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$^{40}Ar/^{39}Ar$ age constraints for the Jaramillo Normal Subchron and the Matuyama-Brunhes geomagnetic boundary

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Abstract. Our mid-Pleistocene $^{40}Ar/^{39}Ar$ age recalibration of the geomagnetic polarity timescale is nearly in accord with the oxygen isotope, climate record calibration of the astronomical timescale proposed by Johnson (1982) and Shackleton et al. (1990). $^{40}Ar/^{39}Ar$ ages of a normally magnetized rhyolite dome in the Valles caldera, northern Mexico, yielded a weighted-mean age of 1.004 ± 0.019 Ma. A K-Ar age of 0.909 ± 0.019 Ma for this rock by Doell and Dalrymple (1966) was the linchpin for the recognition and calibration of the Jaramillo Normal Subchron (JNS). Other $^{40}Ar/^{39}Ar$ ages from the Valles caldera and $^{40}Ar/^{39}Ar$ ages of Ivory Coast tektites indicate that the JNS began at about 1.11 Ma and ended before 0.92 Ma, probably near 0.97 Ma. The Matuyama-Brunhes boundary occurred between 0.79 Ma and 0.76 Ma on the basis of $^{40}Ar/^{39}Ar$ sanidine ages from (1) three reversely magnetized rhyolite domes of the Valles caldera (0.793 ± 0.018 Ma, 0.794 ± 0.007 Ma, and 0.812 ± 0.023 Ma) and pumice (0.789 ± 0.006 Ma) from the reversely magnetized Oldest Toba Tuff of Sumatra and (2) pumice (0.764 ± 0.005 Ma and 0.757 ± 0.009 Ma) from the lower and upper units of the normally magnetized Bishop Tuff. The age of the boundary may be close to 0.77 Ma as deduced from rates of sedimentation in ancient Lake Bonneville, Utah.

Introduction

More than three decades ago, Earth scientists became increasingly aware that the polarity of Earth's magnetic field has changed repeatedly through geologic time, and isotopic dating of these polarity reversals resulted in a geomagnetic polarity time scale (GPTS) for the late Cenozoic. This combined paleomagnetic and isotopic research played a pivotal role in confirming plate tectonic theory [*Glen*, 1982], which revolutionized the Earth sciences. Continual refinement of isotopic ages, which define the GPTS, has increased the usefulness of geomagnetic polarity reversals as marker horizons in many types of geologic studies. We present $^{40}Ar/^{39}Ar$ data and ages for some key volcanic units that support changes in the isotopic age chronology of the GPTS using volcanic rocks erupted near the time of the geologically youngest two geomagnetic polarity reversals (Figure 1).

The older of the two reversals, originally called by *Doell and Dalrymple* [1966] the "Jaramillo event," is now named the "Jaramillo Normal Subchron" (JNS). It is recorded in middle Pleistocene rocks as a brief episode of normal polarity within the late Matuyama Chron. The younger of the two, called the "Matuyama-Brunhes boundary" (MBB), is registered in middle Pleistocene rocks worldwide and consists of a change from reverse (Matuyama Chron) to normal (Brunhes Chron) magnetic polarity.

To calibrate the JNS and MBB, as well as other magnetic polarity events, geochronologists have used the K-Ar method to obtain ages mainly for basalt lava flows but also for sanidine and obsidian of silicic volcanic rocks suspected to have been erupted just before and after these two magnetic polarity events. Sanidine is nearly an ideal K-Ar geochronometer, much better than the more widely available basalt lavas. Whole rock K-Ar ages of basalts generally have larger analytical errors than sanidine K-Ar ages because of their higher air-argon contents [*Mankinen and Dalrymple*, 1979, Table 3a].

The introduction of ultralow-background, ultrasensitive rare gas mass spectrometers coupled with the development of the $^{40}Ar/^{39}Ar$ method (see reviews by *Dalrymple and Lanphere* [1971] and *McDougall and Harrison* [1988]) provided new resolving power for geochronologic studies. The subsequent utilization of a continuous argon ion laser fusion $^{40}Ar/^{39}Ar$ system [*York et al.*, 1981] allowed the dating of minute amounts (~1 mg) of potassium-rich geologic materials with unprecedented precision, approaching 0.2%.

The $^{40}Ar/^{39}Ar$ method has several advantages over the K-Ar method; of paramount importance is that only ratios of argon isotopes are required to calculate an age rather than absolute amounts. Thus it is not necessary to extract all radiogenic argon from a mineral to calculate an accurate age. This advantage mitigates a technical problem inherent in the K-Ar technique of dating sanidine: K-Ar ages of this mineral have a tendency to be anomalously young, because the melt commonly forms a viscous mass that retains some radiogenic argon under ultrahigh vacuum. Even at the highest temperatures attainable (1800°C) in standard RF-induction heaters and resistance furnaces, generally 5–10% argon can remain trapped in some viscous sanidine melts (for example see *McDowell* [1983]). To avoid this problem, we used a $^{40}Ar/^{39}Ar$ analytical system [*Dalrymple*, 1989] to determine the age of certain sanidine-bearing volcanic rocks and obsidian emplaced near the JNS and MBB.

History of Dating the JNS and MBB

Geologic mapping in the Jemez Mountains, northern Mexico, established the lithostratigraphic framework for a large, complex volcanic center of Pleistocene age [*Smith et al.*,

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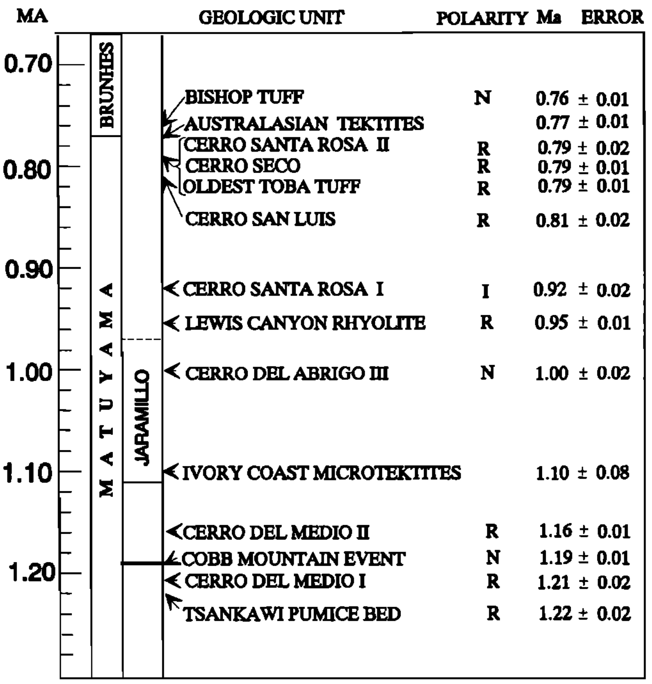

Figure 1. Diagram showing the mid-Pleistocene geomagnetic polarity time scale of this paper based on $^{40}Ar/^{39}Ar$ dating of selected volcanic rocks.

1970]. They showed that following the eruption of the upper unit of the Bandelier Tuff, a series of rhyolite dome flow complexes were emplaced sequentially in and along the ring fracture zone of the Valles caldera. The classic integrated paleomagnetic and K-Ar age study of these rocks was the basis for the recognition of the JNS [*Doell and Dalrymple*, 1966]. Moreover, this work was valuable also for providing calibration points near the MBB. Subsequently, *Doell et al.* [1968] gave a complete summary of the K-Ar ages of sanidine and obsidian from Cerro del Medio, Cerro del Abrigo, and Cerro Santa Rosa in the Valles caldera pertinent to the definition of the JNS.

Recently, isotopic ages of volcanic rocks relevant to the age of the MBB and Jaramillo Subchron were reported by *Izett et al.* [1988], *Izett and Obradovich* [1991, 1992a, 1992d], and *Spell and McDougall* [1992]. These authors determined K-Ar and $^{40}Ar/^{39}Ar$ ages of rhyolite domes of the Valles caldera that formed just prior to the MBB. *Baksi et al.* [1992] provided important new data on the precise age of the MBB by measuring $^{40}Ar/^{39}Ar$ ages of basalt flows extruded during the Matuyama-Brunhes field reversal. The age of the MBB is further constrained by our dating of sanidine from the reversely magnetized Oldest Toba Tuff of Sumatra [*Chesner*, 1988]. *Deino and Potts* [1990] provided a $^{40}Ar/^{39}Ar$ age of 0.974 ± 0.007 Ma (1σ) for anorthoclase from pumice in member 5 of the Olorgesailie Formation of Kenya. *Tauxe et al.* [1992] showed that this unit has reverse magnetic polarity and was deposited presumably just after the close of the Jaramillo.

The isotopic age of the normally magnetized Bishop Tuff of eastern California has been determined repeatedly to establish a calibration point in the earliest Brunhes Chron, thus placing an upper constraint on the time of the MBB. *Evernden et al.* [1957] first measured K-Ar ages of the Bishop using sanidine from samples of welded tuff, and their results suggested the MBB was older than 0.9 Ma. *Dalrymple et al.* [1965], however, suspected that the K-Ar ages of the Bishop were too old because the dated sanidine concentrates contained xenocrystic Sierran-age K-feldspar incorporated from country rock during emplacement of the Bishop welded tuff [see *Glen*, 1982, p. 250]. To circumvent this problem, Dalrymple and colleagues dated sanidine from pumice lumps rather than welded tuff and obtained an age of ~0.7 Ma, younger than the age (~0.9 Ma) of *Evernden et al.* [1957]. The K-Ar age of the Bishop Tuff was recomputed by *Bailey et al.* [1976] at 0.703 ± 0.015 Ma using the K-Ar analytical data of *Dalrymple et al.* [1965] and again was recomputed by *Mankinen and Dalrymple* [1979] at 0.727 ± 0.015 Ma using the newly adopted decay constants of *Steiger and Jäger* [1977]. *Mankinen and Dalrymple* [1979] assigned an age of 0.73 Ma to the MBB based on analysis of statistically acceptable [*Cox and Dalrymple*, 1967] K-Ar ages of normally and reversely magnetized rocks near the boundary, and this age of 0.73 Ma has been used traditionally for the age of the MBB since 1979.

Because progress had been made during the 1970s in mass spectrometers used for K-Ar dating, *Izett* [1982] measured 17 K-Ar ages of the Bishop Tuff and concluded that the basal air fall pumice unit and upper pyroxene-bearing unit were erupted at 0.738 ± 0.003 Ma and 0.736 ± 0.005 Ma, respectively. Using (1) the K-Ar age of the Bishop Tuff as 0.74 Ma, (2) the fact that layers of distal Bishop Tuff (Bishop ash bed) are found at 0.65 m and 1.83 m above the MBB in sedimentary rocks at two sites in the western United States [*Eardley et al.*, 1973; *Hillhouse and Cox*, 1976], and (3) computed deposition rates for sediments between the MBB and Bishop Tuff, *Izett et al.* [1988] proposed that the MBB occurred at 0.75 Ma. Tables 1 and 2 summarize the history of the isotopic dating of rhyolite volcanic rocks in the Valles caldera of New Mexico and the Bishop Tuff of California and their bearing on the ages of the JNS and MBB.

Methods

Material used for our isotopic dating of the JNS and MBB consisted of (1) the archived sanidine concentrates and other materials dated by *Doell and Dalrymple* [1966] and *Doell et al.* [1968], (2) sanidine from pumice lumps of the basal air fall units of the Bandelier Tuff collected by us, and (3) a sample of rhyolite from Cerro San Luis in the Valles caldera collected by R. L. Smith. In addition, we used some of the archived sanidine concentrates from pumice lumps from the basal air fall and upper pyroxene-bearing units of the Bishop Tuff dated by *Izett* [1982] and also new pumice samples of the basal air fall unit of the Bishop collected by us. A sample of the Oldest Toba Tuff of Chesner (1981) and a sanidine concentrate from this rock were obtained from C. A. Chesner.

Only pumice lumps that floated in water were used to prepare our sanidine concentrates, and these were either rolled in a ballmill or trimmed with a diamond saw to remove their rinds. The pumice lumps, thus prepared, were ultrasonically scrubbed in dilute HF (5%) to further remove possible near-surface contamination. Sanidine concentrates were obtained by heavy-liquid separation techniques. Glass adhering to the sanidine crystals was removed by etching in 24% HF accompanied by ultrasonic scrubbing for as long as

Table 1. History of Isotopic Dating of Key Rock Units in the Jemez Mountains, New Mexico, Bearing on the Age of the Jaramillo Subchron Using the K-Ar and ^{40}Ar/^{39}Ar Methods

	Post-Jaramillo Rocks Reversely Magnetized, Cerro Santa Rosa I	Jaramillo Age Rocks Normally Magnetized, Cerro del Abrigo III	Pre-Jaramillo Rocks Reversely Magnetized, Cero del Medio II
	Pre-1977 Decay Constants		
This paper	0.916 (0.929)	1.004 (1.019)	1.161 (1.178)
Izett and Obradovich [1992a]	0.916 (0.929)	1.004 (1.019)	1.161 (1.178)
Spell and McDougall [1992]	(0.915)	(0.973)	(1.13)
Izett and Obradovich [1992d]	0.92 (0.93)	1.00 (1.014)	1.16 (1.18)
Mankinen and Dalrymple [1979]	0.91 (K-Ar)	0.909 (K-Ar)	1.17 (K-Ar)
	Decay Constant Change [Steiger and Jäger, 1977]		
Doell et al. [1968]	0.907 (K-Ar)	0.909 (K-Ar)	1.17 (K-Ar)

^{40}Ar/^{39}Ar ages based on fluence-monitor minerals calibrated against MMhb-1 (513.9 Ma); ^{40}Ar/^{39}Ar ages in parentheses based on fluence-monitor minerals calibrated against MMhb-1 (520.4 Ma). Ages in millions of years. ^{40}Ar/^{39}Ar ages except where otherwise indicated.

3 min. Inspection of the sanidine concentrates dated by *Doell et al.* [1968] showed them to be of excellent quality, nevertheless, we ultrasonically scrubbed them in 24% HF for 3 min. We used only material in the 50–100-mesh size for dating.

A typical irradiation packet consisted of a milligram-size aliquot of sanidine loaded in a 10-mm diameter aluminum foil cup and covered with a 10-mm aluminum foil cap. The flattened, pancakelike packets were sandwiched between similar packets of sanidine neutron fluence monitors, arranged in a vertical stack in a 10-mm diameter quartz tube, and the positions of the packets in the tube were measured. The distance between adjacent packet centers was about 0.5 mm, and the lengths of the irradiation packages were no more than 3.0 cm. The sealed quartz vials were wrapped in cadmium foil to insure that the samples and fluence-monitor minerals were irradiated only with fast neutrons. Quartz vials were irradiated in the core of the U.S. Geological Survey's TRIGA reactor where they received fast neutron

Table 2. History of Isotopic Dating of Sanidine From Key Volcanic Rocks Bearing on the Age of the Matuyama-Brunhes Boundary Using the K-Ar and ^{40}Ar/^{39}Ar Methods

Reference	Bishop Tuff California, Normal	Rhyolite Domes Jemez Mountains Northern New Mexico, Reverse	Matuyama-Brunhes Boundary
	Pre-1977 Decay Constants		
This paper	0.76^a, 0.76^b	0.79	0.77
Baksi et al. [1992]			0.78
Izett and Obradovich [1992a]	0.76^a, 0.76^b	0.79	0.77
Izett and Obradovich [1991]	0.78^a, 0.76^b	0.81	0.79
Izett et al. [1988]	0.74^a, 0.74^b	0.75, 0.80	0.75
Hurford and Hammerschmidt [1985]	0.74^c, 0.73^d	···	>0.74
Izett [1982]	0.74 (K-Ar)	···	0.75 (K-Ar)
Mankinen and Dalrymple [1979]	0.73 (K-Ar)	0.74 (K-Ar)	0.73 (K-Ar)
	Decay Constant Change [Steiger and Jäger, 1977]		
Hildreth [1977]	0.72^a, 0.68^b, 0.73^b (K-Ar)		
Bailey et al. [1976]	0.71 (K-Ar)	···	>0.71 (K-Ar)
Doell et al. [1968]	···	0.71, 0.84 (K-Ar)	>0.70 (K-Ar)
Huber and Rinehardt [1967]	0.66 (K-Ar)	···	>0.66 (K-Ar)
Dalrymple et al. [1965]	0.70 (K-Ar)	···	>0.68 (K-Ar)
Evernden and Curtis [1961]	0.9–1.2 (K-Ar)	···	>0.9 (K-Ar)
Evernden et al. [1957]	0.87 (K-Ar)	···	>0.9 (K-Ar)

^{40}Ar/^{39}Ar ages based on fluence-monitor minerals calibrated against MMhb-1 (513.9 Ma), except ages of *Hurford and Hammerschmidt* [1985], which were based on Bern4M muscovite and Bern4B biotite. Ages in millions of years. ^{40}Ar/^{39}Ar ages except where otherwise indicated.

[a]Lower part of Bishop Tuff.

[b]Upper part of Bishop Tuff.

[c]Total fusion age.

[d]Plateau age.

doses of either 2.0×10^{17} total integrated neutron flux (*nvt*) or 3.0×10^{17} *nvt*.

A few milligrams of each of the irradiated samples were loaded into wells in a copper disk and placed in the sample chamber of the extraction line. Under ultrahigh vacuum, small clusters of sanidine crystals or single obsidian chips were heated with the 5-W argon ion laser at the maximum temperature attainable, 1500°C. The gas released from the samples was cleaned with Zr-Al and Zr-V-Fe getters, and the isotopic composition of the argon released was analyzed with an ultrasensitive rare gas mass spectrometer (Mass Analyzer Products 216 and Baur-Signer ion source) controlled by a computer [*Dalrymple and Duffield*, 1988; *Dalrymple*, 1989]. Absolute amounts of radiogenic ^{40}Ar measured varied from about 2.0×10^{-15} to 2.7×10^{-13} moles. Complete details of the continuous-laser ^{40}Ar/^{39}Ar apparatus in Menlo Park, California, including the nuclear reactor fluence attributes, irradiation procedures, and methods for measuring corrections for interfering argon isotopes induced by undesirable nuclear reactions with calcium and potassium were described by *Dalrymple et al.* [1981] and *Dalrymple* [1989].

Although the ^{40}Ar/^{39}Ar method has important advantages over the K-Ar method, it is a relative method, and ages of unknown samples are relative to assigned ages of fluence-monitor minerals. One fluence-monitor mineral used extensively is a hornblende (MMhb-1) from syenite of the McClure Mountain Complex of the Wet Mountains, Colorado [*Alexander et al.*, 1978]. Its published weighted-mean age, based on measurement of potassium and argon in 18 laboratories worldwide is 520.4 ± 1.7 Ma [*Samson and Alexander*, 1987]. However, the age of MMhb-1, as calibrated in the laboratory where our measurements were made [*Lanphere et al.*, 1990; *Dalrymple et al.*, 1993], is 513.9 Ma, about 1.26% younger than the published weighted-mean age of 520.4 Ma.

We used sanidine from the Fish Canyon Tuff (FCT) of Colorado and the Taylor Creek Rhyolite (TCR) of New Mexico as neutron fluence-monitor minerals because they are chemically uniform and their isotopic ages are within an acceptable range of the suspected ages of the volcanic rocks chosen to be dated. Sanidine from the FCT is used extensively by geochronology laboratories, whereas sanidine from the TCR is primarily an intralaboratory standard [*Dalrymple and Duffield*, 1988]. We emphasize that ages reported herein were calculated using fluence-monitor mineral ages as follows: FCT sanidine, 27.55 Ma; TCR sanidine, 27.92 Ma; both relative to an age of 513.9 Ma for MMhb-1 [*Lanphere et al.*, 1990]. To compare our ^{40}Ar/^{39}Ar ages with those of others, the following equation [*Dalrymple et al.*, 1993] provides an exact mathematical expression for converting from one monitor age to another.

$$t_2 = \frac{1}{\lambda} \log_e \left[\frac{e^{\lambda t_{m2}} - 1}{e^{\lambda t_{m1}} - 1} (e^{\lambda t_1} - 1) + 1 \right]$$

where t_1 is original age, t_2 is converted age, t_{m1} is monitor age used for t_1, t_{m2} is monitor age used for t_2, and λ (decay constant) = 5.543×10^{-10} yr^{-1}.

Errors associated with individual ages in Tables 3, 4, and 5 are estimates of the analytical precision at the 1-σ level and include our evaluation of the precision error (0.5%) of the fluence-calibration parameter J. On average, five determinations were made for each fluence-monitor package in the irradiation stack, and the estimated precision for each monitor was the error of the mean at the 95% level, which was propagated into the unknowns. Summary ages are weighted means, weighted by the inverse of the variance. The error calculated for a group of ages is the error of the mean at the 95% confidence level. All K-Ar and ^{40}Ar/^{39}Ar ages were calculated or recalculated using decay constants recommended by the Subcommission on Geochronology of the International Union of Geological Sciences [*Steiger and Jäger*, 1977].

Jaramillo Normal Subchron

Isotopic age calibration of the mid-Pleistocene GPTS containing the JNS interval was based originally on K-Ar ages of sanidine and obsidian from rhyolite domes, including Cerro del Medio, Cerro del Abrigo, and Cerro Santa Rosa of the Valles caldera, New Mexico [*Doell and Dalrymple*, 1966]. They concluded that the JNS began at 0.99 Ma and ended at 0.90 Ma. In detail, the age of the JNS was controlled by a K-Ar age for one of four satellitic rhyolite domes composing Cerro del Abrigo. The next to youngest of this group, which has normal magnetic polarity, was designated Cerro del Abrigo III. *Doell et al.* [1968, Table 3, site S37] reported a sanidine K-Ar age of 0.909 ± 0.019 Ma for this rhyolite, and it was the linchpin for the definition and calibration of the JNS.

Five ^{40}Ar/^{39}Ar analyses (Table 3) of a split of the sanidine concentrate dated by *Doell et al.* [1968] from Cerro del Abrigo III yielded a weighted-mean age of 1.004 ± 0.019 Ma. This age is ~10% older than the K-Ar age (0.909 ± 0.019 Ma) of *Doell et al.* [1968] and about 4% older than the ^{40}Ar/^{39}Ar age of 0.973 ± 0.010 Ma of *Spell and McDougall* [1992], if differences in ages of irradiation fluence-monitor minerals used are considered.

Onset of the Jaramillo

K-Ar ages constraining the onset of the JNS were first reported by *Doell and Dalrymple* [1966] and later documented by *Doell et al.* [1968, Table 3]. Obsidian from two of three reversely magnetized rhyolite flows of Cerro del Medio I and Cerro del Medio II domes (sites S35 and S34) yielded K-Ar ages of 1.06 ± 0.05 Ma and 1.17 ± 0.03 Ma, respectively. However, these ages conflict with the field stratigraphic relations of the rhyolite flows, which indicate that Cerro del Medio I is older than Cerro del Medio II [*Doell et al.*, 1968, p. 216].

Our ages and related analytical data for these rhyolite domes are listed in Table 3. The weighted mean for three obsidian ages (site S34) from the reversely magnetized rhyolite dome of Cerro del Medio II is 1.161 ± 0.010 Ma, in excellent agreement with the K-Ar age of the obsidian (1.17 ± 0.03 Ma) given by *Doell et al.* [1968]. The onset of the JNS is more broadly constrained by a single age of 1.207 ± 0.017 Ma from a small sanidine concentrate from three reversely magnetized paleomagnetic cores from Cerro del Medio I rhyolite (Table 3).

The start of the JNS is constrained more broadly by ages of sanidine from pumice lumps from the basal air fall units of the two units of the Bandelier Tuff (Table 3). The weighted-mean ages for the reversely magnetized upper and lower units of the Bandelier (Tsankawi and Guaje Pumice Beds) are 1.223 ± 0.018 Ma and 1.613 ± 0.011 Ma, respectively.

Table 3. Total Fusion $^{40}Ar/^{39}Ar$ Data for Sanidine and Obsidian From Rhyolites of the Jemez Mountains, Northern New Mexico, and Sumatra Pertinent to the Age of the Jaramillo Subchron and Matuyama-Brunhes Boundary

Unit, Polarity, Sample	J	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40}Ar^a$ Moles	$^{40}Ar^a/^{39}Ar$	^{40}Ar,[a] %	Age, Ma	Error $\pm 1\sigma$
Oldest Toba Tuff, reverse,	3.97E-04	0.00797	0.00113	1.89E-13	1.0991	76.5	0.787	0.006
T-15A	3.97E-04	0.00859	0.00038	1.24E-13	1.1059	90.4	0.792	0.006
	4.04E-04	0.00743	0.00146	1.03E-13	1.0855	71.4	0.790	0.007
	4.04E-04	0.00763	0.00140	1.33E-13	1.0834	72.2	0.788	0.006
Weighted Mean							0.789	0.006
Cerro Santa Rosa II, reverse	4.00E-04	0.01334	0.00161	8.09E-14	1.1011	69.6	0.794	0.008
4D003	4.00E-04	0.01309	0.00051	8.62E-14	1.1137	87.7	0.803	0.008
	4.00E-04	0.01285	0.00069	2.05E-13	1.1053	84.1	0.798	0.006
	4.00E-04	0.01300	0.00654	1.26E-13	1.0774	35.7	0.777	0.009
Weighted Mean							0.793	0.018
Cerro Seco, reverse,	4.02E-04	0.01309	0.00052	8.03E-14	1.1109	87.7	0.804	0.008
4D001	4.02E-04	0.01307	0.00026	9.26E-14	1.1027	93.2	0.799	0.007
	4.02E-04	0.01375	0.00103	1.51E-13	1.0861	77.9	0.786	0.006
	4.02E-04	0.01324	0.00123	1.24E-13	1.0927	74.9	0.791	0.007
Weighted Mean							0.794	0.007
Cerro San Luis, reverse,	8.0E-04	0.01323	0.00124	6.69E-14	0.5956	61.9	0.827	0.008
82W8	7.0E-04	0.01335	0.00044	1.50E-14	0.6131	82.6	0.804	0.008
	7.0E-04	0.01366	0.00022	1.84E-14	0.6251	90.4	0.820	0.012
	7.0E-04	0.01346	0.00026	1.61E-14	0.6041	88.6	0.792	0.012
	1.0E-04	0.00321	0.01022	1.08E-13	3.7880	55.6	0.820	0.007
	1.0E-04	0.03876	0.00290	9.83E-15	3.7115	81.3	0.804	0.033
	1.0E-04	0.02046	0.00519	6.07E-15	3.5466	69.8	0.768	0.050
	4.0E-04	0.01390	0.00311	3.53E-14	1.0837	54.1	0.873	0.009
	4.0E-04	0.01349	0.00961	1.13E-14	0.9615	25.3	0.775	0.020
Weighted Mean							0.812	0.023
Cerro Santa Rosa I, reverse,	4.04E-04	0.01126	0.00164	1.31E-13	1.2602	72.1	0.918	0.008
4D002	4.04E-04	0.01122	0.00282	7.90E-14	1.2388	59.7	0.903	0.010
	4.04E-04	0.01159	0.00105	1.95E-13	1.2429	79.8	0.905	0.006
	4.04E-04	0.01125	0.00104	1.32E-13	1.2416	79.9	0.905	0.007
	4.04E-04	0.01099	0.00033	9.27E-14	1.2966	92.7	0.945	0.009
	4.04E-04	0.01106	0.00028	8.37E-14	1.2635	93.7	0.921	0.009
Weighted Mean							0.916	0.017
Cerro del Abrigo III, normal,	4.27E-04	0.01286	0.00047	1.75E-13	1.2999	90.0	1.001	0.007
3X189	4.27E-04	0.01283	0.00033	1.89E-13	1.3316	92.8	1.025	0.007
	4.27E-04	0.01206	0.00113	2.11E-13	1.2938	79.2	0.996	0.007
	4.27E-04	0.01223	0.00335	6.28E-14	1.2761	56.2	0.983	0.013
	4.27E-04	0.01271	0.00123	1.99E-13	1.3028	78.0	1.010	0.010
Weighted mean							1.004	0.019
Cerro del Medio II,[b] reverse,	4.18E-04	0.03264	0.00037	1.39E-13	1.5469	93.2	1.164	0.009
J-1	4.18E-04	0.03250	0.00047	1.19E-13	1.5428	91.5	1.161	0.010
	4.18E-04	0.03260	0.00067	2.10E-13	1.5381	88.5	1.158	0.008
Weighted Mean							1.161	0.010
Cerro del Medio I, reverse,	4.02E-04	0.05123	0.00225	5.40E-14	1.6650	71.4	1.207	0.017
3X198, 3X195, 3X200								
Tsankawi Pumice Bed, reverse	4.15E-04	0.00914	0.00076	1.58E-13	1.6499	87.8	1.235	0.009
91G36	4.15E-04	0.00918	0.00048	1.91E-13	1.6187	91.7	1.211	0.008
	4.15E-04	0.00943	0.00131	2.49E-13	1.6440	80.7	1.230	0.008
	4.15E-04	0.00930	0.00156	1.57E-13	1.6264	77.7	1.217	0.009
Weighted Mean							1.223	0.018
Guaje Pumice Bed, reverse,	4.17E-04	0.00986	0.00216	2.66E-13	2.1461	77.0	1.612	0.011
91G35	4.17E-04	0.00945	0.00134	1.97E-13	2.1353	84.2	1.603	0.011
	4.17E-04	0.00959	0.00087	1.49E-13	2.1758	89.3	1.634	0.012
	4.17E-04	0.00959	0.00048	1.96E-13	2.1378	93.6	1.605	0.011
Weighted Mean							1.613	0.011

Samples of basal air fall members of the lower and upper members of the Bandelier Tuff (Guaje and Tsankawi Pumice Beds, 91G35 and 91G36, respectively) collected by G. A. Izett from same sites as those of *Doell et al.* [1968] at road cuts along State Highway 4 to Los Alamos, White Rock quadrangle, Los Alamos County, northern New Mexico. Error of weighted-mean ages is at the 95% confidence level for the error of the mean. J, neutron-fluence parameter. Read 3.97E-04 as 3.97×10^{-4}.

[a]Radiogenic.

[b]Obsidian.

Table 4. Total Fusion $^{40}Ar/^{39}Ar$ Data for Ivory Coast Tektites

Sample	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40}Ar^a$ Moles	$^{40}Ar^a/^{39}Ar$	$J \times 10^{-4}$	$^{40}Ar^a$, %	Age, Ma	Error ± 1σ
IVC-6-64	0.3236	0.00419	1.82E-14	1.2293	4.91	50.2	1.09	0.02
UVC-6-64	0.3253	0.00619	2.65E-15	1.1818	4.91	39.5	1.05	0.12
IVC-6-64	0.2429	0.00432	1.53E-14	1.4506	4.91	53.5	1.28	0.03
IVC-6-64	0.2887	0.00841	1.18E-14	1.3178	4.74	34.8	1.13	0.03
IVC-6-64	0.2803	0.00676	9.85E-15	1.2669	4.91	39.0	1.12	0.04
IVC-9-64	0.2473	0.00270	1.66E-14	1.2686	4.91	61.9	1.12	0.02
IVC-9-64	0.2228	0.01078	2.58E-15	1.3320	4.91	29.6	1.18	0.13
IVC-9-64	0.2538	0.00831	9.16E-15	1.4586	4.77	37.4	1.25	0.04
IVC-9-64	0.2215	0.01688	1.18E-14	1.3893	4.91	21.8	1.24	0.04
IVC-1B-64	0.2256	0.00491	2.85E-15	1.2277	4.91	46.1	1.09	0.11
IVC-1B-64	0.1440	0.00665	2.96E-15	1.3956	4.91	41.6	1.23	0.12
IVC-1B-64	0.3416	0.01684	1.99E-15	1.3116	4.91	20.9	1.16	0.17
IVC-1B-64	0.2822	0.00338	2.77E-15	1.1841	4.91	54.7	1.05	0.11
IVC-1B-64	0.2586	0.00720	2.77E-15	1.2856	4.75	37.8	1.10	0.03
Weighted Mean							1.15	0.05

Localities: IVC-9-64, Amoroki; IVC-6-64, Prikro; IVC-1B-64, Anada-Kouadiokro from the collection of E.C.T. Chao, U.S. Geological Survey transferred to the U.S. National Museum. Ages calculated using Taylor Creek Rhyolite (27.92 Ma) as fluence monitor. Error of weighted-mean ages is at the 95% confidence level for the error of the mean. *J*, neutron-fluence paramerer. Read 1.82E-14 as 1.82×10^{-14}.

[a]Radiogenic.

These ages are about 10% older than $^{40}Ar/^{39}Ar$ ages measured by *Spell et al.* [1990] and *Spell and McDougall* [1992]. *Spell et al.* [1990, p. 179] used an inhomogeneous fluence-monitor mineral (Bern4M muscovite) and an irradiation package geometry that resulted in a large uncertainty for J. According to *Baksi* [1987], the age of the Bern4M muscovite standard is uncertain by 3.5%.

The onset of the JNS can be calibrated by using isotopic

Table 5. Total Fusion $^{40}Ar/^{39}Ar$ Data for Sanidine From the Bishop Tuff of Eastern California Bearing on the Age of the Matuyama-Brunhes Boundary

Unit, Polarity, Sample Number	*J*	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40}Ar^a$ Moles	$^{40}Ar^a/^{39}Ar$	$^{40}Ar^a$, %	Age, Ma	Error ± 1σ
Bishop Tuff Upper Unit, Normal, 79G94	1.20E-04	0.00163	0.00876	1.84E-14	3.51470	57.6	0.761	0.033
	1.20E-04	0.03820	0.03154	4.33E-15	3.54349	27.5	0.767	0.141
	1.20E-04	0.04109	0.02054	8.94E-14	3.38383	35.8	0.732	0.010
	7.68E-04	0.01092	0.00102	1.12E-13	0.54938	64.4	0.761	0.008
	7.68E-04	0.01056	0.00072	1.12E-13	0.55118	72.1	0.763	0.007
	7.68E-04	0.01073	0.00038	1.12E-13	0.55491	82.9	0.769	0.007
	7.17E-04	0.03992	0.00064	2.43E-14	0.56682	75.0	0.733	0.009
	7.17E-04	0.01073	0.00064	1.75E-14	0.58362	75.5	0.755	0.011
	7.17E-04	0.01171	0.00011	1.51E-14	0.59344	94.6	0.767	0.013
	7.17E-04	0.01078	0.00099	7.51E-15	0.60104	67.2	0.777	0.025
	4.60E-04	0.01438	0.00087	1.20E-13	0.92000	78.0	0.763	0.006
	4.60E-04	0.01384	0.00165	5.77E-14	0.91078	65.1	0.755	0.009
Weighted Mean							0.757	0.009
Bishop Tuff, Air Fall Unit, Normal, 79G14, 85G50a	1.20E-04	0.00324	0.00082	9.45E-14	3.58642	93.6	0.776	0.008
	7.70E-04	0.00872	0.00338	2.24E-14	0.53766	35.0	0.747	0.028
	7.67E-04	0.00921	0.00621	1.71E-14	0.53340	22.5	0.738	0.037
	7.65E-04	0.00814	0.00724	1.90E-14	0.57075	21.1	0.787	0.036
	7.20E-04	0.00672	0.00426	2.29E-14	0.58541	31.7	0.760	0.012
	4.55E-04	0.00703	0.00306	2.18E-14	0.94458	51.1	0.775	0.176
	4.55E-04	0.00670	0.00421	3.79E-14	0.93185	42.8	0.765	0.012
	4.55E-04	0.00705	0.00867	1.10E-14	0.91579	26.3	0.751	0.034
	4.60E-04	0.00876	0.00038	3.84E-14	0.92316	89.1	0.765	0.013
	4.60E-04	0.00910	0.00025	3.53E-14	0.92556	92.5	0.767	0.014
	3.97E-04	0.00660	0.00077	1.80E-13	1.06129	82.0	0.760	0.005
Weighted Mean							0.764	0.005

Bishop Tuff, upper unit from 1-m-diameter pumice boulder from NE 1/4 s 27, T. 1 S., R. 29 E., Mono County, California Bishop Tuff, air fall unit from an abandoned pumice mine in NW 1/4 s 4, T. 6 S., R. 33 E., Inyo County, California. Error of weighted-mean ages is at the 95% confidence level for the error of the mean. J, neutron-fluence parameter. Read 1.84E-14 as 1.84×10^{-14}.

[a]Radiogenic.

ages of Ivory Coast tektites. Their submillimeter equivalents, Ivory Coast microtektites, occur near the base of the JNS in deep-sea cores in the equatorial Atlantic Ocean [*Glass and Zwart*, 1979]. Fission track and K-Ar ages of 1.02 ± 0.1 Ma and 1.1 ± 0.1 Ma were measured on Ivory Coast tektites by *Gentner et al.* [1967]. Recent fission track and ^{40}Ar/^{39}Ar ages of Ivory Coast tektites appeared in an abstract by *Koeberl et al.* [1989], although no analytical data were given. They reported fission track and ^{40}Ar/^{39}Ar ages for the tektites of 1.05 ± 0.11 Ma and 1.10 ± 0.10 Ma, respectively, but these ages have a high analytical uncertainty.

We dated three Ivory Coast tektites (14 analyses) using the ^{40}Ar/^{39}Ar method, and the data are given in Table 4. The weighted-mean age for these tektites is 1.15 ± 0.05 Ma (95% confidence limit for the error of the mean). A slightly younger age was obtained from an inverse correlation diagram [*Dalrymple et al.*, 1988]. A plot of the analytical data for the 14 analyses (Table 4, Figure 2) resulted in an intercept on the x-axis of 1633, and the inverse of this value used in the age equation resulted in an age of 1.10 ± 0.08 Ma. Our ^{40}Ar/^{39}Ar ages for the Ivory Coast tektites is a maximum age because the glass may contain small amounts of inherited argon. We consider the correlation diagram age of 1.10 Ma to be the best age for the Ivory Coast tektites.

Schneider and Kent [1990] estimated that Ivory Coast microtektites were deposited on the sea floor about 0.03 Ma after the onset of the JNS. More recently, *Glass et al.* [1991] stated that the Ivory Coast microtektites fell to the ocean floor only 0.008 ± 0.002 Ma after the beginning of the JNS.

As described above and shown graphically on Figure 1, the onset of the JNS is placed questionably at 1.11 Ma. As placed, it raises doubt about the accuracy of the K-Ar age of the normally magnetized rhyolite of Alder Creek, which was used to calibrate the Cobb Mountain polarity event at 1.12 ± 0.02 Ma [*Mankinen et al.*, 1978]. *Obradovich and Izett* [1992] recently showed that sanidine from the rhyolite of Alder Creek, Clear Lake, California (inadvertently called the rhyolite of Cobb Mountain) has a ^{40}Ar/^{39}Ar age of 1.19 Ma. This age indicates that the Cobb Mountain normal event occurred at 1.19 Ma (normalized to an age of 513.9 Ma for MMhb-1 fluence monitor).

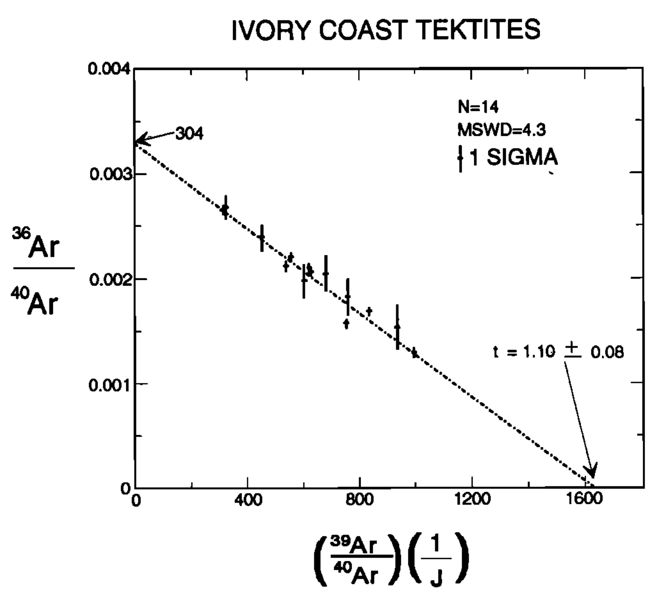

Figure 2. Inverse correlation diagram for analyses of glass of Ivory Coast tektites. The inverse of the intercept on the x-axis of 1633 results in an age of 1.10 ± 0.08 Ma. The inverse of the intercept on the y-axes indicates that the trapped argon component has a ^{40}Ar to ^{36}Ar ratio of 304 ± 3. MSWD, mean square weighted deviates.

End of the Jaramillo

Doell et al. [1968, Table 3, site S38] indicated that the JNS ended at about 0.90 Ma based on a K-Ar sanidine age of 0.907 ± 0.028 Ma for the reversely magnetized rhyolite dome of Cerro Santa Rosa I. They assumed that this rhyolite was extruded near the end of the JNS because of its intermediate magnetic polarity. Our analytical data (Table 3) for six splits of the sanidine concentrate dated by *Doell et al.* [1968, Table 3, site S38] have a weighted-mean age of 0.916 ± 0.017 Ma, not significantly older than their K-Ar age of 0.907 ± 0.028 Ma. These statistically concordant ages of 0.916 Ma and 0.907 Ma provide firm calibration points in the Matuyama Chron for delineating the end of the JNS. A tighter calibration for the end of the JNS will be possible when the age and magnetic polarity of all of the flows that compose the Lewis Canyon Rhyolite in Yellowstone National Park are determined. Sanidine from one of the flows has a weighted-mean ^{40}Ar/^{39}Ar age of 0.954 ± 0.005 Ma (1σ) and has reverse magnetic polarity (R. L. Reynolds, oral communication, 1993).

In summary, some of our sanidine ages from the reversely magnetized rhyolite domes of the Valles caldera are distinctly older than K-Ar sanidine ages of *Doell et al.* [1968, Table 3] and are generally compatible with some of the ages of *Spell and McDougall* [1992]. In contrast, the ^{40}Ar/^{39}Ar age of sanidine from Cerro Santa Rosa I and obsidian for Cerro del Medio II are statistically concordant with the K-Ar ages of *Doell et al.* [1968]. ^{40}Ar/^{39}Ar age data of Table 3 combined with that of Table 4 and Figure 2 for Ivory Coast tektites indicate that the JNS began at about 1.11 ± 0.08 Ma. The JNS ended before 0.92 Ma, probably as early as 0.97 Ma based on the age and magnetic polarity of the Lewis Canyon Rhyolite (Figure 1).

Matuyama-Brunhes Boundary

Our isotopic age calibration of the GPTS near the MBB is based, in part, on ^{40}Ar/^{39}Ar ages of sanidine from three reversely magnetized rhyolite domes of the Valles caldera (Cerro San Luis, Cerro Seco, and Cerro Santa Rosa II). Nine analyses of sanidine from Cerro San Luis yielded a weighted-mean age of 0.812 ± 0.023 Ma (Table 3). This result is about 9% older than the analytically best K-Ar age (0.710 ± 0.015 Ma) for this rock given by *Doell et al.* [1968, Table 3, Figure 12]. They also gave another K-Ar age of 0.845 ± 0.074 Ma for sanidine sample 3X122, but this age has a high uncertainty. The other two rhyolite domes crucial to constraining the time of the MBB are Cerro Seco and Cerro Santa Rosa II. Our data for four analyses of sanidine from each of these rhyolite domes gave essentially identical results of 0.794 ± 0.007 Ma and 0.793 ± 0.018 Ma. The ^{40}Ar/^{39}Ar ages are older than K-Ar ages of 0.745 ± 0.015 Ma and 0.725 ± 0.019 Ma for these rocks reported by *Doell et al.* [1968, Table 3, Figure 12].

Another calibration point relevant to the time of the MBB was obtained by dating sanidine from the reversely magnetized Oldest Toba Tuff on Sumatra [*Chesner*, 1988]. Four analyses resulted in a weighted-mean age of 0.789 ± 0.006 Ma (Table 3). Previously, sanidine from this rock was $^{40}Ar/^{39}Ar$ dated by T. C. Onstott at 0.84 ± 0.030 Ma [*Diehl et al.*, 1987], using Bern4B as a fluence monitor. Although the two ages for the Oldest Toba Tuff differ by 0.05 Ma, they are not statistically different at the two sigma level.

To establish a calibration point within earliest Brunhes time, we analyzed 23 sanidine concentrates of the Bishop Tuff of eastern California (Table 5). The Bishop has normal magnetic polarity and was emplaced just after the MBB. The weighted-mean age of 11 sanidine analyses from single pumice lumps from the basal air fall unit of the Bishop Tuff is 0.764 ± 0.005 Ma. Twelve ages were measured on a large sanidine concentrate from a 1-m pumice boulder [*Izett et al.*, 1988] from the upper pyroxene-bearing unit of the Bishop Tuff. A weighted-mean age of 0.757 ± 0.009 Ma was calculated for the 12 ages, which is statistically identical to the weighted-mean age of sanidine from the basal air fall unit. Inverse correlation diagrams [*Dalrymple et al.*, 1988] prepared from the analytical data for the two units of the Bishop are shown in Figure 3. The correlation diagram age for the basal air fall unit of the Bishop is 0.764 ± 0.006 Ma, exactly the same as the weighted-mean age of 0.764 ± 0.005 Ma. Data for the sanidine of the upper clinopyroxene-bearing unit have an age of 0.762 ± 0.006 Ma, nearly identical to the weighted-mean age of 0.757 ± 0.009 Ma.

Our $^{40}Ar/^{39}Ar$ ages of 0.764 ± 0.005 Ma and 0.757 ± 0.009 Ma for the two subunits of the Bishop Tuff discussed above are generally older than (1) K-Ar ages for the same subunits (0.738 ± 0.003 Ma and 0.736 ± 0.005 Ma) reported by *Izett et al.* [1982] and (2) $^{40}Ar/^{39}Ar$ plateau and total-fusion ages of 0.73 Ma and 0.74 Ma determined by *Hurford and Hammerschmidt* [1985]. Their age for the Bishop Tuff was determined using Bern4M muscovite and Bern4B biotite fluence monitors. Bern4M muscovite has an age uncertain by 3.5% [*Baksi*, 1987]. Recently, *Pringle et al.* [1992] reported a weighted-mean age for the upper unit of the Bishop Tuff of 0.759 ± 0.003 in a paper dealing with the geochronology of the Taupo Volcanic Zone. Their age, although they did not present supporting analytical data, is statistically indistinguishable from our age of 0.757 Ma.

Obviously, the isotopic ages of reversely and normally magnetized volcanic rocks on either side of the MBB bracket but do not date this geomagnetic polarity change. However, an estimate for the age of the MBB can be made by using its stratigraphic position in continental sedimentary deposits relative to a dated marker horizon such as the Bishop ash bed (distal Bishop Tuff tephra). The Bishop ash bed occurs 0.65 m above the MBB in sediments of ancient Lake Tecopa, California [*Hillhouse and Cox*, 1976] and 1.83 m above the boundary in sediments of ancient Lake Bonneville, Utah [*Eardley et al.*, 1973]. Using (1) the average rate of sedimentation (1 m/6.5 Ka) between two isotopically dated volcanic ash beds in the Burmester and Saltair cores in ancient Lake Bonneville [*Eardley et al.*, 1973, p. 212] and (2) the stratigraphic separation of 1.83 m between the Bishop ash (0.76 Ma) and the underlying MBB in the Burmester core, suggest that the MBB occurred about 12 Ka before the Bishop ash bed was deposited, or an age of 0.77 Ma for the MBB. The sedimentation rate was computed using the average thickness of the sediments (9 m and 30 m, respectively) between the Bishop ash bed [*Izett et al.*, 1970] having an age of 0.76 Ma and an overlying Lava Creek B ash bed [*Izett and Wilcox*, 1982] having an age of 0.66–0.67 Ma [*Izett et al.*, 1992] in the Saltair and Burmester core holes.

In the Pacific and Indian Oceans, Australasian microtektites are closely associated with the MBB. The 0.77-Ma age for the MBB, as deduced above, is compatible with a weighted-mean $^{40}Ar/^{39}Ar$ age of 0.769 ± 0.021 Ma (95% confidence limit for the error of the mean) for 54 analyses of Australasian tektites [*Izett and Obradovich*, 1992b, 1992c]. Moreover, we obtained a $^{40}Ar/^{39}Ar$ age of 0.9 ± 0.1 Ma (1σ)

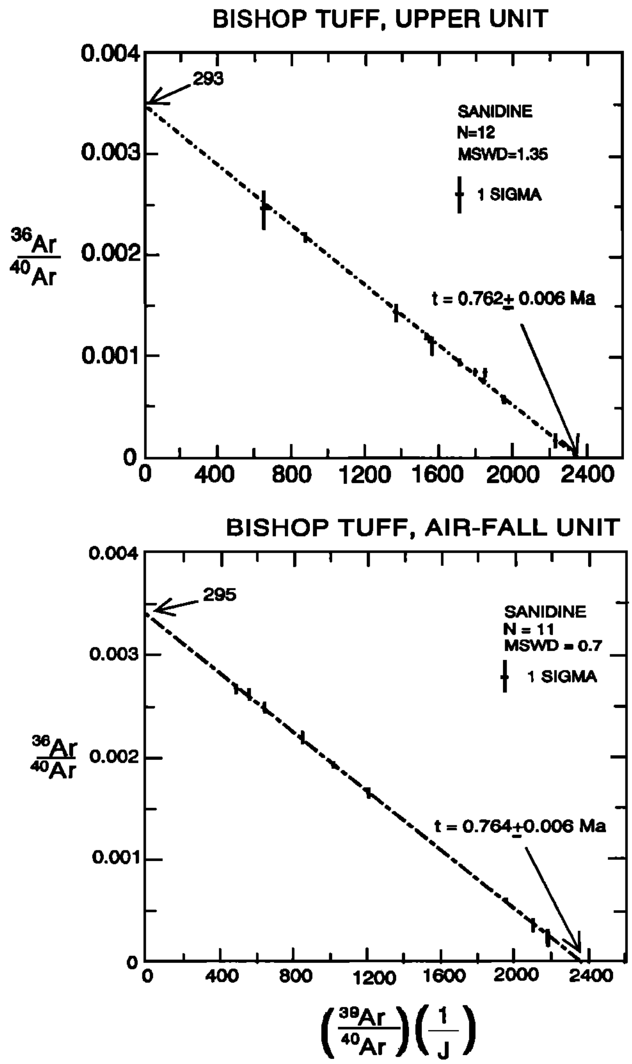

Figure 3. Inverse correlation diagrams for analyses of sanidine from the lower and upper units of the Bishop Tuff of eastern California. Inverse of the intercept on the x-axis of 2352 for the lower unit of the Bishop Tuff results in an age of 0.764 ± 0.006 Ma. Inverse of the intercept on the x-axis of 2311 for the upper unit of the Bishop Tuff results in an age of 0.762 ± 0.006 Ma. The inverses of the intercepts on the y-axes of the two diagrams indicate that the trapped argon component has a ^{40}Ar to ^{36}Ar ratio of 293 ± 2 and 295 ± 2 for the two units of the Bishop, nearly identical to the ratio of these isotopes (295.5) in atmospheric argon. MSWD, mean square weighted deviates.

on a group of 30 Australasian microtektites, the submillimeter equivalents of Australasian tektites, recovered from core at 10.95 meters below seafloor, Ocean Drilling Program (ODP) leg 121 site 758B on the Ninetyeast Ridge, eastern Indian Ocean [see *Smit et al.*, 1991, Figure 3]. The $^{40}Ar/^{39}Ar$ age of the Australasian microtektites (0.9 ± 0.1 Ma) is seemingly older than that of Australasian tektites (0.769 ± 0.021 Ma), but considering their analytical uncertainties at the 2-σ level they are essentially concordant. *Smit et al.* [1991] reported that Australasian microtektites are concentrated 32 cm below the MBB at ODP site 758B. According to *Burns* [1989], the microtektites reach their maximum abundance in reversely magnetized deep-sea cores of the Pacific and Indian Oceans tens of centimeters below the MBB. Using deposition rates computed from the stratigraphic position of oxygen isotope stage 19.1 and the MBB in deep-sea cores, *de Menocal et al.* [1990] reasoned that the microtektites fell to the ocean floor about 15 ka before the onset of the Matuyama-Brunhes transition. If Australasian microtektites are 0.77 Ma, the foregoing information indicates that the MBB occurred at 0.755 Ma (calibrated using an age of 513.9 Ma for MMhb-1 fluence monitor).

Our inferred age of 0.77 Ma for the MBB is statistically compatible with $^{40}Ar/^{39}Ar$ ages of basalt lava flows (0.783 ± 0.011 Ma) erupted during the Matuyama-Brunhes transition on Maui [*Baksi et al.*, 1992]. They pointed out that one of the Maui basalt samples chosen for dating contained excess argon, and others lost some argon after crystallization. Although the isochron age they reported for Maui basalts is analytically sound, some geochronologic studies have shown that incremental $^{40}Ar/^{39}Ar$ ages of whole rock basalts can yield anomalous results [*McDougall and Harrison*, 1988, p. 33; *Baksi*, 1987, p. 149]. Lack of detailed petrographic descriptions of the basalts dated by *Baksi et al.* [1992] make the interpretation of their results uncertain.

Conclusions

1. On the basis of $^{40}Ar/^{39}Ar$ ages of Ivory Coast tektites and sanidine and obsidian ages from rhyolite domes flow complexes in the Valles caldera, the JNS began at about 1.11 Ma and ended before 0.92 Ma, probably near 0.97 Ma. This chronology for the JNS is 10% older than that proposed (0.97–0.90 Ma) by *Mankinen and Dalrymple* [1979] and most other commonly quoted geomagnetic polarity time scales. Our chronology for the JNS is nearly compatible with that proposed by *Shackleton et al.* [1990], who based theirs (1.07–0.99 Ma) on a phase relationship match between the astronomical time scale and oxygen isotope calibrated climate records in deep-sea cores.

2. The MBB is bracketed between $^{40}Ar/^{39}Ar$ sanidine ages of 0.79 Ma and 0.76 Ma (three reversely magnetized rhyolite domes in New Mexico and pumice of the reversely magnetized Oldest Toba Tuff and the normally magnetized Bishop Tuff).

3. Although bracketed between $^{40}Ar/^{39}Ar$ ages of 0.79 Ma and 0.76 Ma, the age of the MBB may be close to 0.77 Ma. This conclusion is reached on the basis of computed sedimentation rates at two sites in the western United States, and the fact that the MBB occurs 1.83 m below a layer of distal Bishop Tuff (0.76 Ma) in the Burmester, Utah, core.

4. Our $^{40}Ar/^{39}Ar$ dating of the MBB at 0.77 Ma is about 5% older than that proposed (0.73 Ma) by *Mankinen and Dalrymple* [1979] and 2–3% younger than the age of the MBB (0.79 Ma and 0.78 Ma) proposed by *Johnson* [1982] and *Shackleton et al.* [1990], respectively. They based their dating of the MBB on a phase relationship match between the astronomical time scale and oxygen isotope calibrated climate records in deep-sea cores.

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