$^{40}Ar/^{39}Ar$ Dating of the Brunhes-Matuyama Geomagnetic Field Reversal

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Magnetostratigraphic studies are widely used in conjunction with the geomagnetic polarity time scale (GPTS) to date events in the range 0 to 5 million years ago. A critical tie point on the GPTS is the potassium-argon age of the most recent (Brunhes-Matuyama) geomagnetic field reversal. Astronomical values for the forcing frequencies observed in the oxygen isotope record in Ocean Drilling Project site 677 suggest that the age of this last reversal is 780 ka (thousand years ago), whereas the potassium-argon–based estimate is 730 ka. Results from $^{40}Ar/^{39}Ar$ incremental heating studies on a series of lavas from Maui that straddle the Brunhes-Matuyama reversal give an age of 783 ± 11 ka, in agreement with the astronomically derived value. The astronomically based technique appears to be a viable tool for dating young sedimentary sequences.

Several variants of the GPTS (for example, *1*) have been used in studies related to geological events in the Mesozoic and Cenozoic. Available time scales are based on calibration of the time scale for the period 0 to 5 Ma (million years ago) with K-Ar dates (*2*), and use of magnetic lineations in the sea-floor spreading record with the calculated spreading rates for the period >5 Ma. But K-Ar data obtained during the last decade for reversals older than 5 Ma (*3*) suggest that there are inaccuracies in the middle to late Miocene sections of the GPTS calculated in this manner. Recent $^{40}Ar/^{39}Ar$ dating (*4*), which yields ages more accurate than the K-Ar method, strengthened this argument, and several studies (*5–8*) have also suggested that there are errors in the GPTS in the age range <5 Ma.

To evaluate this hypothesis, we dated lava flows exposed on the northwestern caldera wall of Haleakala Volcano on the island of Maui, spanning the most recent Brunhes-Matuyama (B-M) geomagnetic field reversal. Our specimens for dating were taken from the Kula series, consisting primarily of alkali basalts and trachybasalts, that rest as a cap ~760 m thick on the Honamanu series (primarily tholeiites), forming the main shield of Haleakala (*9*). Oriented paleomagnetic sample cores were collected from nine lava flows (thickness ranging from ~2 to 10 m) on the Halemauu Trail (Table 1), which begins at 2384 m above sea level at the crater rim and winds down to 2012 m at the caldera floor. In our reconnaissance study, not all flows were sampled, nor are the sampled flows at constant intervals. Among them, flow pairs 2 and 3 and 4 and 5 are separated by ash layers only, and flows 6 and 7 are in direct contact (see Table 1). Paleomagnetic results demonstrate that these flows erupted during a time when the geomagnetic field was in a state of transition from reversed to normal polarity. The K-Ar dates from an earlier study (*10*) suggest that the section sampled includes the B-M transition.

The alkali basalts are strongly magnetized, and alternating field (AF) demagnetization was suitable for removing the secondary magnetization components. In general, the normally magnetized samples had very stable magnetization, without secondary components, whereas the reversely magnetized rocks contained a secondary component roughly parallel to the present geomagnetic field direction. Alternating fields less than 25 mT were sufficient to reveal the primary components of all the samples. The oldest flows (1 and 2) are reversely magnetized (south-pointing declinations and negative inclinations), whereas the youngest flows (7, 8, and 9) are normally magnetized (Fig. 1). Flows 3 through 6 show transitional directions and low intensity of magnetization (see Table 1), suggesting a low geomagnetic field strength during the transition. A separate paleomagnetic study (*11*), with more detailed sampling along a path parallel to ours, confirmed that the section contains a complete reversed to normal geomagnetic transition.

Advances in technology now permit $^{40}Ar/^{39}Ar$ dating studies to be attempted on small samples (<50 mg) of young volcanic rocks (*12*). Samples from lavas 3 through 6 (showing transitional polarity) were selected for $^{40}Ar/^{39}Ar$ dating, to obtain the most precise age of the field reversal (*13*). An initial attempt, utilizing ~3 g of powdered whole-rock sample and an MS 10 mass spectrometer at Queen's University (*14*), suggested that crystallization ages with errors of less than ±2% could be obtained with the use of an ultrasensitive mass spectrometer and a resistance furnace extraction line that yielded low blanks. We used such an experimental setup at Stanford University. Specimens from all four lavas were crushed and sieved to retain the 25- to 60-mesh fraction and irradiated with fast neutrons in position 5C of the McMaster

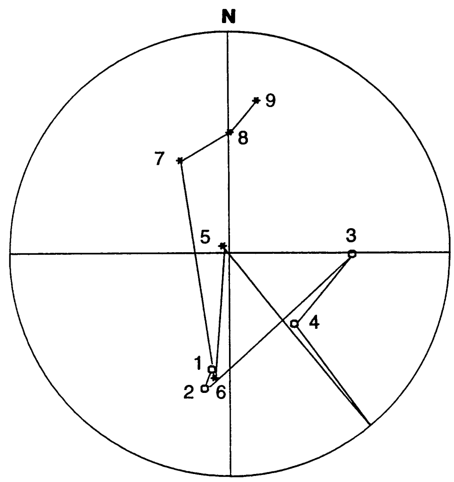

Fig. 1. Equal-angle plot for AF cleaned field directions for nine lava flows from the Kula series, Maui. Flows 1 and 2 and 7 through 9 show reversed and normal magnetic polarity, respectively; flows 3 through 6 show transitional directions (see Table 1). Flows 3 through 6 were used for $^{40}Ar/^{39}Ar$ dating studies.

Table 1. Paleomagnetic results on lava flows from the Kula series, Maui. AF, alternating field used for final demagnetization; for polarity, R = reversed, T = transitional, N = normal.

Flow	Elevation (m)	AF (mT)	Declination (deg)	Inclination (deg)	Intensity (mA/m)	Polarity
9	2271	7.5	10.5	20.1	2550	N
8	2256	5.0	0.5	32.9	3190	N
7	2180	12.5	331.8	39.4	10300	N
6*	2175	10.0	187.2	31.5	760	T
5*	2104	25.0	315.6	85.0	0.13	T
4*	2102	15.0	137.4	−43.2	270	T
3*	2072	7.5	90.9	−32.0	960	T
2	2066	25.0	189.1	−34.4	2630	R
1	2049	7.5	190.9	−26.6	8220	R

*Flows dated by the $^{40}Ar/^{39}Ar$ method.

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University reactor. We used splits of Fish Canyon tuff biotite (FCT-3 Bio) as a monitor, and our results are reported relative to an age of 162.9 Ma for SB-3 biotite (*15*, *16*). Experimental procedures differ slightly from those used in earlier studies (*17*).

The sample from lava 3 yielded step ages >850 ka (thousand years ago), confirming the results of our initial work (*14*) that excess argon was present. The data obtained on subsamples from flows 4 through 6 are more satisfactory and yield acceptable plateau ages (see Fig. 2).

Although the plateau ages of all samples overlap within experimental error, the shape of their spectra suggests that the samples lost some radiogenic ^{40}Ar after crystallization. To investigate this further, we examined the results on isochron diagrams (*18*). In each case, values of the mean-squared weighted deviate (MSWD) were close to or less than 1, for the best fit lines to the data. Isochron plots (see Fig. 3) indicate that these lavas contain initial argon whose isotopic composition is marginally lower than that of the atmosphere ($^{40}Ar/^{36}Ar$ = 295.5). We suggest that the isochron ages (weighted mean value = 783 ± 8 ka) are better approximations to the time of crystallization than the plateau ages. The single result from Queen's University is in good agreement with the other ages (Fig. 3A) and is reassuring in that ~100 times as much rock was used in this experiment as in the work at Stanford. To permit comparison of these results with those obtained at other laboratories, we include a further term of 1% in the error estimate of the mean age, to reflect (conservatively) uncertainty in the age of the monitor sample used. Our weighted mean age for the time of crystallization of lava flows 4 through 6 (one age per flow) is 783 ± 11 ka (1σ error). Because all three lava flows exhibit transitional polarity, this directly dates the B-M geomagnetic field reversal and is in good agreement with recent $^{40}Ar/^{39}Ar$ total fusion data obtained from the laser probe (*19*). These ages for the B-M transition are substantially greater than the ~730 ka listed in a recent version of the GPTS (*1*).

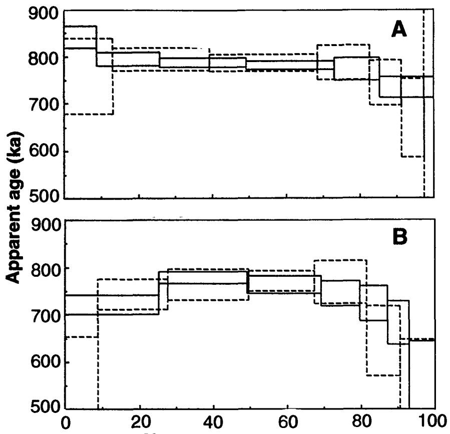

Fig. 2. Age spectra for incremental heating studies on whole-rock specimens taken from lava flows spanning the B-M boundary in Maui. (**A**) Two separate specimens from flow 6 run at Queen's University (Q) and Stanford University (S) (see text). ——, Run 6Q: steps 2 through 5; plateau age, 784 ± 7 ka; – – –, run 6S, steps 2 through 4; plateau age, 778 ± 4 ka. (**B**) Specimens from flows 5 and 4, both run at Stanford University (S). ——, Run 5S: steps 2 through 4; plateau age, 769 ± 14 ka; – – –, run 4S: steps 3 through 5; plateau age, 769 ± 4 ka. Errors shown at 1σ level, internal precision.

Our results confirm the astronomical approach utilized earlier to estimate the age of the B-M transition (*5*, *6*). This new approach to dating has been used to argue in favor of revising the ages of other geomagnetic reversals in the time range 0 to 5 Ma (*6*). It is expected that $^{40}Ar/^{39}Ar$ data pertaining to other field reversals, such as the Olduvai and Reunion Events (*8*, *20*), should provide further calibration of the GPTS during the past 5 million years. In the interim, substantial changes (~7%) of sea-floor spreading rates over the last 800 × 10^3 years are required. If further radiometric results validate the astronomically derived ages for geomagnetic field reversals back to 5 Ma (*6*), the K-Ar calibrated GPTS (*1*) and sea-floor spreading rates for this period will need to be adjusted accordingly.

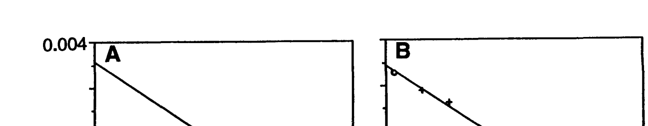

Fig. 3. Isochron plots for $^{40}Ar/^{39}Ar$ incremental heating studies on whole-rock specimens from lava flows spanning the B-M boundary in Maui. (**A**) Specimen from flow 6 run at Queen's University: age = 790 ± 6 ka; initial $^{40}Ar/^{36}Ar$ = 280 ± 7; MSWD = 0.77. (**B to D**) Specimens from flows 6, 5, and 4, respectively, run at Stanford University; (B) age = 787 ± 12 ka; initial $^{40}Ar/^{36}Ar$ = 292 ± 4; MSWD = 0.55; (C) age = 780 ± 10 ka; initial $^{40}Ar/^{36}Ar$ = 284 ± 3; MSWD = 1.06; (D) age = 772 ± 14 ka; initial $^{40}Ar/^{36}Ar$ = 290.9 ± 1.2; MSWD = 0.54. All points used in straight line fitting (*21*), except for the first step on flow 6 at Queen's University, denoted in (A) by an open circle. Errors shown at the 1σ level, internal precision.

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16. Ten splits of FCT-3 Bió were calibrated against six splits of SB-3 Bio (162.9 Ma) at Queen's University, and yielded an age of 27.95 Ma.
17. Samples analyzed at Stanford University weighed ~30 mg and were wrapped in tin foil. After a degassing step at ~450°C, the gas was extracted in six to eight steps analyzed on a MAP 216 mass spectrometer. At Queen's University, a ~4-g subsample from lava 6 (separate neutron irradiation) was analyzed with a Lindberg furnace and an MS 10 mass spectrometer (*4*). The Stanford data were blank-corrected before age calculation, whereas the Queen's data were not.
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