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Dating transitionally magnetized lavas of the late Matuyama Chron: Toward a new ^{40}Ar/^{39}Ar timescale of reversals and events

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Abstract. The K-Ar based geomagnetic polarity timescale was constructed using data from lavas and tuffs that bracketed, but rarely dated, the transitions between polarity intervals. Subsequent ^{40}Ar/^{39}Ar dating indicated that the ages of some polarity transitions had been underestimated by about 6%. Although the accepted ages of the polarity chron boundaries have increased, their precise temporal definition remained uncertain. We have taken a different approach and used incremental-heating techniques to obtain 18 new ^{40}Ar/^{39}Ar ages from basaltic lavas within flow sequences at Punaruu Valley, Tahiti, and Haleakala volcano, Hawaii. These lavas record transitional paleomagnetic directions corresponding to four mid-Pleistocene polarity reversals or events. Three lavas from Punaruu Valley previously thought to record the Cobb Mountain Normal Polarity Subchron (CMNS) gave a mean age of 1.105 ± 0.005 Ma, indicating that they were erupted about 76 kyr after the CMNS; this period of transitional field behavior is designated the Punaruu event. In addition, seven new ^{40}Ar/^{39}Ar ages from the Punaruu Valley indicate that the Jaramillo Normal Polarity Subchron (JNS) lasted about 67 kyr, starting at 1.053 ± 0.006 Ma and ending 0.986 ± 0.005 Ma. This agrees with astronomical estimates but conflicts with JNS ages proposed by *Spell and McDougall* [1992] and *Izett and Obradovich* [1994] on the basis of ^{40}Ar/^{39}Ar dating of rhyolite domes in the Valles Caldera. Indistinguishable ^{40}Ar/^{39}Ar ages of seven lavas, including one from Punaruu Valley and six from Haleakala that record broadly similar intermediate paleodirections, suggest that the Kamikatsura event occurred at 0.886 ± 0.003 Ma. Moreover, these data indicate that the Kamikatsura event occurred 20–40 kyr after another geomagnetic event, most probably taking place at 0.92 Ma. We designate this earlier field behavior the Santa Rosa event, adopting its name from that of a transitionally magnetized rhyolite dome which happened to figure prominently in the original definition of the end of the JNS in the 1968 study of *Doell et al.* [1968]. The discovery of these new short-lived polarity events during the Matuyama reversed chron suggests that the 400 kyr period between 1.18 and 0.78 Ma experienced no less than 7 and perhaps more than 11 attempts by the geodynamo to reverse. This newly determined higher frequency of geomagnetic activity illustrates vividly the importance of obtaining precise age control directly from transitionally magnetized rocks.

1. Introduction

1.1. Geochronology and the Reversal Timescale

Potassium-argon (K-Ar) ages that in the past were used to calibrate the geomagnetic polarity timescale (GPTS) closely bracket the ages of many reversals but only very rarely date them directly [*Mankinen and Dalrymple*, 1979]. Yet any comparison of records of a particular geomagnetic reversal, or for that matter, verification of astronomical ages assigned to reversals, requires knowing precisely the age of the transitional directions of the geomagnetic field acquired by the rocks. More recently, ^{40}Ar/^{39}Ar age determinations and astronomical age calibrations of reversals that occurred during the past 5 Myr indicated that their K-Ar ages were about 6% too young [*Johnson*, 1982; *Shackleton et al.*, 1990; *Tauxe et al.*, 1992; *Spell and McDougall*, 1992; *Baksi et al.*, 1992; *Izett and Obradovich*, 1994; *Turrin et al.*, 1994; *Clement et al.*, 1997]. Despite the good agreement between timescales based on ^{40}Ar/^{39}Ar ages and astronomical calibrations and the remarkable precision of modern ^{40}Ar/^{39}Ar techniques, only a handful of studies have provided precise ages for lava flows with intermediate paleomagnetic directions that record Plio-Pleistocene geomagnetic reversals. These include work on the Matuyama-Brunhes reversal [*Baksi et al.*, 1992; *Singer and Pringle*, 1996], the Reunion event [*Baksi et al.*, 1993], and the Cobb Mountain Normal Polarity Subchron (CMNS) [*Turrin et al.*, 1994]. Two of the papers [*Izett and Obradovich*, 1994; *Spell and McDougall*, 1992] that proposed revisions to the GPTS based on single-crystal

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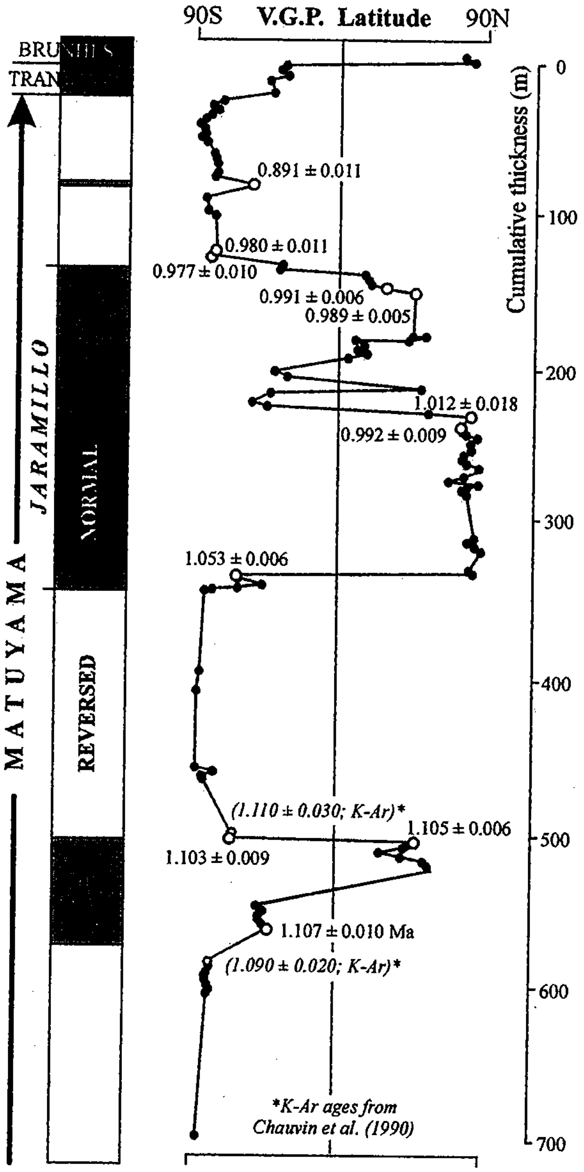

Figure 1. Paleomagnetic stratigraphy of the Punaruu Valley lava sequence. Virtual geomagnetic pole (VGP) latitudes are plotted against the calculated thickness of the section [after *Chauvin et al.*, 1990]. The $^{40}Ar/^{39}Ar$ isochron ages (in Ma) (Table 1) are given for samples shown as open circles. Two K-Ar ages are also shown for reference. Note that there are six polarity transitions or reversals, including the Matuyama-Brunhes reversal in the section.

$^{40}Ar/^{39}Ar$ analyses of sanidine proposed conflicting ages for the onset and termination of the Jaramillo Normal Polarity Subchron (JNS). Moreover, neither set of conclusions agree precisely with the revised astronomical ages of 1.07 and 0.99 Ma for these reversals [*Berggren et al.*, 1995; *Shackleton et al.*, 1990]. In addition, the age of the CMNS is known precisely only from the $^{40}Ar/^{39}Ar$ age of a single lava, the rhyolite of Alder Creek near Cobb Mountain, California [*Turrin et al.*, 1994].

Questions about the ages of geomagnetic reversals in the Matuyama Reversed Polarity Chron reflect, in part, the nature of the lavas used to date them. The Alder Creek rhyolite and the postcollapse rhyolite domes of the Valles Caldera, New Mexico, including Cerro Santa Rosa I and Cerro del Abrigo III, which were originally thought to closely bracket the termination of the JNS [*Doell et al.*, 1968; *Spell and McDougall*, 1992; *Izett and Obradovich*, 1994], are silicic lava domes that cannot easily be placed into a stratigraphic sequence of eruptions. In contrast, sequences including numerous rapidly emplaced basaltic lava flows can provide high-fidelity records of geomagnetic reversals, and their stratigraphy can also be used to test the validity of $^{40}Ar/^{39}Ar$ age determinations [*Pringle et al.*, 1995].

An additional limitation was the precision of conventional K-Ar ages that were typically 3 to 5% (1σ) for sanidines from lava domes [e.g., *Doell et al.*, 1968] and up to 14% or more for basaltic lavas [e.g., *Mankinen and Grommé*, 1982]. Moreover, incomplete extraction of radiogenic argon from sanidine may be the cause for the 6% bias between the K-Ar and astronomical timescales [*Turrin et al.*, 1994; *Izett and Obradovich*, 1994]. Using modern ultrasensitive mass spectrometers, carefully controlled $^{40}Ar/^{39}Ar$ laser fusion and incremental-heating techniques are capable of yielding ages with 1σ precisions of 0.5% from Quaternary sanidine [*Turrin et al.*, 1994] and 0.5 to 1.0% from basaltic or andesitic lavas [*Singer and Pringle*, 1996].

A 700 m thick sequence of Quaternary basaltic lava flows is exposed in the Punaruu Valley on the island of Tahiti. From 123 lava flows in this sequence, *Chauvin et al.* [1990] obtained paleomagnetic intensities and directions that are cast as virtual geomagnetic pole (VGP) latitudes in Figure 1. On the basis of the paleomagnetic data and 12 whole rock K-Ar ages, *Chauvin et al.* [1990] concluded that the cooling lavas had recorded in detail the CMNS, the onset and termination of the JNS, and an unspecified period of intermediate polarity between the JNS and the Matuyama-Brunhes reversal. Another extensive, >160 m thick, sequence of basaltic lava flows erupted from Haleakala volcano on the island of Maui, Hawaii, preserves partial recordings of the Matuyama-Brunhes polarity reversal and an older event that occurred between the JNS and the Matuyama-Brunhes reversal [*Coe et al.*, 1985, 1995; *Pringle et al.*, 1995; *Singer and Pringle*, 1996]. VGP latitudes from a portion of the Haleakala flow sequence older than the Matuyam-Brunhes reversal are shown in Figure 2, and these lavas are discussed further herein. A comprehensive summary of paleomagnetic and $^{40}Ar/^{39}Ar$ data from the rather intricate Haleakala section is beyond the scope of this paper but will be presented elsewhere.

To address some of the remaining questions concerning the timing and number of reversals in the late Matuyama chron, $^{40}Ar/^{39}Ar$ incremental-heating experiments were undertaken on 18 samples of whole rock material from the Punaruu Valley and Haleakala lava flow sequences. These experiments (1) provide the first direct dates for reversals corresponding to the onset and termination of the JNS, (2) show that a transitionally magnetized sequence of lavas interpreted by *Chauvin et al.* [1990] to represent the CMNS were, in fact, erupted ~76 kyr after the CMNS; thus we have designated this newly recognized period of a transitioning geomagnetic field within the Matuyama chron the Punaruu event, and (3) indicate that transitionally magnetized lavas with broadly similar paleomagnetic directions preserved in the Punaruu Valley and at Haleakala were erupted at the same time, about 0.89 Ma. These lavas record geomagnetic field behavior associated with the Kamikatsura event. Together, our geochronologic and paleomagnetic results illustrate that the geodynamo was more lively during the middle Pleistocene than previously imagined.

1.2. What Is a Transition?

The term "transitional" as it relates to paleomagnetic directions has been defined in a number of ways, all definitions invoking a particular virtual geomagnetic pole (VGP) distance from the rotation axis [e.g., *Barbetti and McElhinny*, 1976], or angular distance from the axial dipole direction at the site in question [*Hoffman*, 1984], beyond which typical secular variation may no longer be considered responsible Yet all such definitions are clearly arbitrary as they do not involve the magnitude of the paleomagnetic field. Indeed, there is considerable evidence in the paleomagnetic record for transitional field behavior occurring while the vector direction remains within the commonly accepted realm of secular variation [e.g., *Bogue and Coe*, 1984; *Hoffman*, 1986]. Hence in this paper we choose not to restrict the distinction of transitional behavior to any past definition, but rather argue each questionable case through a consideration of the full paleomagnetic vector.

Further, we choose to follow *Jacobs* [1994] and employ the term "subchron" to denote a determined genuine short polarity interval bounded by two complete polarity transitions, the term "excursion" to denote dramatic field behavior that does not culminate in a complete polarity reversal, and the term "event" to denote behavior that may or may not involve complete polarity transitions. It needs to be emphasized that a given recorded excursion (or event) may be related to the geomagnetic reversal process. Indeed, that reversals can be aborted or that the reversal process involves, perhaps, equal probability for the resulting polarity to be the same as (or opposite to) the initial polarity, is a reasonable starting hypothesis.

2. Analytical Techniques

2.1. Samples and Their Preparation

Following petrographic examination of thin sections from 35 samples from the Punaruu Valley, 11 were found to be suitable for ^{40}Ar/^{39}Ar analysis. All 11 samples are from one-inch diameter paleomagnetic cores studied by *Chauvin et al.* [1990] (see Chauvin et al.'s Table 2 for sample identification numbers). The position of these samples in the stratigraphic sequence is shown in Figure 1. Nine of the 11 samples were nearly holocrystalline and very phenocryst poor. From these samples, ~1 mm thick wafers, weighing 42–62 mg, were cut from 5 mm diameter cores drilled directly into the 1-inch diameter paleomagnetic cores. Two other nearly holocrystalline samples contained large phenocrysts of clinopyroxene and olivine. Phenocryst removal was undertaken to avoid possible mantle-derived extraneous argon components [*Dalrymple and Lanphere*, 1969, p. 125]. This was accomplished by crushing, sieving, and magnetic separation. Nearly holocrystalline 125–315 μm groundmass separates of 29–99 mg were obtained for analysis.

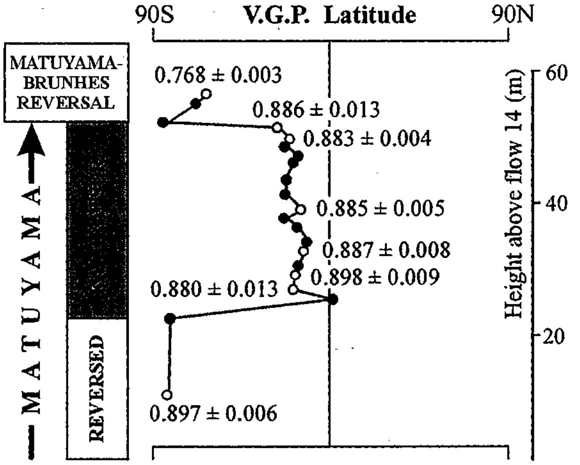

Figure 2. Paleomagnetic stratigraphy of a 50 m portion of the lava sequence at Haleakala volcano, Maui [*Coe et al.*, 1985, 1995]. VGP latitudes are plotted against stratigraphic height relative to reversely magnetized lava flow 14. For the 16 transitional sites, VGP longitudes are mainly between 301° and 312° (Figure 3), and the α_{95} values average 8°. The ^{40}Ar/^{39}Ar isochron ages (in Ma) (Table 1) are given for samples shown as open circles.

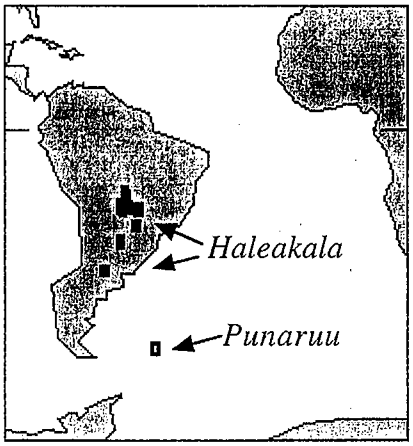

Figure 3. Virtual geomagnetic pole (VGP) positions of 16 lavas from Haleakala volcano and one from the upper portion of the Punaruu Valley sequence. Six of these Haleakala lavas gave ^{40}Ar/^{39}Ar isochron ages between 0.898 ± 0.009 Ma and 0.880 ± 0.013 Ma, whereas the Punaruu lava is 0.891 ± 0.011 Ma (Table 1). The clustered ages and VGPs suggest that these lavas all recorded the Kamikatsura event; see text for discussion.

Coe et al. [1985, 1995] described a continuous sequence of at least 45 basaltic lava flow units at Haleakala volcano that include 36 cooling units which show neither fully reversed nor normal paleomagnetic directions. The uppermost 20 of these flows recorded variable VGP latitudes that cluster in three main groups including approximately −80° to −70° at the base to +40° to 75° in the middle and then −35° to −50° near the top. Six of these lavas gave isochron ages from 0.773 ± 0.004 Ma to 0.766 ± 0.003 Ma and a weighted mean of 0.768 ± 0.002 Ma, corresponding to the Matuyama-Brunhes polarity reversal [*Singer and Pringle*, 1996; *Pringle et al.*, 1995]. In contrast, the lower, and much older, group of 16 transitionally magnetized units has more uniform VGP latitudes mainly between and −11° and −26° (Figures 2 and 3) that are distinctive from the overlying flows. Thin sections from each of the lower 16 units and one underlying reversely magnetized unit were examined and seven samples, representing the two lowermost, two uppermost, and two freshest units from the middle of the transitional section plus the reversely magnetized unit were selected for ^{40}Ar/^{39}Ar experiments. All are nearly aphyric and holocrystalline; flows 16b and 17 contain 2–3% glass or pale clay in an otherwise intergranular groundmass. Whole rock wafers weighing ~100 to 120 mg were cut directly from paleomagnetic cores. From these seven samples, 12 separate incremental-heating experiments were undertaken.

2.2. The $^{40}Ar/^{39}Ar$ Analyses

The $^{40}Ar/^{39}Ar$ method is a relative dating technique in which the age of an "unknown" sample is calculated relative to mineral standards that have been previously dated, usually by conventional K-Ar techniques. The monitor mineral used here was sanidine 85G003 from the Taylor Creek rhyolite (TCs) [*Duffield and Dalrymple*, 1990]. The age of this standard has been determined at 27.92 Ma relative to the U.S. Geological Survey (USGS) primary standard SB-3 biotite at 162.9 Ma [*Lanphere et al.*, 1990]. *Izett and Obradovich* [1994] also utilized the same TCs monitor mineral and age; thus their results are directly comparable to those reported here.

The experiments of *Spell and McDougall* [1992] and *Spell and Harrison* [1993] on sanidine from the Santa Rosa I rhyolite dome, however, were monitored using Fish Canyon sanidine (FCs) assuming its age to be 27.90 Ma based on the K-Ar age of the Fish Canyon Tuff [*Cebula et al.*, 1986]. Furthermore, *Turrin et al.* [1994] determined the age of sanidine from the Alder Creek rhyolite relative to 27.84 Ma for the FCs monitor. In light of new intercalibrations of $^{40}Ar/^{39}Ar$ mineral standards commonly used as neutron fluence monitors [*Baksi et al.*, 1996; *Renne et al.*, 1998], direct comparisons of our ages to the results of *Spell and McDougall* [1992], *Spell and Harrison* [1993], and *Turrin et al.* [1994] require some caveats. In particular, based on 54 isotopic measurements of TCs, *Renne et al.* [1998] found that it is 310 ± 60 kyr older than FCs. Using the equation of *Dalrymple et al.* [1993, p. 7], we have therefore recalculated the ages of *Spell and McDougall* [1992] and *Spell and Harrison* [1993], assuming a 310 kyr difference between our TCs monitor at 27.92 Ma and the FCs monitor used in their experiments. *Renne et al.* [1998] also reported 86 new single-crystal analyses of sanidine from the rhyolite of Alder Creek (ACs), which is the same material used by *Turrin et al.* [1994] to establish an $^{40}Ar/^{39}Ar$ age of 1.186 ± 0.006 for the Cobb Mountain Normal Polarity Subchron. On the basis of calibration of these 86 measurements against the primary K-Ar standard GA-1550 biotite, *Renne et al.*'s [1998] data indicate that the age of ACs, and thus the Cobb Mountain Normal Polarity Subchron, is 1.194 ± 0.007 Ma. Recalculating the latter age to be consistent with TCs at 27.92 Ma gives an age for ACs of 1.181 + 0.007 Ma that we use in the subsequent discussion.

Using the TCs monitor at 27.92 Ma, *Singer and Pringle*'s [1996] $^{40}Ar/^{39}Ar$ incremental-heating experiments on lavas yielded 0.779 ± 0.002 Ma for the age of the Matuyama-Brunhes reversal. This age is identical to the best independent astronomical estimate of 0.778 ± 0.002 Ma [*Tauxe et al.*, 1996]. Thus, despite the uncertainties associated with intercalibration of the TCs and FCs neutron fluence monitors, experiments using both have yielded results consistent with the astronomical calendar for the past several million years [cf. *Renne et al.*, 1994].

2.3. Procedures

The whole rock wafers, the groundmass samples wrapped into 99.99% copper foil packets, and the flux monitor packets were loaded into 6 mm ID quartz vials that were evacuated and sealed for the experiments done in Geneva and left open to air for those done at the Scottish Universities Research and Reactor Centre (SURRC). All samples were first irradiated for 1 or 2 hours at the Oregon State University Triga reactor in the Cadmium-Lined In-Core Irradiation Tube (CLICIT) where they received a total fast neutron dose of 1 to 2 × 10^{17} neutrons/cm^2. On the basis of previous work, corrections for undesirable neutron-induced reactions on ^{40}K and ^{40}Ca are as follows: $[^{40}Ar/^{39}Ar]_K = 0.00086$, $[^{36}Ar/^{37}Ar]_{Ca} = 0.000264$, and $[^{39}Ar/^{37}Ar]_{Ca} = 0.000673$. Isotope ratio measurements were made in an MAP-216 spectrometer operated with a Bauer-Signer ion source, fixed slit, and Johnston electron multiplier at Geneva, or an MAP-215 instrument with a modified Nier source and variable slit at SURRC. Mass discrimination was monitored using on-line air pipettes and was 1.0070 ± 0.0009 and 1.0057 ± 0.0003 per mass unit during the period of analytical work at Geneva and SURRC, respectively. Analytical procedures for furnace degassing, gas clean-up, mass spectrometry, and blank corrections were similar to those of *Singer and Pringle* [1996], except that both laboratories now use two SAES C50 Zr-Al getters operated at 450°C in series for the two-stage gas cleanup.

Experiments consisted of 5 to 14 individual analyses of gas released by stepwise heatings between ~440 and 1300°C. Temperatures for the Geneva experiments are reported at the base of the Ta crucible, as read directly by a W-WRe thermocouple, and range between 650 and 1250°C. Temperatures for the SURRC experiments are reported inside the Mo crucible liner as calibrated by optical pyrometer, range from 490 to 1200°C, and reflect the ~100–200°C difference between the controlling thermocouple and actual sample in the furnace design used in both laboratories.

For each analysis the 1σ errors include estimates of the standard deviation of analytical precision on the peak signals, the system blank, spectrometer mass discrimination, and reactor corrections. Inverse-variance weighted mean ages and standard deviations were calculated according to *Taylor* [1982]. Precision estimates for each monitor point along the neutron fluence curves for the vials suggest that the error in J, the neutron fluence parameter, was about 0.3%; this error was propagated into the final age plateau and isochron ages for each analysis. Ages were calculated using the decay constants of *Steiger and Jäger* [1977] and are reported with $\pm 1\sigma$ uncertainties.

Criteria used to determine whether an incremental heating experiment gave meaningful results and to calculate plateau and isochron ages were as outlined previously [*Pringle*, 1993; *Singer and Pringle*, 1996]. Briefly, these criteria include the following: (1) age spectrum plateaus are defined by at least three contiguous steps all concordant in age at the 95% confidence level and comprising >50% of the ^{39}Ar released, (2) a well-defined isochron exists for the plateau points as defined by the F-variate statistic SUMS/$(N - 2)$ [*York*, 1969], (3) the plateau and isochron ages are concordant at the 95% confidence level, and (4) the $^{40}Ar/^{36}Ar$ intercept on the isochron diagram does not differ from the atmospheric value of 295.5 at the 95% confidence level. The isochron ages are preferred over the weighted mean plateau ages because they combine estimates of analytical precision plus internal disturbance of the sample (scatter about the isochron) and they make no assumption about the trapped argon component. Isochrons were calculated using the methods of *York* [1969].

3. Results

Data from the incremental-heating experiments are summarized in Table 1, with complete analyses of each sample given

Table 1. Summary of ^{40}Ar/^{39}Ar Incremental-Heating Experiments on Punaruu Valley and Haleakala Basalts

				Total Fusion	Age Spectrum				Isochron Analysis			
Sample Site	Material	Weight, mg	K/Ca (Total)	Age, Ma	Increments Used, °C	^{39}Ar, %	Age ± 1σ, Ma	Sums $(N-2)$	N	Sums $(N-2)$	^{40}Ar/^{36}Ar ± 1σ Intercept	Age ± 1σ, Ma
						Tahiti, Punaruu Valley						
R1D	gm	99	0.42	0.875 ± 0.006	750–1200	87.9	0.871 ± 0.005	1.25	8	0.89	291.4 ± 2.1	0.891 ± 0.011
TJ	wr	59	0.80	0.957 ± 0.006	800–975	81.9	0.972 ± 0.005	0.62	4	0.59	283.6 ± 15.1	0.980 ± 0.011
TI	wr	60	0.50	0.981 ± 0.009	700–1250	100.0	0.979 ± 0.008	0.53	9	0.59	295.8 ± 1.5	0.977 ± 0.010
TB	wr	58	0.45	0.987 ± 0.009	690–1220	96.6	0.988 ± 0.005	0.86	8	0.94	294.4 ± 1.2	0.991 ± 0.006
TA	wr	61	0.50	0.983 ± 0.006	800–1250	87.9	0.981 ± 0.005	2.01	6	0.37	292.6 ± 0.8	0.989 ± 0.005
M2G	gm	29	0.42	1.016 ± 0.009	900–1050	63.0	1.007 ± 0.009	0.21	3	0.32	294.8 ± 1.9	1.012 ± 0.018
M2H	wr	42	0.57	1.001 ± 0.009	650–975	92.4	1.002 ± 0.005	0.66	8	0.57	296.9 ± 1.1	0.992 ± 0.009
PF	wr	62	0.70	1.040 ± 0.004	700–1020	89.3	1.050 ± 0.004	2.76	7	3.01[b]	291.3 ± 7.9	1.053 ± 0.006
BKS	wr	59	0.29	1.108 ± 0.008	890–1250	52.0	1.096 ± 0.009	2.17	5	1.79	293.9 ± 1.1	1.102 ± 0.009
BKT	wr	53	0.56	1.097 ± 0.004	700–950	75.7	1.108 ± 0.004	0.45	6	0.47	299.7 ± 6.4	1.105 ± 0.006
BKH	wr	49	0.49	1.097 ± 0.005	775–950	63.9	1.116 ± 0.004	0.45	4	0.16	305.9 ± 10.8	1.107 ± 0.010
						Haleakala, Hawaii						
Flow 20b	wr	120	0.33	1.043 ± 0.018	520–1200[a]	100.0	0.950 ± 0.016	7.27	11	3.08[b]	300.6 ± 0.8	0.886 ± 0.013
Flow 20a	wr	120	0.44	0.878 ± 0.005	440–1140[a]	98.5	0.880 ± 0.004	1.37	13	1.19	293.7 ± 0.8	0.883 ± 0.004
Flow 17l	wr	120	0.47	0.869 ± 0.005	630–930[a]	60.9	0.887 ± 0.004	0.44	6	0.47	297.6 ± 5.1	0.885 ± 0.005
Flow 17b	wr	120	0.66	0.903 ± 0.007	630–990[a]	68.3	0.886 ± 0.004	0.30	7	0.52	295.2 ± 3.1	0.887 ± 0.008
Flow 17	wr	120	0.41	0.971 ± 0.025	490–1060[a]	97.0	0.944 ± 0.021	1.23	6	0.99	287.5 ± 9.5	0.937 ± 0.020
	wr	120	0.43	0.894 ± 0.010	710–1060[a]	68.2	0.878 ± 0.098	0.08	3	0.11	296.0 ± 1.8	0.875 ± 0.018
	wr	120	0.44	0.880 ± 0.012	490–1160[a]	100.0	0.888 ± 0.011	1.12	5	1.24	292.6 ± 1.8	0.915 ± 0.022
	wr	100	0.44	0.910 ± 0.011	700–1060	59.2	0.889 ± 0.007	0.28	10	0.40	295.5 ± 1.2	0.889 ± 0.012
												0.898 ± 0.009[c]
Flow 16b	wr	120	0.44	0.854 ± 0.008	490–1160[a]	100.0	0.876 ± 0.011	6.65	6	7.24[b]	289.0 ± 10.3	0.883 ± 0.016
	wr	100	0.31	0.917 ± 0.011	780–1200	96.3	0.904 ± 0.009	2.12	11	2.49[b]	297.9 ± 1.8	0.874 ± 0.025
												0.880 ± 0.013[d]
Flow 16	wr	100	0.33	0.928 ± 0.009	700–1200	100.0	0.914 ± 0.008	1.59	15	1.78	298.3 ± 1.1	0.887 ± 0.014
	wr	120	0.29	0.900 ± 0.008	490–1160[a]	100.0	0.899 ± 0.006	0.69	6	0.84	295.4 ± 1.9	0.900 ± 0.007
												0.897 ± 0.006[d]

Analytical methods and data reduction are summarized by *Singer and Pringle* [1996]. Groundmass, gm; whole rock, wr. All ages calculated relative to 27.92 Ma for TCs sanidine [*Duffield and Dalrymple*, 1990]; all errors reported at 1σ analytical precision.

[a] Temperatures denote experiments done at SURRC, all others measured in Geneva (see text).

[b] SUMS/$(N-2)$ suggests some geologic or experimental error beyond analytical precision (see text).

[c] Weighted mean isochron age from four experiments.

[d] Weighted mean isochron age from two experiments.

in Table A1.[1] The 11 age determinations from the Punaruu Valley span a period of 216 kyr and are consistent with the stratigraphic order of lava flows when the analytical errors are considered at the 95% confidence level (critical value test). Experiments on the seven lavas from Haleakala gave ages between circa 0.874 Ma and 0.937 Ma that are concordant with one another and with the youngest dated flow in the Punaruu Valley. From the two localities, experimental results are described in sections 3.1 and 3.2 in order of stratigraphic position from the oldest to youngest lava flows.

3.1. Punaruu Valley, Tahiti

Three samples, BKH, BKT, and BKS were analyzed to assess the age of the lowermost polarity transition recorded in the Punaruu Valley (Figure 1). On the basis of K-Ar ages (Figure 1), *Chauvin et al.* [1990] suggested that this period of intermediate field orientations and low magnetic field intensity represented the CMNS, although they pointed out that no fully normal directions were recorded in the Tahitian lavas (Figure 1). All three experiments yielded slightly discordant age spectra (Figure 4), however each met the criteria for reliable age determinations. Samples BKH and BKT gave age spectra with plateaus comprising 64% and 76% of the gas released and whose steps define isochrons of 1.107 ± 0.010 Ma and 1.105 ± 0.006 Ma, respectively (Table 1 and Figure 4). The decreasing apparent ages in the final, highest-temperature gas steps in these and three other experiments (samples PF, TJ, and M2G, Figure 4) may reflect the influence of either (1) a poorly constrained high-temperature furnace blank or (2) minor ^{39}Ar implantation into low K refractory phases like olivine via recoil from fine-grained K-rich matrix phases during irradiation [*Turner and Cadogan*, 1974]. Evidence for the latter includes a tenfold decrease in K/Ca ratios obtained from the discordant high-temperature steps suggesting that olivine contributes heavily to gas released above 1100°C (see electronic Table A1). Sample BKS produced an age spectrum that gradually staircases to lower apparent ages in successively higher-temperature steps. Although this pattern may reflect subtle effects of redistribution of ^{39}Ar by recoil from fine-grained phases in the matrix, the last five steps comprising 52% of the gas released yielded a plateau whose points define an isochron of 1.103 ± 0.009 Ma (Table 1 and Figure 4). It should be emphasized that any ^{39}Ar recoil artifacts appear to be minor and would cause apparent ages slightly in excess of the true age in the lower-temperature gas increments. The observation that isochrons calculated from these experiments give ages perfectly consis-

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[1] Supporting Table A1 is available on diskette or via Anonymous FTP from kosmos.agu.org, directory APEND (Username = anonymous, Password = guest). Diskette may be ordered from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009 or by phone at 800-966-2481; $15.00. Payment must accompany order.

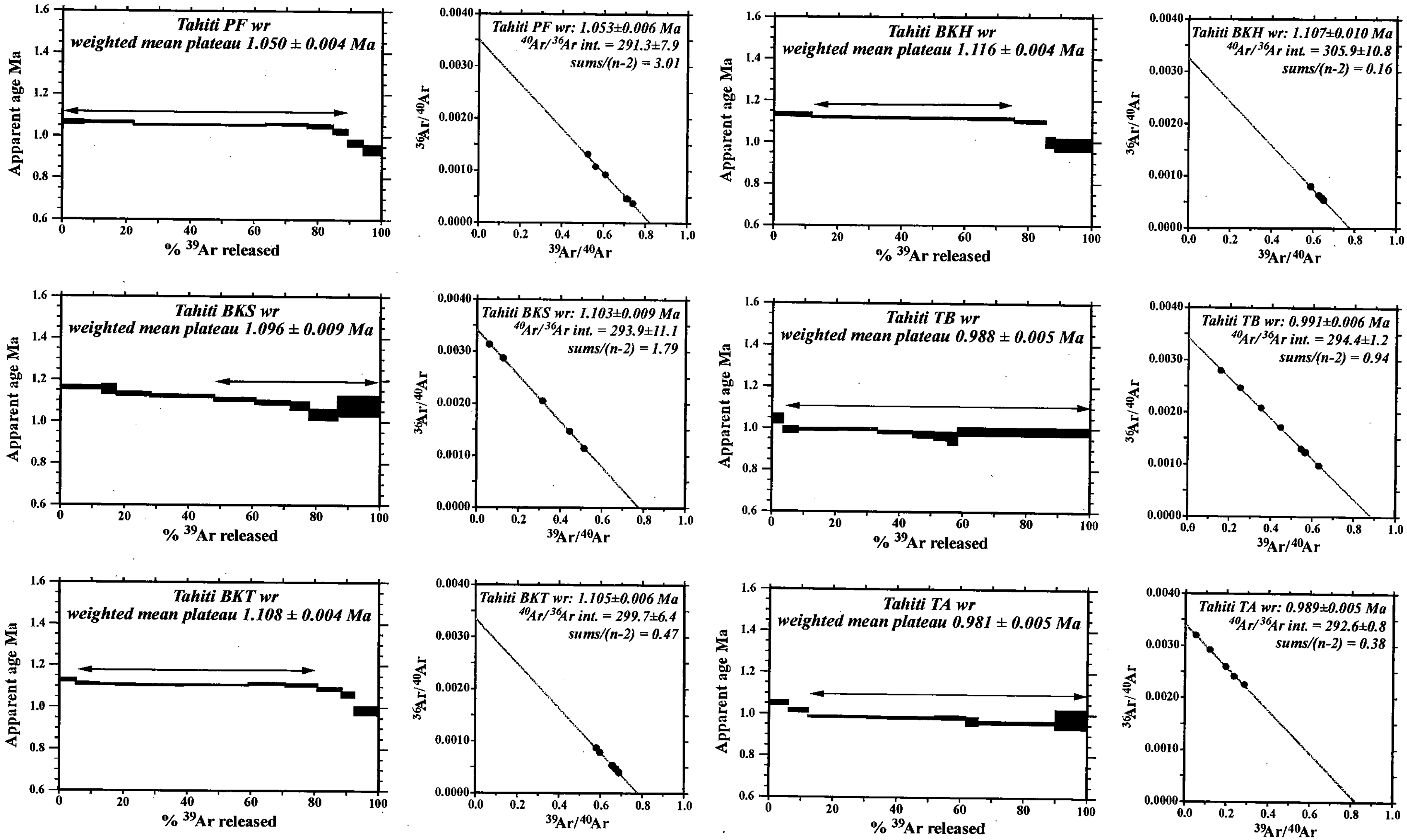

Figure 4. Age spectra and inverse isochron correlation diagrams for 11 samples from the Punaruu Valley basaltic lava flow sequence.

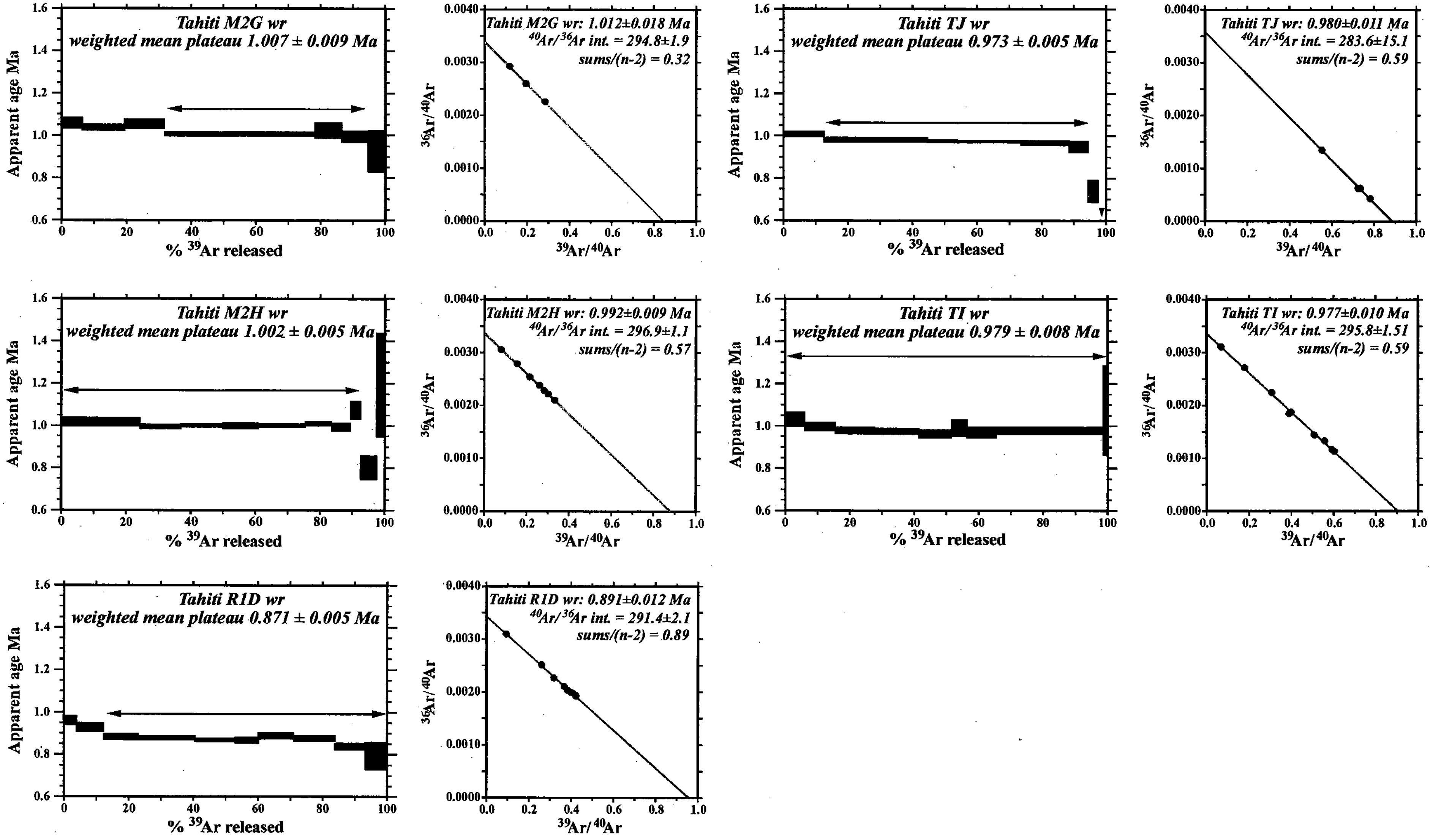

Figure 4. (continued)

tent with the stratigraphy (Figure 1) also argues that ^{39}Ar recoil effects are not significant. The isochron ages of BKH, BKT, and BKS are neither distinguishable from one another or from the K-Ar ages of 1.090 ± 0.020 Ma and 1.110 ± 0.030 Ma of samples BKG and PKB that bracketed the lowermost period of transitional polarity recorded in the Punaruu lava sequence (Figure 1). The weighted mean age of the three isochrons is 1.105 ± 0.005 Ma, our best estimate for the timing of the transitional geomagnetic field behavior recorded by these lavas.

Seven experiments were performed to constrain the onset, duration, and termination of the JNS. From near the base of the JNS, sample PF has an intermediate polarity with a shallow reversed VGP latitude of −62.9° and low intensity (3–5 times lower than adjacent reversely or normally magnetized flows [*Chauvin et al.*, 1990]). We interpret this flow to record transitional field behavior during the onset of the JNS; it yielded a seven-step plateau containing 89% of the gas released whose points define an isochron of 1.053 ± 0.006 Ma (Table 1 and Figure 4). Although the SUMS/(N − 2) value for the isochron is slightly high and may suggest some minor nonanalytical errors associated with this sample, the ^{40}Ar/^{36}Ar intercept of 291.3 ± 7.9 is indistinguishable from the atmospheric value, and we take the isochron as our best age for the onset of the JNS. Two stratigraphically higher normally magnetized samples, M2H and M2G, yielded plateaus with isochrons of 0.992 ± 0.009 Ma and 1.012 ± 0.018 Ma that are indistinguishable from one another (Figure 1). Four additional samples, TA, TB, TI, and TJ, were used to constrain the shift from a transitional to a reversed geomagnetic field at the end of the JNS (Figure 1). The isochrons produced from these samples are 0.989 ± 0.005 Ma, 0.991 ± 0.006 Ma, 0.977 ± 0.010 Ma, and 0.980 ± 0.011 Ma, respectively (Figure 4). The four isochrons are indistinguishable from one another at the 95% confidence level; thus we feel justified in calculating from them a weighted mean age for the field reversal of 0.986 ± 0.005 Ma.

Sample R1D is from a lava that recorded a shallow, −52.7°, intermediate paleomagnetic direction and very low magnetic intensity (tenfold lower than adjacent flows in the sequence [*Chauvin et al.*, 1990]) between the termination of the JNS and the Matuyama-Brunhes reversal (Figure 1). It gave an eight-step plateau comprising 88% of the gas released; the isochron from this experiment is 0.891 ± 0.012 Ma (Figure 4).

3.2. Haleakala Volcano, Hawaii

Experiments done at Geneva and SURRC on the stratigraphically lowest flow unit 16 that has a fully reversed paleomagnetic direction (Figure 2) gave concordant age spectra with a weighted mean age of 0.905 ± 0.004 Ma. The combined isochron calculated from the 21 individual analyses is 0.897 ± 0.006 and indicates a trapped component with an atmospheric composition (Table 1 and Figure 5).

Experiments were also done at Geneva and SURRC on flow unit 16b, the lowest transitionally magnetized lava in the section (Figure 2). These gave similar, but slightly discordant, age spectra whose mean plateau age is 0.886 ± 0.003 Ma. Isochron ages derived from these data are 0.874 ± 0.025 Ma and 0.883 ± 0.016 Ma and give a weighted mean age of 0.880 ± 0.013 Ma (Table 1 and Figure 5). The isochrons indicate an atmospheric trapped component, however, the SUMS/(N − 2) terms are large and suggest some nonanalytical errors have affected these results.

Three experiments at SURRC and one at Geneva were completed on flow 17; these produced similar age spectra that vary in the number and precision of their steps (Table 1 and Figure 2). The four isochron ages are between 0.937 ± 0.020 Ma and 0.875 ± 0.018 Ma and are concordant at the 95% confidence level. The combined isochron from these experiments yielded an age of 0.898 ± 0.009 Ma and indicates an atmospheric trapped component (Figure 5).

A 13-step experiment on flow 17b yielded six steps, composing 68% of the ^{39}Ar released, that define a plataeu age of 0.866 ± 0.004 Ma and an isochron of 0.887 ± 0.008 Ma. A similar experiment on flow 171 yielded a six-step plateau age of 0.887 ± 0.004 Ma and an isochron of 0.885 ± 0.005 Ma (Figure 5). The 14 steps released from flow 20a are nearly concordant and gave a plateau age of 0.880 ± 0.004 Ma and an isochron of 0.883 ± 0.004 Ma. In contrast, the 12-step experiment on the stratigraphically youngest flow, 20b, gave a discordant age spectrum with the initial 43% of the gas released at lower temperatures giving lower apparent ages than the remainder (Figure 5). Despite the discordant age spectrum, the 12 gas steps together define an isochron of 0.886 ± 0.013 Ma that indicates a trapped ^{40}Ar/^{36}Ar value of 300.6 ± 0.8 that is significantly in excess of that found in modern air. In addition, the SUMS/(N − 2) term exceeds that expected from analytical errors; thus we suspect that this lava sample contains a small component of excess ^{40}Ar. The interpretation that excess ^{40}Ar was released from a refractory mineral such as olivine or pyroxene, is supported by the threefold to fourfold lower K/Ca ratios of gas steps released at high temperature (see electronic Table A1).

Despite the high SUMS/(N − 2) values for experiments on the lowest and highest lava samples in the Haleakala section, the isochron ages obtained from the six lava flows are indistinguishable from one another at the 95% confidence level. Because these samples span a sequence of 16 lava flow units that have a similar transitional VGP orientation (Figures 2 and 3), the weighted mean of the six isochrons, 0.886 ± 0.003 Ma, is our best estimate for the age of the geomagnetic field transition recorded by these lavas.

4. Number and Timing of Reversals and Events in the Late Matuyama Chron

Our results from Punaruu Valley and Haleakala volcano, combined with published data and studies in progress, mandate a significant revision of the geomagnetic polarity timescale. Collectively, these data indicate that no less than seven reversals, aborted reversals, or excursions occurred during the 400 kyr that elapsed between the onset of the CMNS and the Matayma-Brunhes reversal. These geomagnetic transitions, their ages, and bearing on understanding reversal processes and the geodynamo are discussed in sections 4.1–4.4 beginning with the oldest event.

4.1. Punaruu Event

The oldest period of transitional field behavior recorded in Punaruu Valley was originally thought by *Chauvin et al.* [1990] to be an expression of the CMNS. It is therefore instructive to review the evidence that defines the CMNS in light of our new age determinations. A further review of published data is also presented to illuminate results that are consistent with the existence of a geomagnetic event shortly after the CMNS. The following discussion leads us to argue the discovery of a new short-lived polarity event in the Punaruu Valley on Tahiti.

The Cobb Mountain Normal-Polarity Subchron was desig-

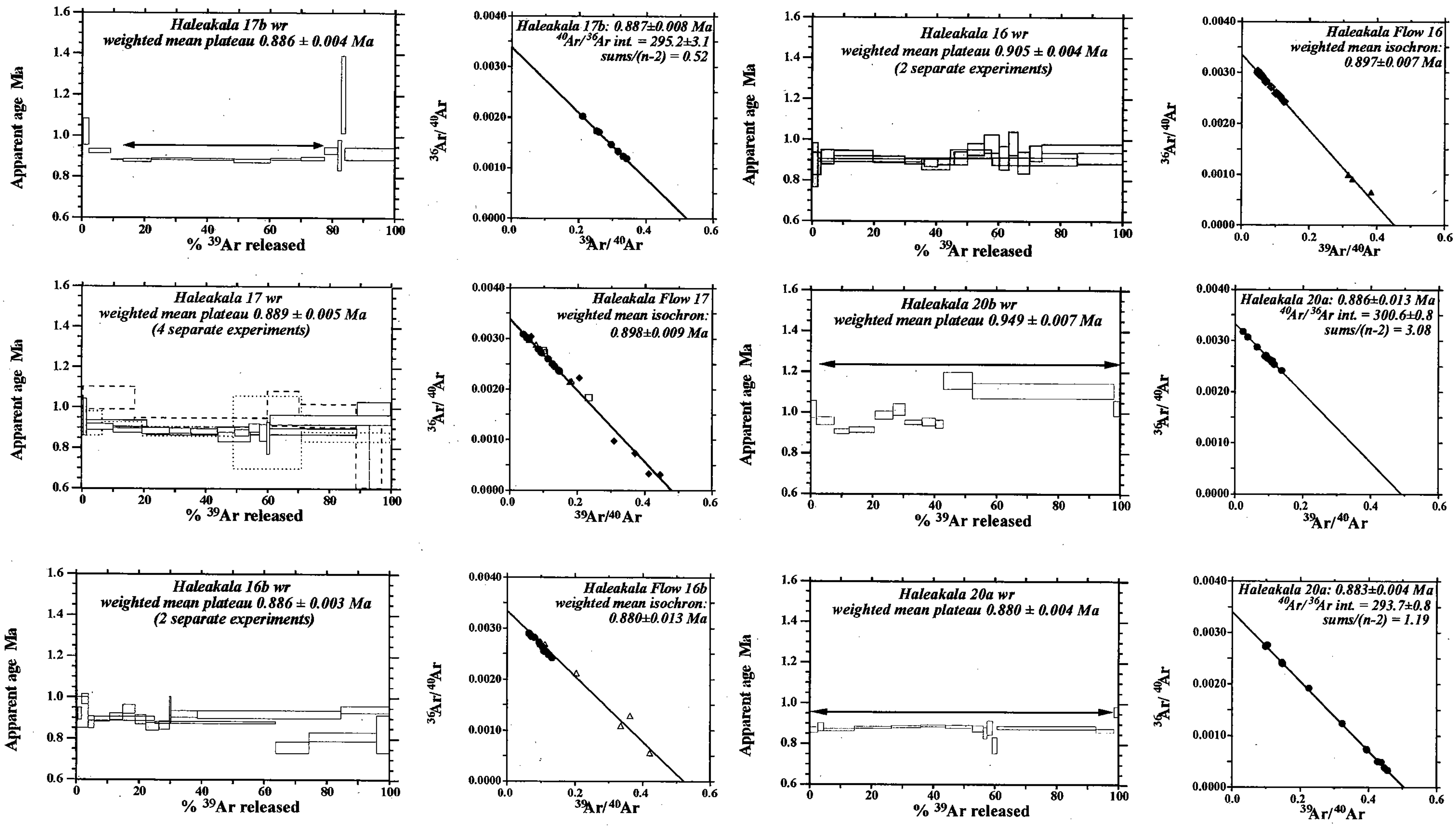

Figure 5. Age spectra and inverse isochron correlation diagrams for seven samples from the Haleakala basaltic lava flow sequence. For flows 16, 16b, and 17, the isochron ages are the weighted means of the multiple isochron ages in Table 1. The plotted isochrons for these three samples include data, normalized for different *J* values, from each separate experiment.

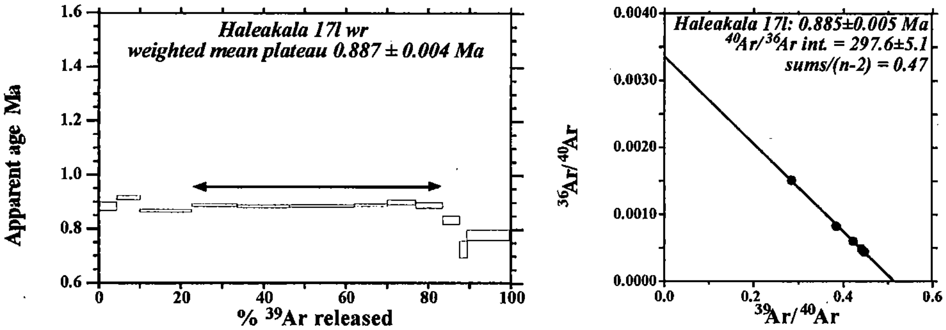

Figure 5. (continued)

nated by *Mankinen et al.* [1978] on the basis of finding that sanidine from the transitionally magnetized rhyolite of Alder Creek, which is overlain by a reversely magnetized lava, gave a K-Ar age of 1.12 Ma, which was older than the JNS but similar to the suggested ages of transitionally magnetized sediments from several localities worldwide. *Turrin et al.* [1994] and *Renne et al.* [1998] refined the age of the rhyolite of Alder Creek using precise $^{40}Ar/^{39}Ar$ laser fusion and incremental-heating techniques on sanidine and concluded that (1) the age of the CMNS is 1.181 ± 0.007 Ma (relative to TCs at 27.92 Ma), consistent with the astronomical estimate of 1.19 Ma (Table 2), and (2) the 6% younger K-Ar age obtained by *Mankinen et al.* [1978] reflected incomplete degassing of argon from the sanidines. In fact, *Izett and Obradovich* [1994] and *Turrin et al.* [1994] argue that the latter problem may have affected the K-Ar age determinations from most sanidine samples used to construct and revise the early GPTS.

Chauvin et al. [1990] reported whole rock K-Ar ages of 1.09 ± 0.02 and 1.11 ± 0.03 from two basalt flows bracketing the lowermost transitionally magnetized lavas in the Punaruu Valley (Figure 1); therefore the transitional directions were interpreted to represent field behavior during the CMNS. The K-Ar ages are identical within error; however, they are significantly younger than the revised age of the CMNS at the 95% confidence level. Thus, even before our $^{40}Ar/^{39}Ar$ experiments were conducted, there was reason to question whether these transitional magnetizations were indeed acquired during the CMNS. Our weighted mean age for these lavas from three concordant isochrons is 1.105 ± 0.005 Ma which agrees with both K-Ar ages but is significantly younger than both the 1.181 ± 0.007 Ma age of *Renne et al.* [1994] and the astronomical age of 1.19–1.24 Ma for the CMNS [*Shackleton et al.*, 1990; *Berggren et al.*, 1995] (see Table 2). We conclude that the transitional paleodirections recorded in these lavas reflect behavior of the Earth's magnetic field that occurred ~76 kyr after the CMNS. This period of transitional behavior occurred well before the onset of the JNS and was closely preceded and postdated by a fully reversed geomagnetic field (Figure 1).

Lava flows in two volcanic areas of California provide additional support for a post-CMNS event. At Cobb Mountain the rhyolite of Alder Creek is the oldest of three successive lava flows; it is overlain by the dacite of Cobb Mountain (sanidine K-Ar age, 1.06 ± 0.02 Ma), which is in turn overlain by the dacite of Cobb Valley (whole rock K-Ar age, 1.08 ± 0.03 Ma)

Table 2. Some K-Ar, $^{40}Ar/^{39}Ar$, and Astronomical Ages for Geomagnetic Reversals in the Late Matuyama Chron

	K-Ar		$^{40}Ar/^{39}Ar$				$^{40}Ar/^{39}Ar$, K-Ar			
Reversal/Event	Mankinen et al.[a]	Champion et al.[b]	Tauxe et al.[c]	Spell and McDoug[d]	Izett and Obrad[e]	Renne et al.[f]	Lanphere et al.[g]	$^{40}Ar/^{39}Ar$ This Study[h]	Astronomical Shackleton et al.[i]	Combined Berggren et al.[j]
Matuyama-Brunhes		0.73		0.78	0.77			0.779 ± 0.002	0.78	0.78
Kamikatsura		0.85						0.886 ± 0.003		
Santa Rosa				0.91	0.92		0.93	0.922 ± 0.012		
Top Jaramillo	0.90	0.90	0.99	0.91	0.97			0.986 ± 0.005	0.99	0.99
Bottom Jaramillo	0.97	0.97		1.00	1.11			1.053 ± 0.006	1.07	1.07
Punaruu	1.08 ± 0.03							1.105 ± 0.005		
Cobb Mountain	1.12	1.10				1.181 ± 0.007			1.19	1.21–1.24

Age in parentheses is K-Ar ages discussed in the text. Data from references d and f are recalculated relative to the TCs fluence monitor at 27.92 Ma.

[a] *Mankinen et al.* [1978, 1981] and *Mankinen and Gromme* [1982]; K-Ar dating of transitionally magnetized lavas at Cobb Mountain and Coso volcanic field.

[b] *Champion et al.* [1988]; K-Ar dating of lavas, compilation, and comparison with sediment and marine data.

[c] *Tauxe et al.* [1992]; $^{40}Ar/^{39}Ar$ age extrapolated to upper Jaramillo reversal.

[d] *Spell and McDougall* [1992]; $^{40}Ar/^{39}Ar$ ages extrapolated or bracketing reversals; ages recalculated relative to TCs at 27.92 Ma.

[e] *Izett and Obradovich* [1994]; $^{40}Ar/^{39}Ar$ ages extrapolated or bracketing reversals.

[f] *Renne et al.*'s [1998] intercalibration data for ACs recalculated to TCs at 27.92 Ma; note that *Turrin et al.*'s [1994] $^{40}Ar/^{39}Ar$ age of ACs was 1.186 ± 0.007 relative to TCs at 27.84 Ma.

[g] *Lanphere et al.* [1997]; $^{40}Ar/^{39}Ar$ and K-Ar dating of two normal lavas and one intermediate polarity lava in the Cascade Range

[h] This work plus *Singer and Pringle* [1996]; direct $^{40}Ar/^{39}Ar$ dating of reversals; age for Santa Rosa event is average of seven determinations discussed in text.

[i] *Shackleton et al.* [1990], astronomical timescale, orbital tuning of marine oxygen isotope record.

[j] *Berggren et al.* [1995]; combined astronomical, $^{40}Ar/^{39}Ar$, and magnetic polarity timescale.

[*Mankinen et al.*, 1978, 1981]. Five sites within the rhyolite of Alder Creek have transitional magnetizations, and only one has a fully normal orientation, whereas the dacite of Cobb Mountain is reversely magnetized, and the dacite of Cobb Valley, the youngest of the three units, has a transitional magnetic remanence direction [*Mankinen et al.*, 1978, 1981]. Thus evidence existed as early as 1978 that a geomagnetic event of some kind older than the JNS had occurred soon after the CMNS, separated from it by a period of reversed polarity.

Subsequently, *Mankinen and Grommé* [1982] found that two basalt flows in the Coso Range have normal polarity. These lavas had earlier given K-Ar whole rock ages of 1.07 ± 0.12 Ma and 1.07 ± 0.14 Ma. A third lava from the Coso Range with a transitional remanence direction was dated at 1.08 ± 0.06 Ma *Duffield et al.*, 1980].

Considering the uncertainties of the K-Ar ages obtained from the Cobb Mountain area and the Coso Range, *Mankinen and Grommé* [1982] claimed that the lavas in the Coso Range and the rhyolite of Alder Creek had all recorded the CMNS at about 1.10 Ma. The possibility that the lavas from the Coso Range actually recorded the later episode of transitional polarity recorded by the dacite of Cobb Valley was not discussed, although the uncertainties of the K-Ar ages and the similar paleomagnetic directions found at all but one of the sites in the rhyolite of Alder Creek and the dacite of Cobb Valley permit such a correlation (Figure 6).

It is also worth noting that the K-Ar age from sanidine in the reversely magnetized dacite of Cobb Mountain may be too young due to incomplete degassing of radiogenic argon as discussed earlier. Although at face value, the K-Ar ages of 1.08 ± 0.03 for the transitionally magnetized dacite of Cobb Valley and 1.07 ± 0.12 Ma for Coso Range basalts are concordant with the Punaruu lavas, they too may slightly underestimate the true eruptive ages for these lavas due to argon loss via alteration or devitrification of groundmass phases [e.g., *Baksi*, 1995]. In any case, the poorer precision of the latter age determinations ensure that they remain consistent with the Punaruu lava ages even if they are increased by up to 6% (Figure 6). The evidence summarized here, combined with our new results, indicates that a geomagnetic event occurred about 76 kyr after termination of the CMNS but before the onset of the JNS. Because fully normal directions have not been observed, we propose that this period of field behavior be named the Punaruu event (Figure 6).

4.2. Age and Duration of the Jaramillo Normal Polarity Subchron

Spell and McDougall [1992] and *Spell and Harrison* [1993] reported several sanidine ^{40}Ar/^{39}Ar laser fusion ages of post-collapse rhyolite domes in the Valles Caldera whose K-Ar ages had earlier formed the basis for defining the JNS [*Doell and Dalrymple*, 1966; *Doell et al.*, 1968]. Using their results to interpolate a new GPTS, *Spell and McDougall* [1992] suggested that reversals bounding the JNS occurred at 1.00 Ma and 0.90 Ma; the choice for the upper boundary of the JNS was apparently constrained by their 0.905 ± 0.004 Ma age for the transitionally magnetized Cerro Santa Rosa I dome (all ages recalculated relative to TCs at 27.92 Ma; see Table 2 and Figure 6).

Izett and Obradovich [1994] published sanidine ^{40}Ar/^{39}Ar laser fusion ages from the same rhyolite domes studied by *Spell and McDougall* [1992], including an age of 1.004 ± 0.019 Ma for the normally magnetized Cerro del Abrigo III dome and 0.916 ± 0.017 Ma for Cerro Santa Rosa I. The former age is significantly older than *Spell and McDougall*'s [1992] 0.973 ± 0.010 Ma age for Cerro del Abrigo III; however, the latter age for Cerro Santa Rosa I is indistinguishable from theirs. On the basis of these results, plus an imprecise ^{40}Ar/^{39}Ar isochron age of 1.10 ± 0.08 Ma for Ivory Coast tektites that were deposited in reversely magnetized marine sediment just below normally magnetized sediment, *Izett and Obradovich* [1994] estimated that the JNS occurred between 1.11 Ma and 0.97 Ma (Figure 6).

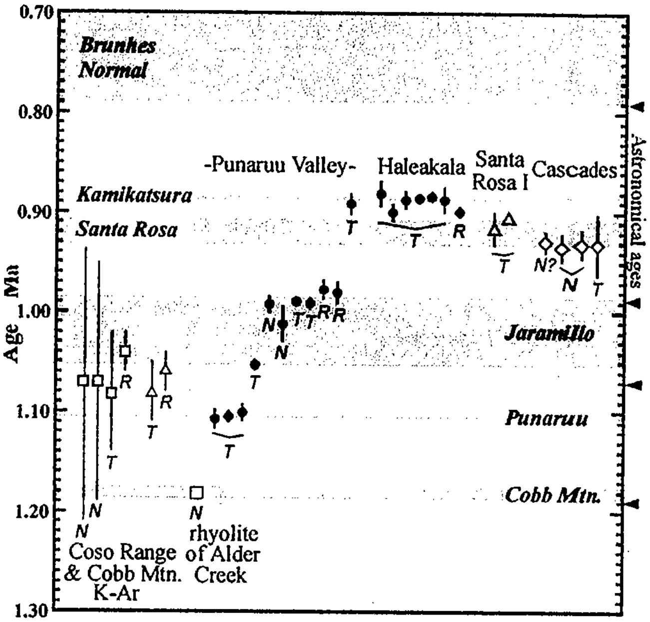

Figure 6. The ^{40}Ar/^{39}Ar and K-Ar ages bearing on reversals and events of the late Matuyama Reversed Chron. Where appropriate ^{40}Ar/^{39}Ar ages were recalculated relative to TCs at 27.92 Ma. K-Ar data from the Coso Range and Cobb Mountain are from *Mankinen and Grommé* [1982] and *Mankinen et al.* [1978]. The ^{40}Ar/^{39}Ar age of sanidine from the rhyolite of Alder Creek is from *Renne et al.* [1994]. ^{40}Ar/^{39}Ar ages in solid symbols are new from this study of basaltic lavas in Punaruu Valley, Tahiti, and Haleakala, Hawaii. Two ^{40}Ar/^{39}Ar ages for Cerro Santa Rosa I are from *Izett and Obradovich* [1994] and *Spell and McDougall* [1992]. K-Ar and ^{40}Ar/^{39}Ar ages for lavas from Mount Baker and Mount Hood, in the Cascade Range are given by *Lanphere et al.* [1997]. N, normally magnetized; T, transitional; R, reversed. Astronomical ages from sources in Table 2.

Our new ^{40}Ar/^{39}Ar results indicate that the JNS lasted about 67 kyr between 1.053 ± 0.006 Ma and 0.986 ± 0.005 Ma (Figure 1); these ages agree neither with the estimates of *Spell and McDougall* [1992] nor with those of *Izett and Obradovich* [1994] (Figures 6 and 7). They are, however, in very good agreement with the interpolated estimate for the top of the JNS of *Tauxe et al.* [1992] and with astronomical estimates for the ages of these reversals (Table 2 and Figure 6). Our age for the onset of the JNS is about 17 kyr (1.6%) younger that the astronomical estimate of 1.07 Ma. The sample chosen for analysis is from the stratigraphically youngest of four lavas that record this transition (Figure 1) and was the only one of the four that was judged to be suitable for ^{40}Ar/^{39}Ar dating. Thus our direct age for this transition may well record the waning stages of a reversal that took several thousand years to complete, similar to the Matuyama-Brunhes reversal [*Singer and Pringle*, 1996].