneous province as visualized by Radhakrishna et al. [18]. Conventional K–Ar ages can be affected by low-temperature alteration which may add K and remove radiogenic Ar, thus causing measured ages to be significantly less than the true crystallization ages. On the other hand, assimilation of older continental crust may add radiogenic Ar at the time of crystallization, causing measured ages to be too old [28]. But with the ^{40}Ar–^{39}Ar incremental heating technique, it is possible to separate the contributions of the primary minerals and secondary (alteration) phases to a sample's total argon isotopic composition [28]. The limitations of K–Ar dating are further borne out by the discussion in the present paper, and the superiority of ^{40}Ar–^{39}Ar ages over K–Ar ages is clear. Future systematic sampling and ^{40}Ar–^{39}Ar dating studies of the numerous dyke swarms crossing the ancient southern Indian shield would go a long way to enable an understanding of the long and complex tectonic and magmatic history of the Indian subcontinent.

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