A minimum age for the active Barren Island volcano, Andaman Sea

Jyotiranjan S. Ray[1,*], Kanchan Pande[2] and Neeraj Awasthi[1]

[1]Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India
[2]Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India

Barren Island of Andaman Sea is the only active volcano in the Indian subcontinent. While the volcano has erupted sporadically many times over the last ~70 ka, it is not known when it formed and breached the sea surface. To provide estimates for the timing of these events, we dated two tephra (ash) layers older than 42 ka and generated by this volcanism in a previously studied marine sediment core collected ~32 km southeast of the island using the newly established modern ^{40}Ar–^{39}Ar facility in India. The ^{40}Ar–^{39}Ar plateau ages of plagioclase separates from successive tephra layers at 310 and 375 cm are 1.8 ± 0.4 (2σ) Ma and 1.5 ± 1.8 (2σ) Ma respectively. We interpret the more robust age of 1.8 Ma as the time of crystallization of plagioclase grains. As this age is very much older than the depositional age of the tephra layer (~61 ka), we infer that it represents the age of older rocks present in the plumbing system of the volcano that were blown out with later pyroclastic eruptions and therefore, sets a strict younger limit to the time of formation of the volcano.

Keywords: ^{40}Ar–^{39}Ar dating, lithic clasts, subduction zone, tephra, volcano.

Introduction

VOLCANIC eruptions are visual extravaganzas of nature, but at the same time can be extremely dangerous. Volcanic eruptions vary greatly in style and the materials they produce. Large-scale explosive volcanism can affect local weather and at times global climate, and cause widespread destruction of life and property. Therefore, it is necessary to study and understand the eruptive styles and cycles of volcanoes located close to civilizations. For the latter, it is essential to establish the timing of initiation and frequency of large eruptions. Most of the large volcanic activities on the Indian subcontinent happened in its geologic history and many of these were globally catastrophic (e.g. Deccan and Rajmahal-Sylhet Traps).

Volcanisms elsewhere have also affected life on the subcontinent; the best example of such an event is the ~73 ka Toba eruption[1]. Toba, Krakatoa, Tambora and other such dangerous volcanoes are located in Indonesia and form part of a volcanic arc of the convergent plate margin where the Indian plate subducts beneath the Eurasian plate (Figure 1). Further north, the Indian plate subducts obliquely beneath the Burmese microplate, a sliver plate between the Indian and Eurasian plates, along the Andaman Trench, at a rate of 4 cm/yr (ref. 2). The Indonesian Arc continues northwards well into the Andaman Sea, with the Barren Island volcano as its northernmost active centre (Figure 1).

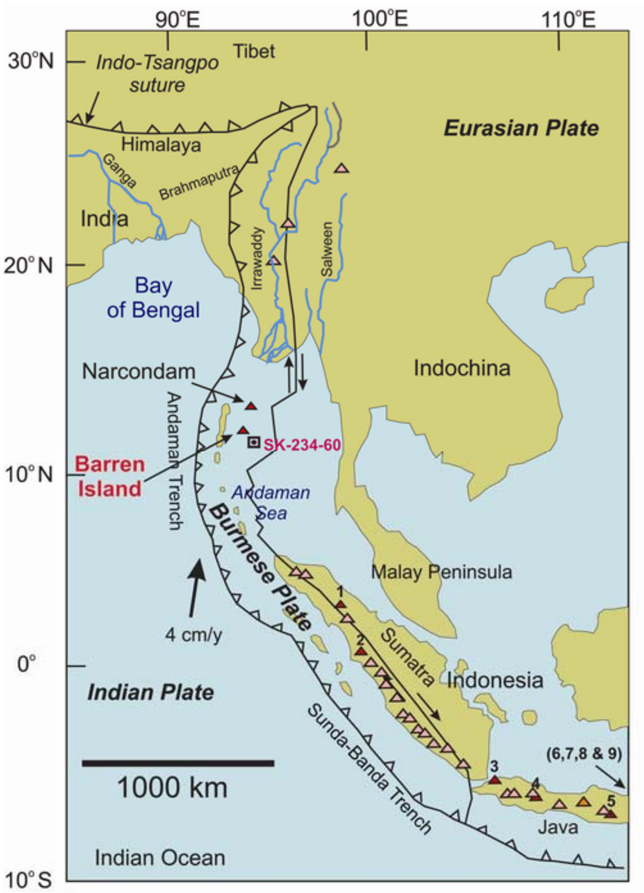

Figure 1. Map of Southeast Asia and Northeast Indian Ocean showing major geological and tectonic features and locations of volcanoes (triangles) of the Indonesia–Andaman volcanic arc. Barren Island and Narcondam are two of these volcanoes in the Andaman Sea. The location of our core[3], SK-234-60, is also marked. The numbered volcanoes are (1) Toba, (2) Sorimerapi, (3) Krakatoa, (4) Galunggung, (5) Merapi, (6) Rinjani, (7) Tambora, (8) Sangeang Api, (9) Iya Flores.

*For correspondence. (e-mail: jsray@prl.res.in)

Barren Island (BI; 12°16′40″N, 93°51′30″E), the lone active volcano of India, is situated ~70 km east of Andaman Islands. It became active in 1991 after 159 years of dormancy, attracting the attention of scientists and general public at large in India and aboard. The volcano has remained active since then, with almost continuous tephra eruptions and produced at least four major lava eruptions[3–5]. Being a stratovolcano, it had in the past and would likely to have in the future massive eruptions that could seriously affect life in the Andaman Sea, Andaman and Nicobar Islands and neighbouring Southeast Asian countries. Tsunamis generated by submarine landslides on the flanks of the volcano can compound the scale of devastation. It is, therefore, necessary that we learn the eruptive history of Barren Island since its formation from any proxy record of its past eruptions. Determining the age of the volcano would elucidate the history of modern volcanism in India and provide information on the evolution in general of the island arc in the Andaman subduction zone. Unfortunately, the oldest lava flows and ash deposits on BI are too young to be suitably dated by long-lived radioisotopic methods[6]. Radiocarbon dating of charcoal fragments derived from burnt vegetation of the island has not yet been attempted. Therefore, Awasthi *et al.*[3] looked at the marine sediment record near the volcano (Figure 1) and dated distinct tephra (ash) layers interbedded with normal ocean sediments in a sediment core and determined that the volcano had seven major ash eruptions at ~70, 69, 61, 24, 19, 15 and 10 ka (Figure 2). This study, however, could not establish the timing of emergence of the volcano either from the seafloor or sea surface. In an effort to shed some light on this issue, we dated two of the oldest ash layers in the above core by ^{40}Ar–^{39}Ar method.

Barren Island volcano

Barren Island is roughly circular with a diameter of ~3.2 km. The volcano rises ~2 km above the seafloor with an average height of 300 m above mean sea level. A cinder cone is located roughly at the centre of a ~1.5 km wide caldera. The circular caldera wall has a breach on the northwestern side, through which most of the historic and recent lavas have flowed into the sea. Bathymetry of the region shows that a large part of the volcano is submarine, suggesting that much of the eruptive history of the volcano is older than the emergent island. Sheth *et al.*[4,5,7] describe volcanological aspects and discuss origin of various structures and deposits of the island. Although earlier workers have characterized the eruptive style of the volcano primarily as Strombolian (rarely sub-Plinian), from the ash dispersal patterns as revealed from the marine sediment core SK234-60, collected ~32 km away from Barren Island (Figures 1 and 2)[3], many of the past eruptions of the volcano can be classified as Plinian. This basically implies that the pyroclastic ejecta of the volcano can get dispersed much farther than previously thought.

The lavas and tephra found on Barren Island are subalkalic basalts and basaltic andesites, with rare andesites[4]. All lavas are porphyritic, with abundant phenocrysts of plagioclase and clinopyroxene in a glassy/microcrystalline groundmass. Many lava flows contain xenocrysts

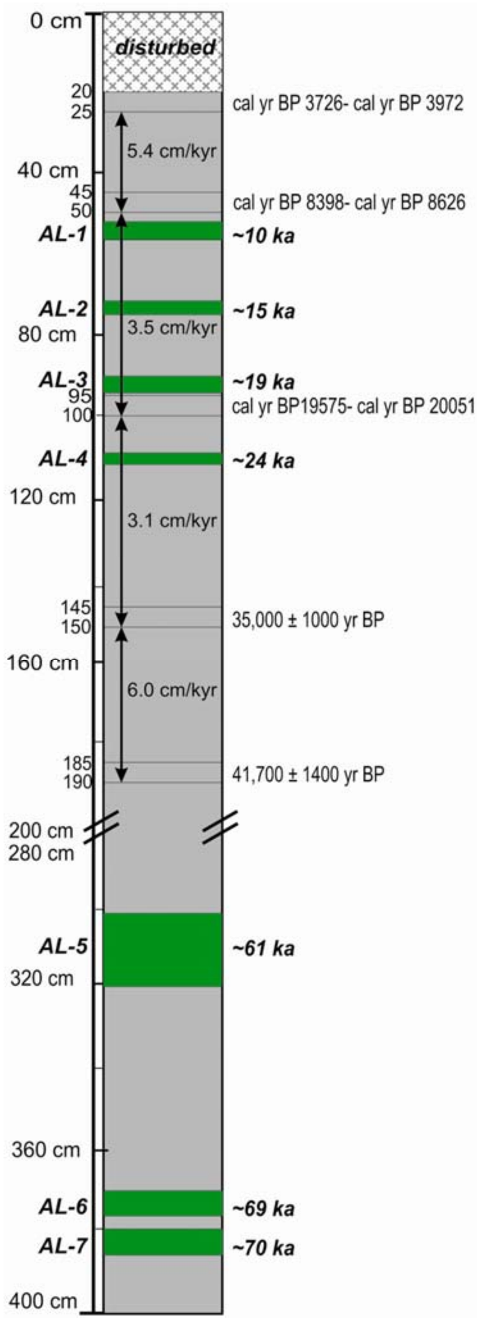

Figure 2. Litholog of core SK-234-60 (12°05′46″N, 94°05′18″E). The top 20 cm of the core is disturbed. Calibrated radiocarbon ages[3] for selected sediment layers are shown. Tephra (ash) layers (AL) are shown in green, numbered and their estimated ages marked. The rates of sedimentation (cm/kyr) between various dated intervals are shown inside the litholog. AL-5 and AL-6 were selected for ^{40}Ar–^{39}Ar dating.

of plagicoclase and pyroxene, possibly derived from gabbro cumulates in a shallow magma chamber. Primitive-mantle normalized trace elemental patterns of these rocks are typical of subduction zone magmas (depleted in Nb and Ta and enriched in Sr and Pb). Sr–Nd–Pb isotopic ratios suggest their derivation from a large-ion-lithophile-element-depleted mantle[8]. The $^{87}Sr/^{86}Sr$ and ε_{Nd} of volcanics on Barren Island vary from 0.70381 to 0.70413 and from 4.1 to 7.4 respectively (Figure 3)[6,8,9]. $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ of these lavas vary between 18.063 and 18.309 and 38.098 and 38.411 respectively[6,8]. Petrological and geochemical characteristics of these volcanics indicate that their mantle source is much less contaminated by subducting material in comparison to that of the more evolved magmas of Narcondam, an extinct volcano located 137 km north of Barren Island[6,10] (Figures 1 and 3).

Barren Island is located on the seafloor segment that lies between the ~20 Ma Alock Rise[11] of magmatic origin and forearc deposits of Invisible Bank of Miocene age (~17 Ma)[11], which implies that the volcano is younger than 17 Ma. An earlier ^{40}Ar–^{39}Ar dating[6] of subaerial lavas of the volcano yielded two ages with very large errors, 33 ± 70 and 32 ± 88 ka respectively. The study by Awasthi *et al.*[3] on the tephra/ash layers in a marine sediment core SK-234-60 (Figure 2) was more successful in determining timings of seven major eruptions of the volcano. These tephra layers (Figure 2) were unequivocally linked to the Barren Island volcano by Nd–Sr isotopic ratio fingerprinting (Figure 3). The ages of the top four tephra layers (AL-1 through AL-4) were determined from radiocarbon ages of sediment bands and rates of sediment deposition between them (Figure 2), with the oldest of them being 24 ka. The ages of the three deeper tephra layers (AL-5, AL-6 and AL-7) were determined indirectly as 61, 69 and 70 ka respectively, by extrapolation from the age of AL-4 and assuming a constant rate of sedimentation below it (i.e. 6 cm/kyr; Figure 2). As such ages are subject to large extrapolation errors, they need to be confirmed by direct and reliable radiometric dating methods. As the ^{40}Ar–^{39}Ar method is capable of measuring such young ages, we dated the plagioclase separates from the tephra layers AL-5 and AL-6. If these grains came from rocks formed during or just prior to their eruption, the measured ages should correspond closely with the depositional ages.

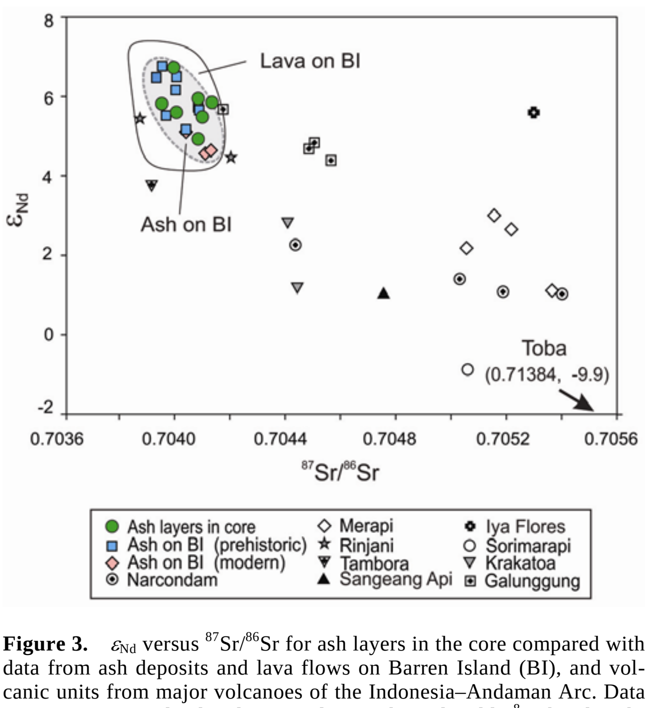

Figure 3. ε_{Nd} versus $^{87}Sr/^{86}Sr$ for ash layers in the core compared with data from ash deposits and lava flows on Barren Island (BI), and volcanic units from major volcanoes of the Indonesia–Andaman Arc. Data sources: Barren Island and Narcondam: Luhr and Haldar[8]; Chandrasekharam *et al.*[9]; Kumar[17]; Streck *et al.*[6] and Indonesian volcanoes: Turner and Foden[18].

Samples and methods

The tephra/ash layers in the core contained grains of glass shard, plagioclase, pyroxene, lithic clasts/fragments and

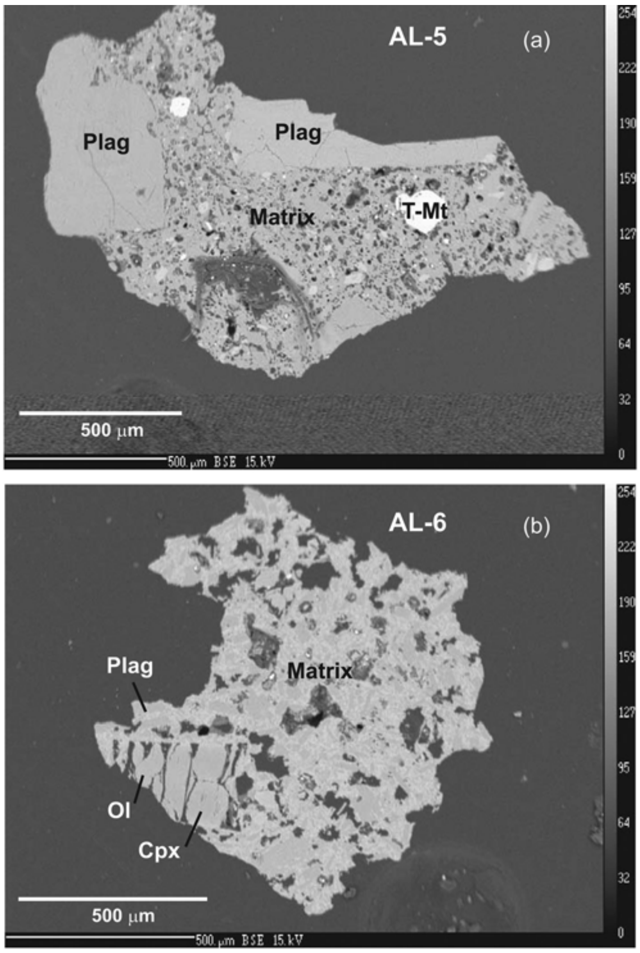

Figure 4. Backscattered X-ray images of typical lithic clasts from AL-5 and AL-6. Mineral grains (phenocrysts) and vesicular matrix are marked. Plag, Plagioclase; T-Mt, Titaniferous magnetite; Ol, Olivine; Cpx, Clino-pyroxene.

Table 1. Summary of results of ^{40}Ar–^{39}Ar dating of plagioclase separates from ash layers from the core SK-234-60

Sample	Plateau			Isochron*			Inverse Isochron*		Integrated age (Ma)
	Steps	^{39}Ar (%)	Age (Ma)	Age (Ma)	Initial ^{40}Ar/^{39}Ar	MSWD	Age (Ma)	MSWD	
AL-5	11	72.1	1.8 ± 0.4	1.9 ± 0.4	295.1 ± 1.7	0.4	1.9 ± 0.3	0.4	3.5 ± 1.2
AL-6	6	52.4	1.5 ± 1.8	1.4 ± 2.5	295.6 ± 2.2	0.02	1.4 ± 2.5	0.1	17.6 ± 1.0

*Isochron and inverse isochron data are only for the plateau steps. Errors are 2σ.
MSWD, Mean square weighted deviation.

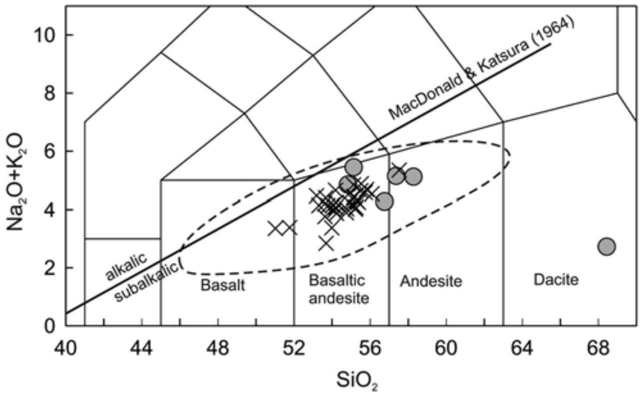

Figure 5. Total alkalis versus silica (wt %) for glass matrices of lithic fragments from AL-5 (grey circle) and AL-6 (cross). The fields are from Le Maitre[19], and the boundary between sub-alkalic and alkalic compositions is from Macdonald and Katsura[20]. Relevant compositional fields are marked. The dashed envelope represents the known composition of Barren Island lavas[8,9,17,21].

rare amphibole. The gain size of these layers was much coarser (>200 μm) than the normal sea sediments (<20 μm) in the core. The grains of AL-5 were the coarsest of all (>1.5 mm). Lithic clasts, which are abundant in the bottom three tephra layers, contain grains of large phenocrysts of plagioclase, clino-pyroxene, olivine and titanomagnetite embedded in vesicular-glassy matrices (Figure 4). Since AL-6 and AL-7 occur very close to each other and have identical isotopic compositions (ε_{Nd} = 5.7 ± 0.1)[3], we consider them to represent a single event and only one of them was selected for dating. Major element analyses, using an Electron Probe Micro Analyser (EPMA), were done on glass matrices of several lithic fragments to characterize these ash layers. Results of these analyses reveal that the lithic clasts in AL-5 came from highly evolved magmas, whereas those in AL-6 were derived from comparatively less evolved magmas, and most samples are compositionally similar to the lava flows exposed on the island (Figure 5).

For the purpose of dating we picked pure plagioclase grains from these ash layers using the standard mineral separation technique[12]. About 200 mg of plagioclase separates (grain size > 250 μm) from each of AL-5 and AL-6 were picked, cleaned with dilute HCl and deionized water and packed in aluminium capsules for neutron irradiation in the DHRUVA reactor at the Bhabha Atomic Research Centre (BARC), Mumbai, for ~120 h. The samples were coirradiated with the 523.1 ± 2.6 Ma old Minnesota hornblende standard (MMhb-1) as the flux monitor[13], and high purity CaF_2 and K_2SO_4 salts for interference corrections arising from production of Ar from Ca and K isotopes. Argon was extracted by incremental heating between 500°C and 1350°C at steps of 50°C. After removal of reactive gases using Ti–Zr getters, the argon released in each step was analysed for isotopic ratios in a Thermo Fisher ARGUSVI multi-collector mass spectrometer at the National Facility in the Department of Earth Sciences, IIT Bombay. Fluence-corrected *J*-values (based on high-purity Ni wares irradiated with the samples and the monitor) for AL-5 and AL-6 respectively, are 0.001746 ± 0.000007 and 0.001512 ± 0.000006 (2σ). Plateau and isochron ages were calculated and plotted using the program ISOPLOT 2.49 (ref. 14). We define a plateau age as the weighted mean of ages of contiguous, concordant steps comprising >50% of the total ^{39}Ar released. The isochron age is calculated from the slope of collinear step compositions, of plateau steps, plotted in a ^{40}Ar/^{36}Ar versus ^{39}Ar/^{36}Ar correlation diagram. A reliable sample crystallization age is concluded if the plateau and isochron ages are concordant within analytical uncertainty, and indicate no significant presence of mantle or deep crust-derived ('excess') Ar. Plateau age is usually more precise and hence preferred. Sen *et al.*[15] give a detailed description of the new ^{40}Ar–^{39}Ar facility used in this work.

Results and discussion

Table 1 summarizes ^{40}Ar–^{39}Ar dating results and Figure 6 shows the argon release age spectra. The plagioclase separate from AL-5 yields an 11-step (500–1000°C) plateau age of 1.8 ± 0.4 Ma with 72.1% of ^{39}Ar released and that from AL-6 a six-step (600–850°C) plateau age of 1.5 ± 1.8 Ma with only 52.4% of 39Ar released. We consider the age of AL-5 as analytically sound in view of its higher precision and acceptable MSWD on isochrons. Poorer precision on the age of AL-6 and unrealistically low MSWD on its isochrons are a result of overestimation of errors associated with extremely low contribution of radiogenic ^{40}Ar (<0.5%) in individual plateau steps. Unlike AL-5 data, the higher temperature steps (900–

1350°C) for AL-6 contain a significant amount of excess argon with an average trapped (initial) $^{40}Ar/^{36}Ar$ of 321 and have higher apparent ages (Figure 6 *b*).

The most plausible interpretation of the 1.8 Ma age of AL-5 is that it represents the time of crystallization of the plagioclase grains. As this age is much older than the conceivable age of their deposition in the ocean (~61 ka), we infer that these grains came from rocks of 1.8 Ma present along the magma feeding system of this stratovolcano. Such a conclusion is well in accord with the observation that pyroclastic deposits often contain materials torn from the walls of the dike and vent system feeding the eruption, apart from juvenile grains[16]. The implication of this finding is that Barren Island contains volcanic rocks that are at least as old as 1.8 Ma; hence this age provides a minimum time constraint for the formation of the volcano.

The presence of non-atmospheric initial $^{40}Ar/^{36}Ar$ in most temperature steps in AL-6 suggests that a majority of these plagioclase grains had crystallized in much deeper part of the magma plumbing system – possibly inside the crust. The lithic clasts that contain these plagioclases are smaller and less vesicular than those found

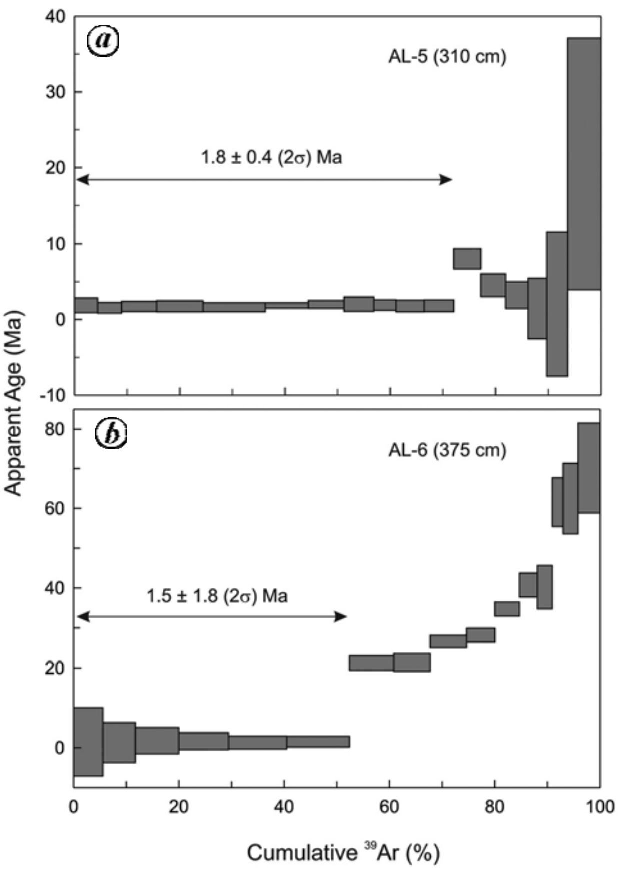

Figure 6. Step-heating $^{40}Ar–^{39}Ar$ apparent age spectra for plagioclase separates from (***a***) AL-5 and (***b***) AL-6. Plateau ages, which are the weighted means of contiguous, concordant step ages comprising >50% of the total gas released, are indicated. Box heights and errors on ages are at 2σ. Relevant data are given in Table 1.

in other tephra layers, suggesting their derivation during a low explosive eruption of the volcano. The lithic clasts of AL-5, on the other hand, with their atmospheric initial $^{40}Ar/^{36}Ar$ apparently were derived from that part of the volcano which was already above the seafloor. Considering that AL-5 is the thickest layer of all and contains the largest of grains that are highly vesicular in nature, we infer that it formed during an explosive subaerial eruption of the volcano. This means that Barren Island was already subaerial at 61 ka.

Conclusions

The tephra layers in a 400-cm long sediment core raised from the Andaman Sea are unequivocally linked to sporadic pyroclastic eruptions of the Barren Island volcano located ~32 km to the northwest. As the bottom layers were deposited at a time beyond the range of radiocarbon dating, they were dated by $^{40}Ar–^{39}Ar$ method in the newly established modern $^{40}Ar–^{39}Ar$ dating facility in India. Reliable $^{40}Ar–^{39}Ar$ age of 1.8 ± 0.4 Ma for plagioclase grains separated from the tephra layer at a depth of 310 cm is surprisingly very much older than its conceivable depositional age of 61 ka. The most plausible interpretation of this old age is that it represents very old magmatic rocks present in the plumbing system of the volcano. This in turn implies that the volcano is at least 1.8 million years old.

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