Eruptive history of Earth's largest Quaternary caldera (Toba, Indonesia) clarified

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ABSTRACT

Single-grain laser-fusion $^{40}Ar/^{39}Ar$ analyses of individual sanidine phenocrysts from the two youngest Toba (Indonesia) tuffs yield mean ages of 73 ±4 and 501 ±5 ka. In addition, glass shards from Toba ash deposited in Malaysia were dated at 68 ±7 ka by the isothermal plateau fission-track technique. These new determinations, in conjunction with previous ages for the two oldest tuffs at Toba, establish the chronology of four eruptive events from the Toba caldera complex over the past 1.2 m.y. Ash-flow tuffs were erupted from the complex every 0.34 to 0.43 m.y., culminating with the enormous (2500–3000 km^3) Youngest Toba tuff eruption, caldera formation, and subsequent resurgence of Samosir Island. Timing of this last eruption at Toba is coincident with the early Wisconsin glacial advance. The high-precision $^{40}Ar/^{39}Ar$ age for an eruption of such magnitude may provide an important marker horizon useful as a baseline for research and modeling of the worldwide climatic impact of exceptionally large explosive eruptions.

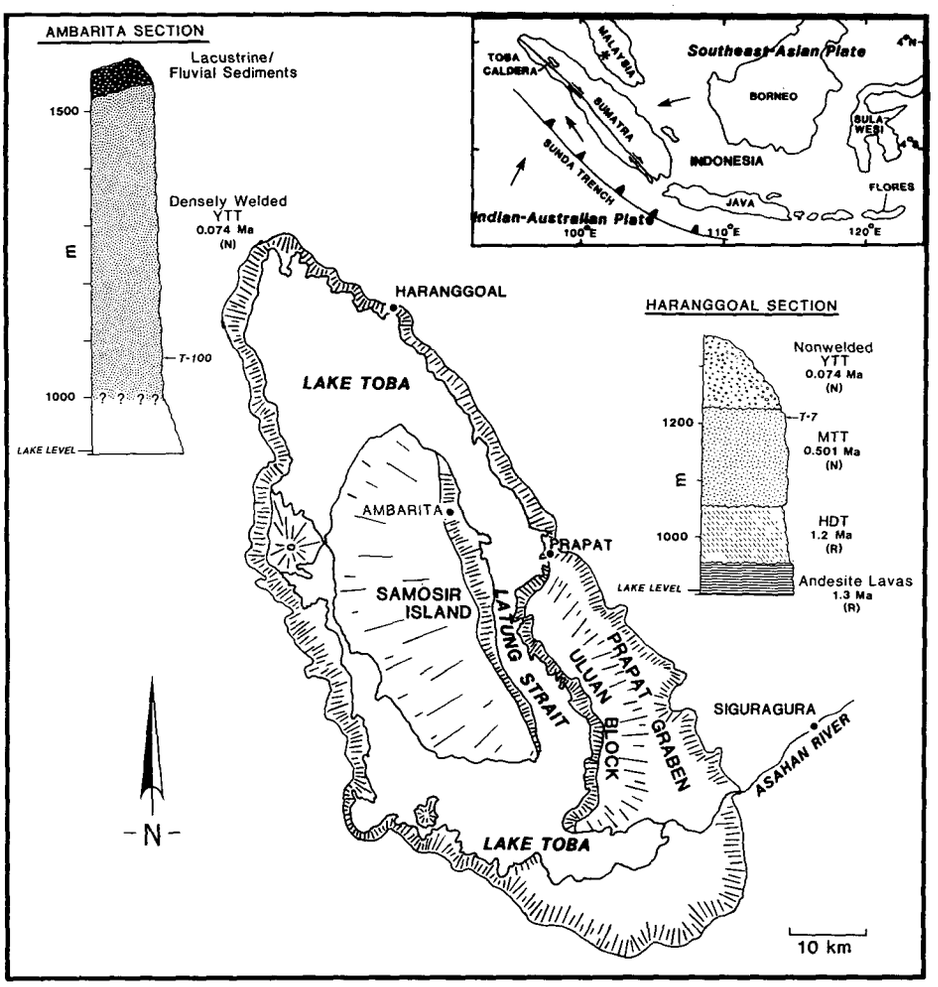

Figure 1. Tectonic setting and location maps of Toba caldera complex. Samples dated by $^{40}Ar/^{39}Ar$ technique were collected near Haranggoal and Ambarita; stratigraphic positions are indicated on corresponding columns. YTT = Youngest Toba tuff; MTT = Middle Toba tuff; HDT = Haranggoal Dacite tuff; R = reverse polarity; N = normal polarity. Malaysian ash sampling site (*) indicated on inset map.

INTRODUCTION

The Toba caldera complex in northern Sumatra, Indonesia, consists of four overlapping calderas that parallel the Sumatran volcanic front (Chesner and Rose, unpublished) (Fig. 1). The youngest caldera is the world's largest Quaternary caldera (100 × 30 km; Smith and Bailey, 1968) and envelops the three older calderas. An estimated 2500–3000 km^3 of dense-rock-equivalent pyroclastic material, termed the Youngest Toba tuff, was erupted from the youngest caldera during one of the largest single volcanic eruptions in geologic history (Rose and Chesner, 1987). Following the Youngest Toba tuff eruption, a classical resurgent dome formed within the caldera, consisting of two half-domes separated by a longitudinal graben (Van Bemmelen, 1949; Smith and Bailey, 1968) (Fig. 1).

Samples of both welded and nonwelded Youngest Toba tuff from the outflow sheet have K-Ar dates of 75 ±12 ka on biotite and 74 ±3 ka on sanidine (Ninkovich et al., 1978a). A deep-sea ash layer in the Indian Ocean, geochemically correlated with the Youngest Toba tuff (Ninkovich et al., 1978a, 1978b; Ninkovich, 1979; Rose and Chesner, 1987) has an oxygen-isotope–biostratigraphic age of 75 ka (Ninkovich et al., 1978a). No previous isotopic ages have been reported for the Middle Toba tuff. The Oldest Toba tuff has an $^{40}Ar/^{39}Ar$ age on sanidine of 840 ±30 ka (Diehl et al., 1987). The first tuff erupted at Toba, the Haranggoal Dacite tuff, has a zircon fission-track age of 1.20 ±0.16 Ma (Nishimura et al., 1977).

An ash horizon in Malaysia, up to 90 cm thick, has been described at several localities and genetically linked to eruptions from Toba (Stauffer, 1971, 1973; Stauffer and Batchelor, 1978; Stauffer et al., 1980). A fission-track age of 30 ±4.5 ka was determined by Nishimura and Stauffer (1981) on zircons from this ash. In addition, three C^{14} dates from wood directly below the Malaysian ash were determined to be 33.25 ±1.8 ka, 36.5 ±2.5 ka, and >39.9 ka (Stauffer, 1973). Nishimura (1980) has also dated a "superficial deposit of unconsolidated ash only 1 m thick (typically 20–60 cm thick [Yokoyama et al., 1980]) found at some places on the east side of Lake Toba, including Prapat Pass" at 30 ±0.3 ka. Although Stauffer et al. (1980) suggested that these dates indicate the occurrence of another large eruption at Toba, ash-shard chem-

istry (Ninkovich et al., 1978a; Rose and Chesner, 1987), mineral chemistry, and Sr isotopic ratios (Chesner, 1988) all suggest that the Malaysian ash is correlative with the Youngest Toba tuff. Furthermore, a major eruptive event is required to deposit a 90-cm-thick ash horizon 350 km from the source. No major on-land counterparts to this ash are known near Toba. In addition, no deep-sea ash deposits younger than the 75 ka horizon have been correlated with Toba (T. Imbert, 1988, oral commun., Laboratoire de Géochimie des Roches Sédimentaires, Université de Paris-Sud).

Paleomagnetic studies indicate that the Youngest Toba tuff and Middle Toba tuff have normal geomagnetic polarities, whereas the Oldest Toba tuff and Haranggoal Dacite tuff are reversed (Knight et al., 1986). These distinctions and their mineralogy allowed correlation of the rocks of the resurgent dome's eastern block (Uluan block) with the Oldest Toba tuff. It was further suggested that Samosir Island, the western half of the resurgent dome, may consist of Middle Toba tuff (Knight et al., 1986). However, the Samosir rocks are chemically unlike the Middle Toba but similar to the Youngest Toba tuff (Chesner, 1988). Correct correlation of the tuff on Samosir Island is crucial for evaluation of the history and evolution of the Toba caldera complex. Eruptive volumes calculated for the Youngest Toba tuff would be greatly reduced if Samosir Island consists of Middle Toba tuff. Caldera fill was calculated as approximately 1000 km^3, on the basis of an average thickness of 400 m suggested by outcrops of welded tuffs in the cliffs of Samosir Island (Rose and Chesner, 1987).

We present new $^{40}Ar/^{39}Ar$ ages for a sample (T-100) from Samosir Island that indicates it is Youngest Toba tuff caldera fill. An isothermal plateau fission-track age of Toba glass shards from Malaysia (UT778) further suggests a genetic link of this ash with the Youngest Toba tuff. An $^{40}Ar/^{39}Ar$ age for the Middle Toba tuff (T-7) completes the chronology of major ignimbrite eruptions at Toba. Confirmation of the age and immense volume of the Youngest Toba tuff allow speculation on the global impact of a volcanic eruption of great magnitude.

SAMPLES DATED

Sample T-100 is a densely welded quartz-latite tuff collected from the steep cliffs of northeastern Samosir Island near Ambarita (Fig. 1). Sample T-7, a densely welded rhyolite tuff, was collected from the northeastern wall of the caldera near Haranggoal (Fig. 1). Samples were crushed to liberate individual sanidine phenocrysts from their matrix. Crystal concentrates were then stained with sodium cobaltinitrate which made identification and hand-picking of 1–2-mm-diameter sanidine crystals possible.

Sample UT778 (Serdang ash), was collected near Serdang, Selangor, Malaysia, 15 km south of Kuala Lumpur (Fig. 1). At this locality the ash is in a clay pit, is 85–90 cm thick, and has been relatively undisturbed since its rapid deposition in a lacustrine environment (Stauffer and Batchelor, 1978). The ash sample was collected from an interval 25–50 cm above its base termed the "coarse middle zone" by Stauffer and Batchelor (1978). In this zone the ash is characterized by abundant euhedral biotite phenocrysts. These were removed by standard separation techniques to concentrate the glass shards for fission-track dating.

TABLE 1. $^{40}Ar/^{39}Ar$ ANALYTICAL DATA, TOBA TUFFS

	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40}Ar^*/^{39}Ar$	^{40}Ar (10^{-11} cm^3)	$^{40}Ar^*$ (%)	Age (ka)†
Sample T-100							
Initial degassing step							
777-01A	10.96	-0.1145‡	0.0365	0.15 ±0.51	1.6	1.4	90 ±308
777-02A	5.92	-0.0302	0.0194	0.17 ±0.23	1.5	2.9	100 ±140
Fusion							
777-01B	0.198	0.0035	0.00023	0.123 ±0.009	0.9	61.9	73 ±6
777-02B	0.317	0.0089	0.00067	0.112 ±0.026	0.5	35.4	67 ±16
777-04	0.246	0.0098	0.00039	0.126 ±0.011	1.1	51.1	75 ±6
777-05	0.252	0.0037	0.00038	0.133 ±0.026	0.4	52.9	80 ±15
777-06	0.187	-0.0008	0.00018	0.126 ±0.026	0.3	67.3	75 ±16
777-07	0.184	0.0045	0.00022	0.111 ±0.015	0.5	60.5	67 ±9
777-08	2.079	0.0115	0.00675	0.078 ±0.055	3.0	3.7	47 ±33
Weighted mean ±1σ error§ =				0.122 ±0.004			73 ±2
±1σ error including uncertainties in J and isotopic interferences =							±4
Sample T-7							
778-01	0.907	0.0147	0.00027	0.822 ±0.014	2.6	90.6	493 ±8
778-02	0.935	0.0177	0.00025	0.854 ±0.014	2.8	91.4	512 ±8
778-03	0.881	0.0231	0.00011	0.844 ±0.019	1.8	95.8	506 ±11
778-04	0.891	0.0138	0.00017	0.835 ±0.011	3.3	93.6	500 ±7
778-06	0.904	0.0000	0.00025	0.824 ±0.012	2.7	91.2	494 ±8
778-08	0.893	-0.0040	0.00009	0.861 ±0.020	1.7	96.3	516 ±12
778-09	1.037	0.0087	0.00072	0.817 ±0.025	1.7	78.8	490 ±15
Weighted mean ±1σ error§=				0.836 ±0.006			501 ±4
±1σ error including uncertainties in J and isotopic interferences =							±5
Rejected							
778-05	0.974	0.2334	0.00237	0.285 ±0.068	1.4	29.3	171 ±41
778-07	0.761	0.5145	0.00366	-0.289 ±0.047††	1.5	38.0	-174 ±28

NOTE: Neutron irradiation flux parameter: $J = (3.321 \pm 0.006) \times 10^{-4}$. Isotopic decay constant: $\lambda = 5.543 \times 10^{-10}$ yr^{-1}. Isotopic interference corrections: $(^{40}Ar/^{39}Ar)_K = (6.7 \pm 4.7) \times 10^{-3}$, $(^{39}Ar/^{37}Ar)_{Ca} = (2.59 \pm 0.30) \times 10^{-4}$, $(^{36}Ar/^{37}Ar)_{Ca} = (9.0 \pm 5.1) \times 10^{-4}$.

* Radiogenic.

† Errors in age quoted for individual runs are 1σ analytical uncertainty excluding errors in the neutron irradiation flux parameter, J, and errors in the isotopic interference corrections.

‡ Negative values of $^{37}Ar/^{39}Ar$ occasionally result from the subtraction of system blank ^{37}Ar from the sample ^{37}Ar in cases where very little ^{37}Ar is present.

§ Standard error of the weighted mean calculated according to the formula of Samson and Alexander (1987), and excludes errors in J and the isotopic interference corrections.

†† Negative values of $^{40}Ar^*/^{39}Ar$ (hence negative age) result from subtraction of too large an air component $^{40}Ar/^{39}Ar$ from the measured $^{40}Ar/^{39}Ar$. The source of this artifact is measurement error in ^{36}Ar for small sample volumes.

ANALYTICAL TECHNIQUES

The $^{40}Ar/^{39}Ar$ dating employed a continuous Ar-ion laser to melt individual crystals under ultra-high vacuum. Samples were irradiated for 1 h at 1 MW in the central-thimble facility of the TRIGA reactor at the University of California, Berkeley. Argon-isotope abundances were measured with a computer-controlled extraction system and Mass Analyzer Products Series 215 noble-gas mass spectrometer. Measured abundances were corrected for system blank, and calculated ratios were corrected for mass discrimination, radioactive decay of ^{37}Ar and ^{39}Ar, and isotopic interferences resulting from irradiation byproduct reactions. Blanks for ^{40}Ar, ^{39}Ar, ^{37}Ar, and ^{36}Ar were approximately 1, 0.05, 0.02, 0.07, and 0.02 $\pm 10^{-12}$ cm^3, respectively. Optical-grade fluorite for $(^{36}Ar/^{37}Ar)_{Ca}$ and $(^{39}Ar/^{37}Ar)_{Ca}$ and artificial kalsilite glass for $(^{40}Ar/^{39}Ar)_K$ were used to calibrate isotopic interferences (Table 1). Corrections to $^{40}Ar/^{39}Ar$ were a maximum of 1% for the $^{36}Ar_{Ca}$ interference and much less than 1% for the $^{39}Ar_{Ca}$ contribution. In sample T-7, the corrections to $^{40}Ar/^{39}Ar$ for $^{40}Ar_K$ interference are only about 0.8%, but they constitute a maximum of 9% and average of 6% in sample T-100. Corrections to the measured $^{40}Ar/^{39}Ar$ for the atmospheric $^{40}Ar/^{39}Ar$ component were calculated under the assumption that initial argon was of atmospheric composition. Sanidine from the Fish Canyon Tuff (27.84 Ma; recalculated from Cebula et al. [1986], based upon the revised age of monitor MMhb-1 in Samson and Alexander [1987]) was used as a neutron flux monitor for this irradiation.

The atmospheric ^{40}Ar component of the fusion runs was reduced by a preliminary degasing step during which the crystal was heated by low-power laser light to expel surficial atmospheric Ar contamination. Analyses of two of these initial steps for T-100 are given in Table 1 (777-01A, 777-02A). Calculations of Ar abundances indicate that this two-step procedure resulted in tripling the percentage of radiogenic argon of the subsequent fusion step for these runs (777-01B and 777-02B).

Seven replicate analyses of sanidine phenocrysts from T-7 (Middle Toba tuff) gave a weighted mean age of 501 ±5 ka (1 σ standard

error of the mean; Table 1; see also Appendix I for a discussion of error analysis). Two runs were rejected because of small sample size and poor analytical quality (778-05, 778-07). Of the remaining seven analyses, all contained greater than 90% $^{40}Ar^*$—with one exception, which contained 79% $^{40}Ar^*$ (778-09). Although this low radiogenic-yield run also gave the youngest age (490 ±15 ka), it has little influence on the weighted mean because of its relatively large analytical uncertainty.

Seven replicate dates on T-100 yielded a weighted mean age of 73 ±4 ka (Table 1). Most of the runs yielded excellent $^{40}Ar^*$ component for materials of this age, between 50% and 70%, with exceptions of 35.4% and 3.7%. The lowest $^{40}Ar^*$ component analysis (777-08) is clearly anomalous, but because of a relatively large uncertainty (47 ±33 ka), it has little influence on the weighted mean or its uncertainty.

Two sample splits of UT778 were prepared for isothermal plateau fission-track dating by following the technique described by Westgate (1989). Etch time for each split was varied to ensure that fission tracks were adequately etched. In order to correct for partial track fading, the samples were heated for 30 days at 150 °C. This resulted in a nearly ideal ratio for diameter of mean spontaneous track to mean induced track of 1.07. Individual sample split ages of 67.6 ±9.6 and 67.6 ±11.0 ka (Table 2) were determined by the population-subtraction technique (Naeser, 1976). Concordance of the two age estimates under differing etch conditions and a mean track diameter in the range of 6–8 μm indicates that UT778 was adequately etched (Westgate, 1989). The weighted mean age and uncertainty of sample UT778 is 68 ±7 ka.

DISCUSSION

The 501 ±5 ka date of sample T-7 from the Middle Toba tuff completes the major ash-flow tuff chronology at Toba (Table 3) and allows assessment of the temporal development of the Toba Caldera Complex (Chesner and Rose, unpublished). Repose periods between Toba ignimbrite eruptions were approximately 0.360, 0.340, and 0.426 m.y. These periods are similar to that of Valles Caldera, New Mexico (0.350 m.y.) (Doell et al., 1968; Izett et al., 1981), but briefer than that of Yellowstone Caldera, Wyoming (0.700 m.y.) (Christiansen and Blank, 1972).

The 73 ±4 ka $^{40}Ar/^{39}Ar$ date of sample T-100 from Samosir Island is very close to that of the conventional K-Ar dates on the Youngest Toba tuff outflow sheet of 74–75 ka, confirming that this densely welded tuff is an intracaldera facies of the Youngest Toba tuff. These new data force revision of the eruptive history of Toba postulated by Knight et al. (1986). The assumption used in Rose and Chesner's (1987) Youngest Toba tuff volume calculation, that Samosir Island is Youngest Toba tuff caldera fill, is confirmed, and the minimum volume estimate of 2500–3000 km^3 (dense rock equivalent) remains valid. Our best age estimate for the Youngest Toba tuff eruption is 74 ±2 ka—the weighted mean age of the $^{40}Ar/^{39}Ar$ (73 ±4 ka) and K-Ar (75 ±12 ka and 74 ±3 ka) analyses. Another important implication of this chronology is that the resurgence of Samosir Island took place entirely within the past 74 ka. This is an important constraint on the rate of caldera resurgence (Chesner and Rose, unpublished), which is usually described in terms of ranges of 10^3–10^5 yr (Marsh, 1984).

The 68 ±7 ka age on the Malaysian ash shards is within analytical error of the K-Ar and $^{40}Ar/^{39}Ar$ ages determined for the Youngest Toba tuff. This new age, in conjunction with results from chemistry and field geology studies, support, the assertions of Van Bemmelen (1949), Ninkovich et al. (1978a), and Rose and Chesner (1987) that the ash in Malaysia originated from the 74 ka Youngest Toba tuff eruption. Therefore, a large explosive eruption originating from Toba at 30 ka as postulated by Stauffer et al. (1980) seems unlikely.

The close agreement between the $^{40}Ar/^{39}Ar$ date of Youngest Toba tuff with K-Ar ages of the outflow sheet and oxygen-isotope–biostratigraphic data of the Indian Ocean ash helps to delimit the timing of one of the largest volcanic eruptions on Earth (Table 3). This recent eruption presents a unique opportunity to document the global effects associated with this type of volcanic event. Data from the Vostok ice core from Antarctica indicate that a worldwide drop in temperature of about 4 °C occurred between 80 and 75 ka (Lorius et al., 1988). Associated with this drop in temperature was the next-to-last continental glacial advance, the early Wisconsin Glaciation in North America, 75 ka (Goldthwait, 1988). Modeling by atmospheric physicists and chemists of the global effects of the Youngest Toba tuff eruption could establish whether it contributed to the observed global cooling.

Eruptions of the scale of the Youngest Toba tuff are unknown in the historic record. The largest is the 50 km^3 Tambora eruption of 1815 (Self et al., 1984), which was associated with significant climatic effects in North America and Europe (Stothers, 1984). The largest of the past 25 years, when atmospheric sampling of eruptions has been possible, is the 0.3–0.6 km^3 Agung eruption of 1963, which caused a persistent stratospheric injection of gas, ash, and aerosol (Rampino and Self, 1984) and a measurable temperature decrease of about 0.3 °C in the Northern Hemisphere (Jones et al., 1982). The Toba event, two orders of magnitude larger than the Tambora eruption and three orders of magnitude larger than that at Agung, is known to have produced an enormous ash-fall deposit over the Indian Ocean and southern Asia (Ninkovich, 1979; Rose and Chesner, 1987), and it may represent an end-member example of instantaneous impact of volcanism on the atmosphere. The Toba event may have contributed about 1×10^{16} g of H_2SO_4 aerosol (based on f_{H_2O} and f_{H_2S} computed from mineral chemistry of the Youngest Toba tuff pumice; Chesner, unpublished), which has been viewed as an important component of the atmosphere impact of small eruptions. Injection of similar quantities of aerosols into the atmosphere would result in substantial reduction of solar transmission to Earth's surface. For Toba, the estimated fraction of sunlight transmitted would have ranged between 10% (similar to an overcast day) to 0.001% (below the level of photosynthesis, only slightly brighter than the full moon) (Rampino et al., 1988). Such worldwide reduction in solar transmission is similar to what would be expected from a major nuclear exchange or bolide impact. Since the mass of gas, ash, and aerosol that reaches the stratosphere is a small fraction of the total erupted, extreme climatic perturbations may have been short-lived, but an elevated

TABLE 2. ISOTHERMAL PLATEAU FISSION-TRACK AGES OF HYDRATED GLASS SHARDS OF TOBA TEPHRA FROM MALAYSIA

Sample Identification	Spontaneous Track Density (t/cm²)	Induced Track Density (10^5t/cm²)	Neutron Fluence (10^{15}n/cm²)	Age (ka)	Etching Conditions HF (%)	Temp. (°C)	Time (s)
Toba Tephra							
UT778	78.65 (50)	2.68 (19976)	3.84 (14021)	67.6 ±9.6	26	21	145
UT778	77.18 (38)	2.63 (11375)	3.84 (14021)	67.6 ±11.0	26	21	160
Internal Standard							
UT Moldavite	11590 (516)	1.71 (6478)	3.80 (14021)	15350 ±710	24	24	125

NOTE: Number of tracks counted is indicated in parentheses and error is calculated by combining the Poisson errors in spontaneous and induced track counts and on the counts in the detector covering the dosimeter. The weighted mean age and uncertainty of sample UT778 is 68 ±7 ka. Results on the internal standard (Moldavite tektite glass) compare well with the $^{40}Ar/^{39}Ar$ plateau age of 15.21 ±0.15 Ma (Staudacher et al., 1982).

TABLE 3. AGES DETERMINED ON THE TOBA TUFFS

Tuff	Location	Sample Description*	Material Dated	Age (Ma)	Technique†
Youngest	Samosir Island	DWT	Sanidine	0.073 ±0.004	$^{40}Ar/^{39}Ar$
Youngest	Siguragura	IWT	Biotite	0.075 ±0.012	K-Ar
Youngest	Prapat	Pumice	Sanidine	0.074 ±0.003	K-Ar
Youngest	Malaysia	Ash	Shards	0.068 ±0.007	F-T
Youngest	Indian Ocean	Ash	Ash	0.75	$^{18}O/^{16}O$-B
Middle	Haranggoal	DWT	Sanidine	0.501 ±0.005	$^{40}Ar/^{39}Ar$
Oldest	Siguragura	DWT	Sanidine	0.840 ±0.030	$^{40}Ar/^{39}Ar$
Haranggoal	Prapat Pass	DWT	Zircon	1.20 ±0.16	F-T

*DWT = Densely welded tuff; IWT = Incipiently welded tuff.
†$^{40}Ar/^{39}Ar$ dates from this study, except Oldest Toba tuff, from Diehl et al. (1987). K-Ar and oxygen isotope-biostratigraphy dates from Ninkovich et al. (1978a). Fission-track date for Youngest Toba tuff from this study, for Haranggoal dacite tuff from Nishimura et al. (1977). F-T = Fission-track; $^{18}O/^{16}O$-B = Oxygen isotope and biostratigraphy.

level of H_2SO_4 undoubtedly remained in the atmosphere for several years following the eruption.

APPENDIX 1. MEANS AND ERRORS

Two types of errors must be considered in reducing the individual grain analyses to an overall representative age for a rock sample. The first are random errors encountered from run to run and arising from measurement of Ar-isotope abundances. The second can be considered systematic errors from the viewpoint of calculating an average age, since they derive from errors in parameters that are determined externally and are applied to each analysis in the same manner. These parameters include the calibrated neutron flux intensity for the particular irradiation (J), and the isotopic interference corrections appropriate to the reactor used. A third type of error can be considered systematic from the point of view of operations within a single laboratory, and those are errors in the internationally accepted ^{40}Ar decay constants and natural-isotope abundances of K and Ar (Steiger and Jäger, 1977), as well as uncertainty in the age of the $^{40}Ar/^{39}Ar$ monitor mineral (Fish Canyon Tuff sanidine). This third category of error is not normally treated in the reporting of $^{40}Ar/^{39}Ar$ isotopic ages, except for example high-precision ages used in the context of time-scale calibration. In the context of the relatively large analytical errors encountered in the dating of young sanidines, errors in the decay constants and isotopic abundances are relatively insignificant, although the error in the age of the standard remains a potential concern.

Errors in the calculated ages for the individual grains reported in Table 1 reflect only uncertainties in the argon isotopic ratios for that analysis. (These isotopic ratios are corrected for mass-dependent measurement bias of the mass spectrometer, termed "discrimination." The error in the discrimination correction factor for one atomic mass unit is small, about 0.2%; thus, it has little effect on the error analysis.) On the basis of these estimated analytical errors, weighted mean ages are calculated in the conventional manner by using the inverse of the analytical variance as the weighting factor (Mandel, 1964; Taylor, 1982). The standard error of the weighted mean is calculated from the formula given by Samson and Alexander (1987), which recomputes deviations about the weighted mean to generate a weighted uncertainty, thus incorporating the observed run-to-run variability in the error estimate.

Although this procedure provides a reasonable estimate of the precision of the analytical process in measurement of this particular sample, it does not encompass errors in J and the isotopic interference corrections. These additional uncertainties are incorporated through the application of the usual propagation of errors formulae to the age equation (e.g., Dalrymple et al., 1981), with the simplifying assumption that $(^{40}Ar^*/^{39}Ar) \approx (^{40}Ar/^{39}Ar)_a$, where $(^{40}Ar/^{39}Ar)_a$ is corrected for atmosphere only. The increase in the standard error of the mean age, due to incorporation of these additional error factors, from ±2 to ±4 ka for T-100 and ±4 to ±5 ka from T-7, reflects the large uncertainty in knowledge of the $(^{40}Ar/^{39}Ar)_K$ isotopic interference and the importance of this correction for young samples (Table 1).

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