Origin of the Mile Tilek Tuff, South Andaman: evidence from $^{40}Ar–^{39}Ar$ chronology and geochemistry

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The Mile Tilek Tuff is one of several consolidated volcanic ash deposits in the Andaman and Nicobar Islands that has preserved evidence of a large-scale volcanic eruption in Southeast Asia. Assumed to be of Mio–Pliocene age (~25–2 Ma), the tuff was thought to have been generated by the Andaman–Indonesia volcanic arc. Little was known about its source volcano because of absence of critical isotope data. To provide accurate age information and determine its source, we dated the tuff by $^{40}Ar–^{39}Ar$ method and measured its trace element contents and Sr–Nd isotopic ratios. The $^{40}Ar–^{39}Ar$ plateau age for the whole rock is 0.73 ± 0.16 (2σ) Ma, which suggests that the tuff got deposited much later than previously believed. Chemically, the tuff possesses typical characteristics of subduction zone magmatism. Its Sr–Nd isotopic compositions ($^{87}Sr/^{86}Sr = 0.7073$ and $\varepsilon_{Nd} \leq 0.9$) suggest substantial continental crustal contamination of its source magma, which points to a source volcano in Sumatra. Based on available age information on large-scale volcanic eruptions in Indonesia, we speculate that the Ranau volcano in south Sumatra could have been the source of the Mile Tilek Tuff.

Keywords: $^{40}Ar–^{39}Ar$ dating, geochemical fingerprinting, Mile Tilek Tuff, Sumatra.

Introduction

TUFFS are rocks formed as a result of consolidation of tephra/ash deposits of volcanic origin. Classified as sedimentary rocks, tuffs can be extremely useful in dating sedimentary sequences and thus help link geological, palaeoenvironmental and archaeological events. Good examples of such studies in Indian geology/archaeology come from the dating of the Porcellanite Formation of the Vindhyan Supergroup of the Proterozoic[1] and the linking of ~75 kyr old widespread ash deposits in India to the youngest explosive eruption of the Toba volcano in Sumatra[2]. The former settled longstanding controversies on stratigraphic position of the Vindhyan Supergroup and age of its fossil record, whereas the latter could establish a clear link between near extinction of human species to catastrophic changes in climate resulting from a massive eruption of Toba volcano of Indonesia. Considering that geochronological information in many of the sedimentary sequences of India is limited, it may be worthwhile to look for tuff horizons that could be dated using isotopic methods for absolute chronology. In addition, determining the sources of such tuffs through geochemical fingerprinting can provide valuable information on scales of volcanism and their effects on regional/global environment and climate. To test the efficacy of such a proposal we established chronology by $^{40}Ar–^{39}Ar$ dating and determined the possible source using geochemical and isotopic signatures of a tuff horizon in the Andaman and Nicobar Islands, which is located near some of the most explosive and dangerous volcanoes of Indonesia and the world.

The geology of the Andaman and Nicobar Islands of India is different from that of mainland India because of the tectonic setting, an active subduction zone, in which they occur. As a result of subduction related tectonic activities, diverse and spectacular landforms have been generated on these islands, including an active subaerial volcano. Most of these islands form part of an accretionary prism, located at the boundary between the obliquely subducting Indian Plate and the overriding Burma Microplate (Figure 1 *a*). Although it is believed that subduction along the western boundary of Southeast Asia got initiated more than 160 million years ago[3], the present configuration came into existence only ~4 m.y. ago with the opening of the Andaman Sea along the Central Andaman Ridge and the creation of the Burma Microplate[4]. The volcanic islands of Narcondam, an extinct volcano, and Barren Island, the only active volcano in India, occupy the northern end of the volcanic arc that runs parallel to the accretionary prism. The southern end of the volcanic arc is located in Sumatra and contains 34 volcanoes. The same chain of volcanoes extends further east into other islands of Indonesia as part of a separate volcanic arc linked to the subduction of Indian Plate beneath the Eurasia Plate. About 80% of these volcanoes are either active or have had eruptions in the Holocene[5].

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Available literature on these arcs suggests that many of these volcanoes had large eruptions during the Pleistocene and earlier[5]. Like subduction zone volcanoes elsewhere, those in this region are stratovolcanoes and their style of eruption is usually explosive in nature – during which they pump large quantities of tephra high into the atmosphere, causing dispersal of ejecta over long distances. The ocean basins of the region, including the northeastern Indian Ocean must therefore possess records of large-scale volcanic eruptions of Indonesia in their sediment pile. The sedimentary sequences present on the Andaman and Nicobar accretionary prism, which are currently exposed on top of the thrusted oceanic crustal blocks, are also expected to preserve such records as tuffs. Indeed, tuff beds have been reported from various islands of the Andamans[6–8], however, knowledge about their ages and sources remains highly speculative. Bedded tuff at Mile Tilek, South Andaman is one such tuff deposit, which because of its presence close to the top of the stratigraphic sequence, is likely to yield information on the volcanic activities in the region during or immediately prior to the latest thrusting event in the accretionary prism.

Geology

A large part of the Andaman and Nicobar Islands is inaccessible and chronological information on rock sequences that form the core of the islands is meagre. Therefore, complete understanding of their geology and stratigraphy is still lacking. The currently accepted stratigraphy is fairly simple; it comprises of four units or groups, which in ascending chronological order are: (1) the Ophiolite Group belonging to the Cretaceous, (2) the Eocene Mithakhari Group, (3) the Oligocene Andaman Flysch Group and (4) the Mio–Pliocene Archipelago Group (Figures 1 *b* and 2 *a*)[9,10]. Following the suggestion of Curray[4], we advocate that there is a need to add a new group, which should include Pliocene to Recent mudstones, limestones, coral reefs, tuffs, island arc lava and ash sequences, beach deposits, etc. at the very top in the stratigraphy (Figure 2 *a*). The Ophiolite Group forms the basement of these islands and contains thrusted blocks of supra-subduction zone ophiolite complexes and pelagic sediments such as chert, limestone and shale. A couple of recent studies, based on U–Pb zircon dating of plagiogranites have suggested that these ophiolites could be at least 94 m.y. old[11,12]. The Mithakhari Group rocks, comprising polymict conglomerate, sandstone and shale, are identified as trench-slope deposits that received materials derived from a volcanic arc and/or thrusted ophiolites of the overriding plate[13]. The rocks of the Andaman Flysch and Archipelago groups represent siliciclastic and carbonate turbidites respectively, deposited in a forearc basin. The siliciclastic turbidites of the Andaman Flysch Group not only contain sediments derived from local sources, but also have a significant contribution from distal continental sources[13]. Although biostratigraphic age constraints (Figure 2 *a*) suggest that the deposition of the Archipelago Group ceased sometime during the Miocene, some believe that it could have continued well into the Pliocene or beyond[7].

All known tuff formations on the main chain of the Andaman Islands and on Havelock Islands are believed to belong to the Archipelago Group[7,9]. However, absence of age data and lack of proper correlation with other formations in the group make accurate stratigraphic placement of these tuffs difficult. In the absence of ample geochemical and isotopic data it has been difficult to predict the nature of their source(s). These tuff horizons are known from three localities in the Andamans: the Hubdeypur–Mile Tilek sector of South Andaman, the Krishnanagar–Shyamnagar area of Havelock Island and the north-eastern Rutland Island[7,8]. Pal *et al.*[7,8] provide some details of the outcrop patterns, petrography and major/trace element geochemistry of these tuffs – some of which are discussed below. From the Hubdeypur–Mile Tilek sector two different types of tuffs have been reported – a massive-bedded white/pink tuff and a well-sorted green tuff. The former is believed to have been deposited rapidly from a sub-aqueous debris flow, whereas the latter is a turbidite. The major minerals present are quartz, plagioclase, alkali feldspar, mica, analcime and

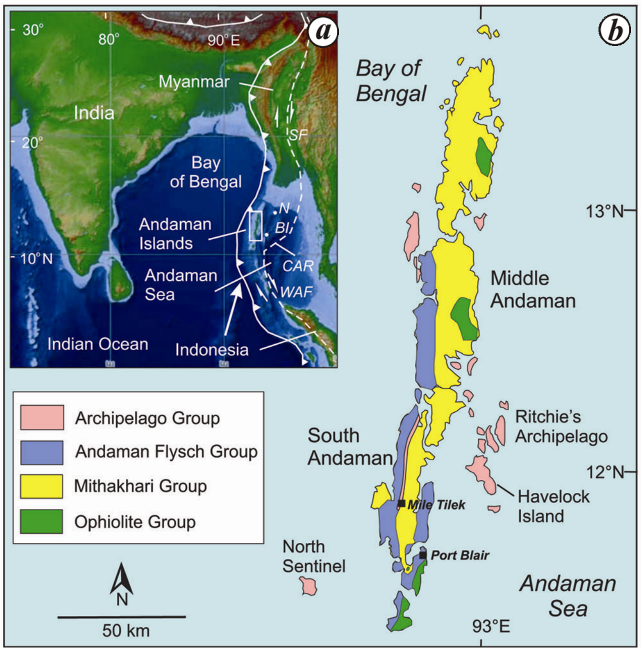

Figure 1. Geological map of the Andaman Islands (after Pal *et al.*[9]) showing distribution of various lithological rock units. Location of the sampled horizon of the Mile Tilek Tuff is marked. (Inset) Location of the islands in Southeast Asia, the Andaman–Sumatran subduction zone, Central Andaman Ridge (CAR) and major faults in the region. Arrow shows the directions of motion of the Indian plate. N, Narcondam; BI, Barren Island; SF, Sagaing Fault; WAF, West Andaman Fault.

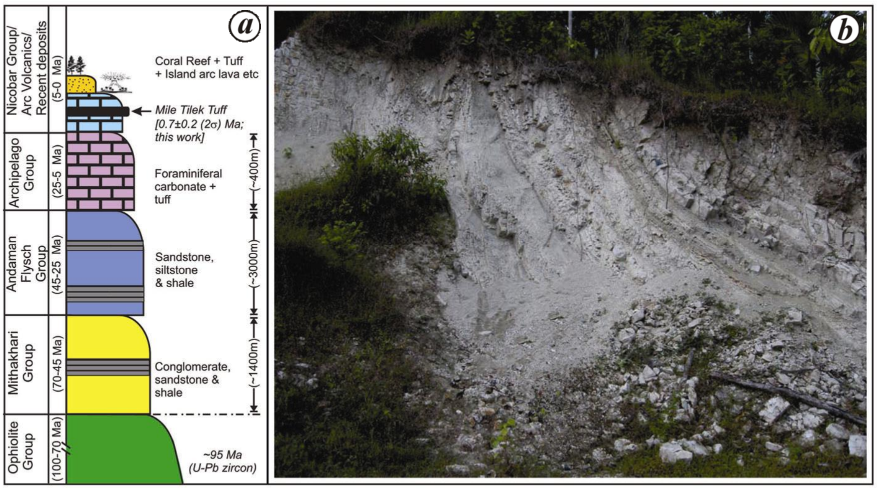

Figure 2. ***a***, Schematic of a simplified stratigraphic log of the Andaman and Nicobar Islands (modified after Curray[4]) showing the position of the Mile Tilek Tuff marked. The age brackets given on the left are approximate and based on biostratigraphy. ***b***, Photograph of the tuff horizon at Mile Tilek.

clinoptilolite, where the last two minerals being alteration products of volcanic glass. They do not contain any lithic fragments. SiO_2 content varies from 66 to 75 wt% and compositionally these are andesites, dacites and rhyolites. They possess abnormally high amounts of Sr and Ba, and show lighter rare earth (LREE)-enriched chondrite-normalized trace element patterns with negative Eu anomalies. Pal *et al.*[7,8] speculated they are of Mio–Pliocene age and have been derived from felsic volcanism in the Andaman–Sumatra volcanic arc.

Sample and methods

For our study we collected samples of white to pink and green tuffs from two outcrops in Mile Tilek along the Andaman Trunk Road (NH 223). The white tuffs (11.798N; 92.653E) showing a thickness >40 m are bedded. The beds dip north and are heavily jointed (Figure 2 *b*). The green tuffs are exposed ~1.5 km south of the previous outcrop (11.783N; 92.654E). These are relatively coarser in grain size and quartz-rich and show thin laminations in hand specimen. Both the tuffs are devoid of carbonate minerals. There exists no field evidence to suggest that these tuff beds are reworked deposits of some earlier tephra. A sample of the green tuff was selected for $^{40}Ar–^{39}Ar$ dating and both green and white tuffs were analysed for trace element contents and Sr–Nd isotopic compositions. Dating was done at IIT Bombay and the chemical analyses were performed at PRL, Ahmedabad.

About 200 mg of pre-cleaned whole-rock powder (grain size > 250 μm) was packed in aluminum capsules and irradiated in the DHRUVA reactor at BARC, Mumbai, for ~120 h. The 17.3 ± 0.2 Ma B4B biotite[14] was used as the flux monitor and high-purity CaF_2 and K_2SO_4 salts for interference corrections arising from the production of Ar from Ca and K isotopes. Argon was extracted by incremental heating between 750°C and 1400°C at steps of 50°C and isotopic ratios were measured in a Thermo Fisher ARGUS-VI multi-collector mass spectrometer at the National Facility in the Department of Earth Sciences, IIT Bombay[15]. Fluence-corrected *J*-value for the sample is 0.00142929 ± 0.00004359 (2σ). Plateau and isochron ages were calculated and plotted using the software ISOPLOT 2.49. Trace element contents in two whole-rock samples (AND-11-54W and AND-54G) were determined using a quadruple-inductively coupled plasma mass spectrometer (Q-ICPMS) and their Sr–Nd isotopic ratios were measured on a thermal ionization mass spectrometer (TIMS). Details of the experimental procedures for isotopic/trace element analyses are given in Ray *et al.*[16]. BHVO-2, NBS-987 and JNdi-1 international standards were used for accuracy checks (Table 1).

Results and discussion

The results of $^{40}Ar–^{39}Ar$ dating are presented in form of apparent age spectrum isochron diagram in Figure 3. The green tuff yielded an 8-step (850–1200°C) plateau age of 0.73 ± 0.16 (2σ) Ma with 69% of ^{39}Ar released (Figure 3 *a*). The isochron age is 0.68 ± 0.39 (2σ) Ma that essentially overlaps with the plateau age and trapped (initial) argon composition is atmospheric (Figure 3 *b*). Plateau age is more precise and hence, it is considered to represent the age of crystallization of the volcanic materials that make up the tuff. The higher temperature steps (1250–1400°C) show a staircase pattern with the highest temperature step giving an apparent age of ~60 Ma, which we infer to be a result of the presence of older magmatic components in the tephra. Since direct deposition of volcanic ash or tephra, either through air or water, is a rapid process compared to normal rate of sedimentation

Table 1. Geochemical and isotopic data for Mile Tilek Tuff, South Andaman

Sample	AND-11-54(G)	AND-11-54(W)	Mithakhari* (Average ± 1σ)	Andaman Flysch* (Average ± 1σ)	BHVO-2 (m)	BHVO-2$^\$$ (r)
Cs	1.90	2.02	2.64 ± 1.68	4.31 ± 1.43	0.11	0.11
Rb	30.9	48.8	41.5 ± 27.0	91.3 ± 17.1	10.6	10.1
Ba	1750	960	174 ± 132	295 ± 41	133	128
Th	9.7	11.9	4.9 ± 2.6	14.3 ± 7.1	1.2	1.2
U	2.34	3.07	1 ± 0	2 ± 1	0.45	0.44
Nb	3	4	5 ± 2	9 ± 2	17	16
Ta	0.39	0.36	0.3 ± 0.1	0.7 ± 0.2	0.96	0.94
La	26	21	18 ± 7	39 ± 15	15	15
Ce	54	41	38 ± 12	85 ± 33	39	38
Pb	17.9	16.3	10.6 ± 2.7	14.4 ± 4.3	1.5	1.4
Pr	6.2	4.3	5.1 ± 2.2	9.4 ± 3.3	5.5	5.4
Sr	969	487	96 ± 49	80 ± 32	413	382
Nd	22	14	21 ± 10	35 ± 12	25	24
Zr	52	73	45 ± 33	22 ± 10	146	160
Hf	2.3	2.7	1.7 ± 0.9	0.9 ± 0.3	4.2	4.1
Sm	4.7	2.5	4.8 ± 2.8	6.7 ± 2	6.2	6.0
Eu	1.1	0.7	1.3 ± 0.9	1.3 ± 0.3	2.1	2.0
Gd	4.66	2.31	4.80 ± 2.96	5.74 ± 1.55	6.4	6.2
Tb	0.7	0.3	0.7 ± 0.5	0.7 ± 0.2	0.88	0.86
Dy	4.6	2.0	4.2 ± 3.1	3.6 ± 1.0	5.5	5.3
Y	21.3	10.8	18.7 ± 16.1	14.6 ± 5.8	23.6	23.0
Ho	0.85	0.41	0.77 ± 0.55	0.60 ± 0.16	0.94	0.91
Er	2.5	1.4	2.3 ± 1.6	1.7 ± 0.5	2.6	2.6
Tm	0.3	0.2	0.3 ± 0.2	0.2 ± 0.1	0.3	0.3
Yb	2.1	1.6	2.0 ± 1.3	1.4 ± 0.4	2.0	2.0
Lu	0.29	0.28	0.29 ± 0.20	0.19 ± 0.06	0.28	0.27
Sc	3.8	5.9	11.4 ± 5.9	8.6 ± 3.3	32.1	31.0
V	5	20	73 ± 33	61 ± 22	353	329
Cr	2	8	60 ± 43	59 ± 30	289	285
Co	65	51	12 ± 6	56 ± 88	49	47
Ni	4	13	67 ± 56	46 ± 18	117	112
$^{87}Sr/^{86}Sr$	0.70916	0.70725	0.708 ± 3	0.722 ± 5	0.70345	0.70344
$^{143}Nd/^{144}Nd$	0.512606	0.512683	0.5126 ± 2	0.51207 ± 6	0.512949	0.512957
$\varepsilon_{Nd}(0)$	−0.6	0.9				

Element concentrations are in ppm. G and W respectively, stand for green tuff and white tuff. *Average compositions for two sedimentary groups of the Andamans are from Awasthi[13]. The last two columns present measured (m) and reported (r) values of trace element concentrations and isotopic ratios in USGS rock standard BHVO-2, analysed as an unknown. Reproducibility of trace element contents, based on the repeated analyses of the standard, was ≤ 5% for REE and ≤ 10% for all other trace elements at 2σ level. $Data from refs 23–25. Analytical methods are discussed in Ray *et al.*[16]. The average values for NBS 987 Sr and JNdi-1 Nd standards analysed over a period of 4 years at PRL, Ahmedabad respectively, are $^{87}Sr/^{86}Sr = 0.710234 \pm 0.000008$ and $^{143}Nd/^{144}Nd = 0.512104 \pm 0.000004$ (± 0.1 in ε_{Nd} units) at 2σ level of uncertainty.

(e.g. ~3–11 cm/ky in the Andaman Sea[17]), the entire >40 m of tuff horizon at Mile Tilek can be considered to have been deposited at 0.73 Ma and represents a single eruption of a volcano. This newly determined age for the Mile Tilek Tuff calls for a revision of its position in the stratigraphy of the Andamans. It should now be included in the topmost group and not in the Archipelago Group (Figure 2 *a*).

The trace element concentration and Sr–Nd isotopic ratio data are presented in Table 1 and plotted in Figure 4. The geochemical and isotopic data for the Mile Tilek Tuff samples show the following features: (1) typical volcanic arc-type primitive mantle-normalized trace element patterns (e.g. negative anomalies of Nb and Ta and positive anomalies of Ba, Sr and Pb; Figure 4 *a*), (2) abnormally high Ba and Sr contents (Table 1); (3) enriched LREE patterns (not shown), with a small negative Eu anomaly in the green tuff; (4) higher large ion lithophile element (LILE) contents compared to that in the lavas of Barren Island or Narcondam, but similar to lower heavy rare earth element (HREE) contents (Figure 4 *a*); (5) very different trace element contents/patterns than that of the oldest and the youngest Toba tuffs (Figure 4 *a* and *b*); (6) isotopically different than the lava/tephra of Barren Island and Narcondam and the Indonesian volcanoes for which isotopic data are available (Figure 4 *b*). Although the tuff is certainly derived from a volcano within the Andaman–Indonesia subduction zone, its unusual chemistry, particularly the high Sr and Ba contents coupled with strongly radiogenic $^{87}Sr/^{86}Sr$ (0.707–0.709), makes the determination of the source difficult. Post-depositional alteration of $^{87}Sr/^{86}Sr$ is ruled out because the high concentration of Sr (480–2657 ppm; Table 1 and Pal *et al.*[7]) would have buffered it against alteration. Assuming that this tuff originally came from either Barren Island or Narcondam and got mixed with the sediments having higher $^{87}Sr/^{86}Sr$ or lower ε_{Nd} (e.g. the Mithakhari/ Andaman Flysch sediments) during deposition, one can explain its observed isotopic compositions; however, such a mixing cannot generate the observed concentration of most of the trace elements (Table 1). The same arguments would remain valid for ruling out the possibility of Toba being the source volcano (Figure 4).

Available chronological information on volcanic eruptions in the Andaman–Indonesia arc reveals that there were two major eruptions in the region that fall in the 2σ age range of the Mile Tilek Tuff, viz. 0.84 ± 0.30 Ma Oldest Toba Tuff (OTT)[18] and the 0.55 ± 0.15 Ma Ranau Tuff[19] of Sumatra. Also several 0.7 Ma old lava flows have been reported from Narcondam[20]. However, as discussed above, these are chemically different from the Mile Tilek Tuff. Absence of lithic fragments in these tuffs[7], which suggests a long distance transport, also rules out Narcondam as the source. The higher $^{87}Sr/^{86}Sr$ (0.7073–0.7092) and lower ε_{Nd} (–0.6 to 0.9) of the Mile Tilek Tuff, than normal mantle wedge compositions in the region (as observed in lavas of Barren Island or Narcondam, Figure 4 *b*), suggest that the source magma was contaminated by continental crust ($^{87}Sr/^{86}Sr > 0.710$; $\varepsilon_{Nd} < -8.0$)[21,22]. This would mean that the source volcano was located on a continental crust and therefore, one of the Sumatran volcanoes is the most likely candidate. Interestingly, both OTT and Ranau Tuff are widespread tephra and had originated from large eruptions of two super volcanoes. The slightly older age for OTT and more enriched trace element pattern (and different isotopic compositions; Figure 4 *b*) make it an unlikely source. Although the above reported age for the Ranau Tuff, by Bellier *et al.*[19] on feldspar is younger than that of the Mile Tilek Tuff, the whole-rock age of 0.73 ± 0.13 Ma of the tuff and the timing of collapse of the caldera of the Ranau volcano (0.7 Ma) are contemporaneous with the deposition of the Mile Tilek Tuff, which point towards a possible genetic link between the Mile Tilek and Ranau tuffs. However, in the absence

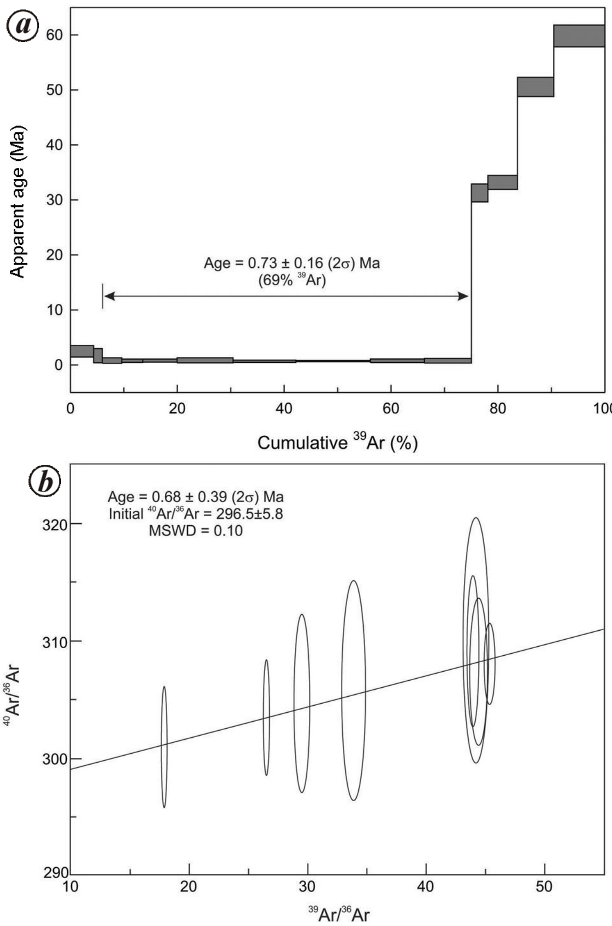

Figure 3. Plot of step-heating $^{40}Ar–^{39}Ar$ apparent age spectrum (***a***) and isochron (***b***) for a whole-rock sample (AND-11-54G) from the Mile Tilek Tuff Formation. The plateau age, calculated as the weighted mean of ages for nine contiguous and concordant steps, comprising 69% of the total ^{39}Ar released, is indicated in (***a***). The isochron in (***b***) is drawn only on the plateau steps. Box heights in (***a***), error ellipses in (***b***), and errors on calculated ages and intercept are 2σ.

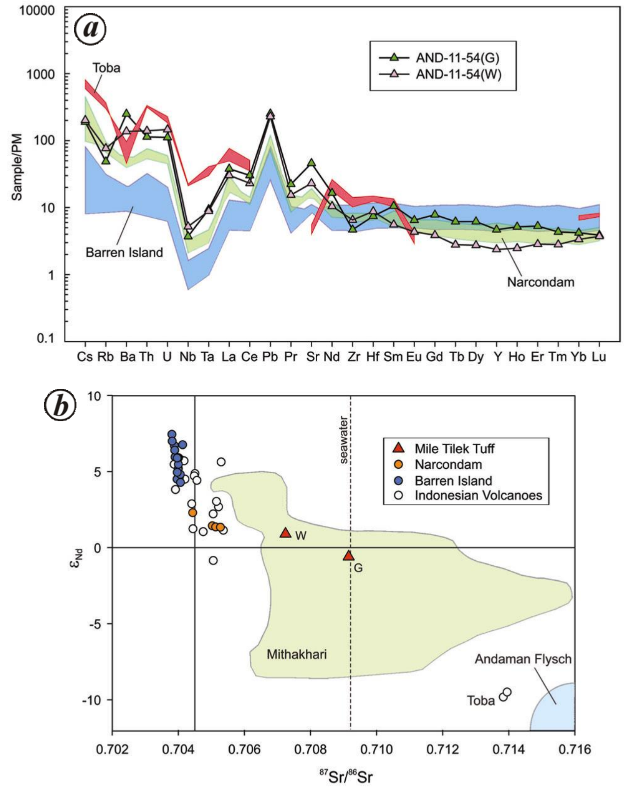

Figure 4. ***a***, Primitive-mantle normalized incompatible element patterns of two tuff samples, compared with average composition of lava flows of Barren Island and Narcodam and ash derived from Toba in Sumatra. ***b***, Plot of ε_{Nd} versus $^{87}Sr/^{86}Sr$ for the Mile Tilek Tuff samples (G, Green Tuff; W, White Tuff), lava flows and ash deposits of Barren Island, Narcondam and Indonesian volcanoes including Toba. Also shown are the fields for the turbidite deposits (the Mithakhari and Andaman Flysch groups) of the Andamans. Data sources: Barren Island and Narcondam: Refs 20, 26 and 27; Indonesian volcanoes: Ref. 28; Mithakhari and Andaman Flysh deposits: Ref. 13.

of chemical and isotopic data, it is difficult to confirm this.

Conclusions

An ~40 m thick bedded tuff deposit located at Mile Tilek, South Andaman has been dated by ^{40}Ar–^{39}Ar incremental heating method and studied for its geochemical and Sr–Nd isotopic characteristics. Based on the ^{40}Ar–^{39}Ar plateau age of 0.73 ± 0.16 Ma for a whole-rock sample we propose an upward revision of the position of the tuff, from its earlier position within the Archipelago Group, into the Nicobar Group. Although this dacitic–rhyolitic tuff is chemically heterogeneous, its average composition is unequivocally similar to island arc lavas and suggests that its parental magma had assimilated continental crustal material – which points to a source volcano in Sumatra. Based on geochronological and geochemical fingerprinting, we propose that the tephra deposited as Mile Tilek Tuff in the Andamans was generated during a large-scale eruption of the Ranau volcano in Sumatra.

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