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^{40}Ar-^{39}Ar DATING OF THE JARAMILLO NORMAL SUBCHRON AND THE MATUYAMA AND BRUNHES GEOMAGNETIC BOUNDARY

by

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Abstract

Our laser-fusion ^{40}Ar-^{39}Ar calibration of the mid-Pleistocene Geomagnetic Polarity Time Scale (GPTS) is nearly in accord with the oxygen-isotope, climate-record calibration of the Astronomical Time Scale proposed by Johnson in 1982 and Shackleton and colleagues in 1990. We suggest that the Jaramillo Normal Subchron (JNS) began as early as 1.11 Ma and ended before 0.92 Ma, perhaps as early as 0.97 Ma. The Matuyama-Brunhes boundary (MBB) occurred at about 0.77 Ma.

A calibration point within the JNS was obtained from ^{40}Ar-^{39}Ar analyses of sanidine from a normally magnetized rhyolite dome, Cerro del Abrigo III, in the Valles caldera, New Mexico, which yielded a weighted-mean age of 1.004 ± 0.019 Ma. A conventional K-Ar age (Doell and Dalrymple, 1966) of 0.909 ± 0.019 Ma for this rhyolite was the linchpin for the recognition of the JNS. The onset of the JNS is constrained by obsidian ages of 1.161 ± 0.010 Ma from the reversely magnetized rhyolite of Cerro del Medio in the Valles Caldera and Ivory Coast tektites ages of 1.10 ± 0.10 Ma. Ivory Coast microtektites occur near the base of the JNS in Atlantic Ocean deep-sea cores, and sedimentation rates in the cores combined with the age of the microtektites suggest that the JNS began at 1.11 Ma. The JNS ended before 0.916 ± 0.017 Ma, possibly as early as 0.97 Ma, as calibrated by sanidine ages of the reversely magnetized Cerro Santa Rosa I dome in the Valles caldera and sanidine ages of a lava of the Lewis Canyon Rhyolite in Yellowstone National Park.

The Matuyama-Brunhes boundary (MBB) 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 MBB may be close to 0.77 Ma as deduced from rates of sedimentation in ancient Lake Bonneville, Utah, where the MBB is separated from an overlying layer of distal Bishop Tuff (0.76 Ma) tephra by 1.83 m of sediment.

Introduction

More than three decades ago, earth scientists became increasingly aware that the polarity of the Earth's magnetic field had 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 pertinent to the GPTS has increased the usefulness of geomagnetic polarity reversals as marker horizons in many types of geologic studies. The purpose of this paper is to present further isotopic-age refinement of the GPTS using volcanic rocks erupted near the time of the geologically youngest two geomagnetic polarity reversals.

The older of the two, which was 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 geomagnetic polarity field reversals, 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 used the conventional K-Ar method to obtain ages mainly from basalt lava flows, but also sanidine from silicic volcanic rocks suspected to have been erupted just before and after these two magnetic polarity events. Sanidine, which is a high temperature K-rich feldspar common in silicic volcanic rocks, is *nearly* an ideal K-Ar geochronometer, much better than the more widely available basalt lava flows. Whole rock K-Ar ages of basalt generally have larger analytical errors than sanidine K-Ar ages because of their higher air Ar contents (see Mankinen and Dalrymple, 1979, table 3a).

The development 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; McDougall and Harrison, 1988) provided new resolving power for geochronologic studies. The subsequent invention of a continuous Ar-ion laser-fusion ^{40}Ar-^{39}Ar system (York et al., 1981) allowed the dating of minute amounts (~1 µg) of K-rich geologic materials with unprecedented precision, approaching 0.2%.

The ^{40}Ar-^{39}Ar method has an important advantage over the conventional K-Ar method; only *ratios* of Ar isotopes are required to calculate an age rather than *absolute amounts*. Thus, it is not necessary to extract all of the radiogenic Ar from a mineral to calculate an age. This advantage mitigates a technical problem inherent in K-Ar dating of sanidine. K-Ar ages of this mineral have a tendency to be anomalously young, because the melted sanidine commonly forms a viscous mass that retains some radiogenic Ar under ultrahigh vacuum (McDowell, 1983). Even at the highest temperatures attainable (1,800 °C) in standard RF-induction heaters and resistance furnaces, a few percent Ar can remain trapped in some viscous sanidine melts. For this reason, we investigated the age of certain sanidine-bearing volcanic rocks emplaced near the JNS and MBB using a continuous laser-fusion ^{40}Ar-^{39}Ar dating system (Dalrymple, 1988) housed in a U.S. Geological Survey laboratory in Menlo Park, Calif. In this paper we report ^{40}Ar-^{39}Ar data and ages for some key volcanic units that support changes in the isotopic-age chronology of the mid-Pleistocene GPTS (fig. 1).

History of the JNS and MBB in the mid-Pleistocene GPTS

Geologic mapping in the Jemez Mountains, N. Mex., established the lithostratigraphic framework for a large, complex volcanic center of Pleistocene age (Ross and Smith, 1961; Smith et al. 1970). They showed that following the eruption of the upper unit of the Bandelier Tuff, a series of rhyolite domes and associated lava flows were extruded sequentially in the ring fracture zone of the Valles caldera. The classic integrated paleomagnetic and K-Ar age study of these volcanic rocks was the basis for the recognition of the JNS (Doell and Dalrymple, 1966). Moreover, this work was also valuable for providing calibration points on either side of the MBB. Subsequently, Doell et al. (1968, fig. 12) gave a complete summary of the K-Ar ages of sanidine and obsidian from Cerro del Medio, Cerro del Abrigo, and Cerro Santa Rosa rhyolite domes in the Valles caldera, New Mexico, pertinent to the definition of the JNS. The existence and timing of the JNS was confirmed quickly by McDougall and Chamalaun (1966).

Recently, isotopic ages of volcanic rocks relevant to the time of the MBB were reported by Izett et al. (1988), Izett and Obradovich (1991, 1992a, 1992d), and Spell and McDougall (1992). They determined K-Ar and ^{40}Ar-^{39}Ar ages of reversely magnetized rhyolite domes of the Valles caldera that formed just prior to the time of the MBB. Baksi et al. (1992) provided important 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 a split of a sanidine concentrate from the reversely magnetized Oldest Toba Tuff of Sumatra (Chesner, 1988).

The isotopic age of the normally magnetized Bishop Tuff of eastern California (Hildreth, 1977) has been determined repeatedly to establish a calibration point in the earliest Brunhes Chron, thus placing a 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 first 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). Accordingly, Dalrymple and colleagues used pumice lumps rather than samples of welded tuff for a source of sanidine 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 original K-Ar analytical data of Dalrymple et al. (1965). The K-Ar age of the Bishop was again recomputed by

Mankinen and Dalrymple (1979) at 0.727 ± 0.015 Ma using decay constants recommended by the IUGS Subcommission on Geochronology (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.

Because progress had been made during the 1970's in mass spectrometers used for K-Ar dating, Izett (1982) measured 17 K-Ar ages for 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 radiometric 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 original 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 the original 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.

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 conventional heavy-liquid separation techniques. Glass adhering to the sanidine crystals was removed by etching in 24% HF accompanied by ultrasonic scrubbing for as much as 3 minutes. 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 minutes. 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 9-mm-diameter aluminum-foil cup covered with a 9-mm aluminum-foil cap. The flattened pancake-like packets were sandwiched between similar packets of sanidine fluence monitors, arranged in a vertical stack in a 10-mm-diameter quartz tube, and the positions of the packets in the tube 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 Cd 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 doses of either 2.0×10^{17} nvt or 3.0×10^{17} nvt. The nuclear reactor fluence attributes, irradiation procedures, and methods for measuring corrections for interfering Ar isotopes induced by undesirable nuclear reactions with Ca and K were described by Dalrymple et al. (1981) and Dalrymple (1989).

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 continuous Ar-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 Ar 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 4.3×10^{-15} to 2.7×10^{-13} moles.

Although the ^{40}Ar-^{39}Ar method has important advantages over the conventional K-Ar method, recall that it is a relative method and ages of unknown samples are relative to assigned ages of fluence-monitor minerals. One of the fluence-monitor minerals used extensively is a hornblende (MMhb-1) from the McClure Mountain Complex of the Wet Mountains, Colo. (Alexander et al., 1978). Its published weighted-mean age, based on measurement of K and Ar in 18 laboratories worldwide, is 520.4 ± 1.7 Ma (Sampson and Alexander, 1987). However, the age of MMhb-1, as calibrated by G.B. Dalrymple and M.A. Lanphere in Menlo Park, Calif., where our measurements were made, 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 fluence-monitor minerals because 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 (Cebula et al., 1986), 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 hornblende (Lanphere et al., 1990). To compare our ages with those of others, an approximation can be obtained by using the ratio of the ages of the two fluence-monitor minerals used. But the age equation has an *exponential term*, and ages normalized in this way are not exactly correct. (For the correct conversion method, refer to an equation given in Dalrymple et al., in preparation).

Errors associated with individual ages in tables 3 and 4 are estimates of the analytical precision at the 1 σ level and include our evaluation of the precision error (0.3-0.5%) of the fluence-calibration parameter, J. Summary ages are weighted means, weighted by the inverse of the variance (Taylor, 1982). The error calculated for a group of ages is the error of the mean at the 95% confidence level. Data reduction and age calculations were made with a computer program written by G.B. Dalrymple and M.S. Pringle. All K-Ar and ^{40}Ar-^{39}Ar ages were calculated or recalculated using decay constants recommended by the Subcommission on Geochronology of the IUGS (Steiger and Jäger, 1977).

Jaramillo Normal Subchron

Isotopic age calibration of the mid-Pleistocene GPTS containing the JNS interval was originally based on K-Ar ages of sanidine and obsidian from rhyolite domes and flows, including Cerro del Medio, Cerro del Abrigo, and Cerro Santa Rosa of the Valles caldera, New Mexico (Doell and Dalrymple, 1966). In detail, the age of the JNS was controlled essentially by a K-Ar age for one of four satellitic rhyolite domes composing Cerro del Abrigo (Doell et al., 1968; R.L. Smith, written commun., 1992). The next to youngest of this group, which has normal magnetic polarity, was designated Cerro del Abrigo III. They measured a sanidine K-Ar age of 0.909 ± 0.019 Ma for this rhyolite (Doell et al., 1968, table 3, site S37), and this age determination was the linchpin for the recognition and calibration of the JNS.

Five ^{40}Ar-^{39}Ar age determinations (table 3) of the original sanidine concentrate dated by Doell et al. (1968) from Cerro del Abrigo III form a tightly grouped array. The data have a weighted-mean age of 1.004 ± 0.019 Ma, ~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 assigned 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 formalized 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 (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 of three tightly grouped obsidian ages 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 obsidian sample dated was collected by P.W. Lipman from site S34 of Doell et al. (1968, table 3). 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-means of four ages each of sanidine from 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. These ages are nearly identical to several K-Ar ages (G.A. Izett, unpublished data) for these units, but about 10% older than ^{40}Ar-^{39}Ar ages measured by Spell et al. (1990) and Spell and McDougall (1992). They (Spell et al., 1990, p. 179) stated that they used an inhomogeneous fluence-monitor mineral (Bern 4M muscovite) and an irradiation package geometry that resulted in a large error for J, the irradiation parameter. Three large packets of this fluence-monitor mineral were placed at the center and both ends of a 4.5 cm quartz tube, but only the fluence monitors at the ends were used to calibrate the neutron-irradiation dose.

The onset of the JNS can be calibrated also by using the isotopic ages of Ivory Coast tektites. Their sub-millimeter 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). More 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 Ivory Coast tektites of 1.05 ± 0.11 Ma and 1.10 ± 0.10 Ma, but these ages have a high analytical uncertainty. 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. The best currently available age for the IC tektites is perhaps 1.10 Ma, and this age together with the data of Schneider and Kent (1990) suggest the JNS began at 1.11 Ma.

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 (inadvertently called the rhyolite of Cobb Mountain), Clear Lake, Calif., and the Wapiti Lake rhyolite (transitional magnetic polarity) in Yellowstone National Park have ^{40}Ar-^{39}Ar ages of 1.19 Ma and 1.22 Ma, respectively. These data indicate that the Cobb Mountain normal event occurred at 1.19 Ma (normalized to an age of 513.9 Ma for MMhb-1 fluence monitor).

End of the Jaramillo

Doell et al. (1968, table 3, site S38) indicated that the JNS ended about 0.90 Ma based on a K-Ar sanidine age of 0.907 ± 0.028 Ma for the rhyolite dome of Cerro Santa Rosa I. They assumed that this rhyolite was intruded near the end of the JNS because of its intermediate magnetic polarity.

Our analytical data (table 3) of six splits of the original sanidine concentrate dated by Doell et al. (1968, table 3, site S38) from the reversely magnetized rhyolite dome of Cerro Santa Rosa I 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 essentially 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 is possible after the age and magnetic polarity of the several flows that compose the Lewis Canyon Rhyolite in Yellowstone National Park are determined. Sanidine from one of the units of the Lewis Canyon has a weighted-mean ^{40}Ar-^{39}Ar age of 0.954 ± 0.005 Ma (1 σ) (J.D. Obradovich, unpublished data), but it is not certain that the dated flow is the same as the one having reverse magnetic polarity as measured by Reynolds (1975).

In summary, some of our sanidine ages from the reversely magnetized rhyolite domes of the Valles caldera are distinctly older than the conventional K-Ar sanidine ages of Doell et al. (1968, table 3) and 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). Our age data combined with the ^{40}Ar-^{39}Ar age of Ivory Coast tektites indicate that the JNS began at 1.11 ± 0.10 Ma, but a more precise age for the Ivory Coast tektites is needed. The JNS ended before 0.92 Ma, perhaps as early as 0.97 Ma, if the reverse polarity of the dated Lewis Canyon rhyolite flow can be confirmed. Doell et al. (1968, fig. 12) indicated that the JNS began at 0.99 Ma and ended at 0.90 Ma, which conflicts with their conclusion of p. 244 that the Jaramillo lasted only about 0.05 Ma.

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 analytical best age (0.710 ± 0.015 Ma) for this rock given by Doell et al. (1968, table 3, fig. 12). They also gave another 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, respectively. The ^{40}Ar-^{39}Ar ages are older than the conventional K-Ar ages of 0.745 ± 0.015 Ma and 0.725 ± 0.019 Ma for these two rhyolite domes reported by Doell et al. (1968, table 3, fig. 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 described by Chesner (1988). Four age determinations resulted in a weighted-mean age of 0.789 ± 0.006 Ma (table 3). Two of these age determinations were made on a sanidine concentrate originally prepared by C.A. Chesner that we subsequently reprocessed in heavy liquids and hand picked. The original sanidine concentrate was previously ^{40}Ar-^{39}Ar dated by T.C. Onstott at 0.84 ± 0.030 Ma (in Diehl et al., 1987). The remaining two age determinations were made on a sanidine concentrate that we prepared from a sample of the tuff sent by Chesner.

To establish a calibration point within earliest Brunhes time, we analyzed 23 sanidine concentrates of the Bishop Tuff of eastern California (table 4). 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, 1982) 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 Tuff are shown in figure 2. The correlation-diagram age for the basal air-fall unit of the Bishop using an intercept on the X-axis of 2,311 is 0.764 ± 0.006 Ma, almost exactly the same as the weighted-mean age of 0.764 ± 0.005 Ma. Data for the sanidine of the upper cliopyroxene-bearing unit has an intercept on the *x*-axis of 2,352 and an age of 0.762 ± 0.006 Ma, nearly identical to the weighted-mean age of 0.757 ± 0.009 Ma. The inverse of the intercepts on the *y*-axes of the two diagrams (fig. 2) indicate that the trapped Ar component has a ^{40}Ar to ^{36}Ar ratio of 293 and 295, respectively, nearly identical to the ratio of these isotopes (295.5) in atmospheric Ar.

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) conventional K-Ar ages for the same subunits (0.738 ± 0.003 Ma and 0.736 ± 0.005 Ma) reported by Izett et al. (1982), (2) a fission track age of 0.74 Ma counted by Izett and Naeser (1976), (3) and ^{40}Ar-^{39}Ar plateau and total-fusion ages of 0.73 Ma and 0.74 Ma determined by Hurford and Hammerschmidt (1985).

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, Calif. (Hillhouse and Cox, 1976, p. 56) and 1.83 m above the boundary in sediments of ancient Lake Bonneville, Utah (Eardley et al., 1973, p. 212). 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 and Gvosdetsky, 1960 ; 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 (Eardley and Gvosdetsky, 1960; Izett, et al., 1970) having an age of 0.76 Ma and an overlying Lava Creek B ash bed (Izett et al., 1970; Izett and Wilcox, 1982) having an age of 0.66-0.67 Ma (Izett et al. 1992) in the Saltair and Burmester core holes.

This inferred age of 0.77 Ma for the MBB is compatible with a weighted-mean ^{40}Ar-^{39}Ar age of 0.769 ± 0.021 Ma (95% C.L.) for 54 analyses of Australasian tektites (see also Izett and Obradovich, 1992b, 1992c). According to Burns (1989) and Smit et al. (1991) Australasian microtektites, the sub-millimeter equivalents of Australasian tektites, 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, deMenocal et al. (1991) 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 he 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), if the difference in ages of fluence-monitor minerals adopted in the two studies is taken into account. To make them exactly comparable our age should be increased (or theirs reduced) by about 1.45%, because we used an age of 27.55 Ma for sanidine from the Fish Canyon Tuff, whereas they used 27.92 Ma for biotite from the same rock.

Conclusions

1. Based on ^{40}Ar-^{39}Ar ages of Ivory Coast tektites and sanidine and obsidian ages from rhyolite domes-flow complexes in the Valles caldera of New Mexico, the JNS lies within the bounds 1.11-0.92 Ma. It began at about 1.11 Ma and ended before 0.92 Ma, perhaps as early as 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 (1.11-0.92 Ma) 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 on the basis of(1) three reversely magnetized rhyolite domes in New Mexico and pumice of the reversely magnetized Oldest Toba Tuff of Sumatra and (2) the normally magnetized Bishop Tuff of California.
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 (calibrated using an age of 513.9 Ma for MMhb-1 fluence monitor). This conclusion is reached on the basis of computed sedimentation rates at two sites in the western U.S.A., 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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TABLE 1. HISTORY OF ISOTOPIC DATING OF KEY ROCK UNITS BEARING ON THE AGE OF THE JARAMILLO SUBCHRON USING THE K-Ar AND ^{40}Ar-^{39}Ar METHODS.
[AGES IN MILLIONS OF YEARS; CONVENTIONAL K-AR IN NORMAL PRINT, ^{40}Ar-^{39}Ar AGES SHOWN IN BOLD]

REFERENCE	POST-JARAMILLO ROCKS- REVERSELY MAGNETIZED CERRO SANTA ROSA I	JARAMILLO AGE ROCKS NORMALLY MAGNETIZED CERRO ABRIGO III	PRE-JARAMILLO-ROCKS REVERSELY MAGNETIZED CERRO DEL MEDIO II
This paper	**0.916**	**1.004**	**1.161**
Izett & Obradovitch (1992a)	**0.916**	**1.004**	**1.161**
Spell & McDougall (1992)	**0.915**	**0.973**	**1.13**
Izett & Obradovich (1992d)	**0.92**	**1.00**	**1.16**
Mankinen & Dalrymple (1979)	0.91	0.909	1.17
DECAY CONSTANT CHANGE (STEIGER AND JAGER, 1977)			
Doell et al. (1968)	0.907	0.909	1.17

Note, Ages of Izett and Obradovitch (this paper) should be increased about 1.26% to make them comparble to those of Spell McDougall (1992).

TABLE 2.--HISTORY OF ISOTOPIC DATING OF SANIDINE-BEARING KEY VOLCANIC ROCKS BEARING ON THE AGE OF THE MATUYAMA-BRUNHES BOUNDARY USING THE K-Ar AND ^{40}Ar-^{39}Ar METHODS.

[AGES IN MILLION OF YEARS; CONVENTIONAL K-AR IN NORMAL PRINT AND ^{40}Ar-^{39}Ar AGES SHOWN IN BOLD; L, LOWER PART OF BISHOP TUFF; U, UPPER PART OF BISHOP TUFF; T, TOTAL FUSION AGE; P, PLATEAU AGE]

REFERENCE	BISHOP TUFF CALIFORNIA NORMAL	RHYOLITE DOMES JEMEZ MTS., NM REVERSE	M-B BOUNDARY
This paper	**0.76 (L); 0.76 (U)**	**0.79**	**0.77**
Baksi et al. (1992)			**0.78**
Izett & Obradovitch (1992a)	**0.76 (L); 0.76 (U)**	**0.79**	**0.77**
Izett & Obradovich (1991)	**0.78 (L); 0.76 (U)**	**0.81**	**0.79**
Izett et al. (1988)	0.74 (L); 0.74 (U)	0.75, 0.80	0.75
Hurford & Hammerschmidt (1985)	**0.74 (T); 0.73 (P)**	--	>0.74
Izett (1982)	0.74	--	0.75
Mankinen & Dalrymple (1979)	0.73	0.74	0.73
	DECAY CONSTANT CHANGE (STEIGER AND JAGER, 1977)		
Hildreth (1977)	0.72 (L); 0.68, 0.73 (U)		
Bailey et al. (1976)	0.71	--	>0.71
Doell et al. (1968)	--	0.71, 0.84	>0.70
Huber & Rinehardt (1967)	0.66	--	>0.66
Dalrymple et al. (1965)	0.70	--	>0.68
Evernden & Curtis (1965)	0.9-1.2	--	>0.9
Evernden & others (1957)	0.87	--	>0.9

Note, Ages of Izett and Obradovitch (this paper) should be increased by about 1.45% to make them comparable with age of Baksi et al. (1992).

Table 3. Total-fusion ^{40}Ar-^{39}Ar data for sanidine and obsidian from rhyolites of the Jemez Mountains, N. Mex., and Sumatra pertinent to the age of the Jaramillo Subchron and Matuyama-Brunhes boundary

[Samples of basal air-fall members of the lower and upper members of the Bandelier Tuff [Guaje (91G35) and Tsankawi (91G36) Pumice Beds] 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, N. Mex. Error of weighted-mean ages is at the 95% confifdence level. **, obsidian ages

UNIT POLARITY SAMPLE NUMBER	EXP. NO.	J	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40}Ar^*$ MOLES	$^{40}Ar^*/^{39}Ar$	$^{40}Ar^*$ %	AGE Ma	ERROR ± 1 SIGMA
OLDEST TOBA TUFF	92Z0244	3.97E-04	0.00797	0.00113	1.89E-13	1.0991	76.5	0.787	0.006
REVERSE	92Z0245	3.97E-04	0.00859	0.00038	1.24E-13	1.1059	90.4	0.792	0.006
T-15A	92Z0209	4.04E-04	0.00743	0.00146	1.03E-13	1.0855	71.4	0.790	0.007
	92Z0210	4.04E-04	0.00763	0.00140	1.33E-13	1.0834	72.2	0.788	0.006
					WEIGHTED MEAN			0.789 ± 0.006 Ma	
CERRO SANTA ROSA II	92Z0237	4.00E-04	0.01334	0.00161	8.09E-14	1.1011	69.6	0.794	0.008
REVERSE	92Z0201	4.00E-04	0.01309	0.00051	8.62E-14	1.1137	87.7	0.803	0.008
4D003	92Z0259	4.00E-04	0.01285	0.00069	2.05E-13	1.1053	84.1	0.798	0.006
	92Z0260	4.00E-04	0.01300	0.00654	1.26E-13	1.0774	35.7	0.777	0.009
					WEIGHTED MEAN			0.793 ± 0.018 Ma	
CERRO SECO	92Z0202	4.02E-04	0.01309	0.00052	8.03E-14	1.1109	87.7	0.804	0.008
REVERSE	92Z0203	4.02E-04	0.01307	0.00026	9.26E-14	1.1027	93.2	0.799	0.007
4D001	92Z0261	4.02E-04	0.01375	0.00103	1.51E-13	1.0861	77.9	0.786	0.006
	92Z0262	4.02E-04	0.01324	0.00123	1.24E-13	1.0927	74.9	0.791	0.007
					WEIGHTED MEAN			0.794 ± 0.007 Ma	
CERRO SAN LUIS	90Z0921	8.0E-E	0.01323	0.00124	6.69E-14	0.5956	61.9	0.827	0.008
REVERSE	91Z0460	7.0E-4	0.01335	0.00044	1.50E-14	0.6131	82.6	0.804	0.008
82W8	91Z0459	7.0E-4	0.01366	0.00022	1.84E-14	0.6251	90.4	0.820	0.012
	91Z0458	7.0E-4	0.01346	0.00026	1.61E-14	0.6041	88.6	0.792	0.012
	90Z0445	1.0E-4	0.00321	0.01022	1.08E-13	3.7880	55.6	0.820	0.007
	90Z0406	1.0E-4	0.03876	0.00290	9.83E-15	3.7115	81.3	0.804	0.033
	90Z0404	1.0E-4	0.02046	0.00519	6.07E-15	3.5466	69.8	0.768	0.050
	91Z0953	4.0E-4	0.01390	0.00311	3.53E-14	1.0837	54.1	0.873	0.009
	91Z0954	4.0E-4	0.01349	0.00961	1.13E-14	0.9615	25.3	0.775	0.020
					WEIGHTED MEAN			0.812 ± 0.023 Ma	
CERRO SANTA ROSA I	92Z0238	4.04E-04	0.01126	0.00164	1.31E-13	1.2602	72.1	0.918	0.008
REVERSE	92Z0239	4.04E-04	0.01122	0.00282	7.90E-14	1.2388	59.7	0.903	0.010
4D002	92Z0263	4.04E-04	0.01159	0.00105	1.95E-13	1.2429	79.8	0.905	0.006
	92Z0264	4.04E-04	0.01125	0.00104	1.32E-13	1.2416	79.9	0.905	0.007
	92Z0194	4.04E-04	0.01099	0.00033	9.27E-14	1.2966	92.7	0.945	0.009
	92Z0200	4.04E-04	0.01106	0.00028	8.37E-14	1.2635	93.7	0.921	0.009
					WEIGHTED MEAN			0.916 ± 0.017 Ma	
CERRO DEL ABRIGO III	92Z0186	4.27E-04	0.01286	0.00047	1.75E-13	1.2999	90.0	1.001	0.007
NORMAL	92Z0187	4.27E-04	0.01283	0.00033	1.89E-13	1.3316	92.8	1.025	0.007
3X189	92Z0233	4.27E-04	0.01206	0.00113	2.11E-13	1.2938	79.2	0.996	0.007
	92Z0234	4.27E-04	0.01223	0.00335	6.28E-14	1.2761	56.2	0.983	0.013
	92Z0235	4.27E-04	0.01271	0.00123	1.99E-13	1.3028	78.0	1.010	0.010
					WEIGHTED MEAN			1.004 ± 0.019 Ma	
CERRO DEL MEDIO II**	92Z0249	4.18E-04	0.03264	0.00037	1.39E-13	1.5469	93.2	1.164	0.009
REVERSE	92Z0211	4.18E-04	0.03250	0.00047	1.19E-13	1.5428	91.5	1.161	0.010
J-1	92Z0212	4.18E-04	0.03260	0.00067	2.10E-13	1.5381	88.5	1.158	0.008
					WEIGHTED MEAN			1.161 ± 0.010 Ma	
CERRO DEL MEDIO I	92Z0247	4.02E-04	0.05123	0.00225	5.40E-14	1.6650	71.4	1.207	0.017
REVERSE									
3X198, 3X195, 3X200									
						MEAN		1.207 ± 0.017 Ma	
TSANKAWI PUMICE BED	92Z0215	4.15E-04	0.00914	0.00076	1.58E-13	1.6499	87.8	1.235	0.009
REVERSE	92Z0216	4.15E-04	0.00918	0.00048	1.91E-13	1.6187	91.7	1.211	0.008
91G36	92Z0267	4.15E-04	0.00943	0.00131	2.49E-13	1.6440	80.7	1.230	0.008
	92Z0268	4.15E-04	0.00930	0.00156	1.57E-13	1.6264	77.7	1.217	0.009
					WEIGHTED MEAN			1.223 ± 0.018 Ma	
GUAJE PUMICE BED	92Z0265	4.17E-04	0.00986	0.00216	2.66E-13	2.1461	77.0	1.612	0.011
REVERSE	92Z0266	4.17E-04	0.00945	0.00134	1.97E-13	2.1353	84.2	1.603	0.011
91G35	92Z0213	4.17E-04	0.00959	0.00087	1.49E-13	2.1758	89.3	1.634	0.012
	92Z0214	4.17E-04	0.00959	0.00048	1.96E-13	2.1378	93.6	1.605	0.011
					WEIGHTED MEAN			1.613 ± 0.011 Ma	

* Radiogenic

Table 4. 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
[Bishop Tuff, upper unit from 1-m-diameter pumice boulder from NE 1/4 sec. 27, T. 1 S., R. 29 E., Mono County, Calif. Bishop Tuff, air-fall unit from an abandoned pumice mine in NW 1/4 sec. 4, T. 6 S., R. 33 E., Inyo County, Calif. Error of weighted-mean ages is at the 95% confidence level.]

UNIT POLARITY SAMPLE NO.	EXP. NO.	J	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40}Ar^*$ MOLES	$^{40}Ar^*/^{39}Ar$	$^{40}Ar^*$ %	AGE	ERROR ± 1 SIGMA
BISHOP TUFF	90Z0409	1.20E-04	0.00163	0.00876	1.84E-14	3.51470	57.6	0.761	0.033
UPPER UNIT	90Z0410	1.20E-04	0.03820	0.03154	4.33E-15	3.54349	27.5	0.767	0.141
Normal	90Z0446	1.20E-04	0.04109	0.02054	8.94E-14	3.38383	35.8	0.732	0.010
79G94	90Z0917	7.68E-04	0.01092	0.00102	1.12E-13	0.54938	64.4	0.761	0.008
	90Z0918	7.68E-04	0.01056	0.00072	1.12E-13	0.55118	72.1	0.763	0.007
	90Z0923	7.68E-04	0.01073	0.00038	1.12E-13	0.55491	82.9	0.769	0.007
	91Z0447	7.17E-04	0.03992	0.00064	2.43E-14	0.56682	75.0	0.733	0.009
	91Z0448	7.17E-04	0.01073	0.00064	1.75E-14	0.58362	75.5	0.755	0.011
	91Z0449	7.17E-04	0.01171	0.00011	1.51E-14	0.59344	94.6	0.767	0.013
	91Z0450	7.17E-04	0.01078	0.00099	7.51E-15	0.60104	67.2	0.777	0.025
	91Z1119	4.60E-04	0.01438	0.00087	1.20E-13	0.92000	78.0	0.763	0.006
	91Z1120	4.60E-04	0.01384	0.00165	5.77E-14	0.91078	65.1	0.755	0.009
					WEIGHTED MEAN			0.757 ± 0.009 Ma	

BISHOP TUFF	90Z0411	1.20E-04	0.00324	0.00082	9.45E-14	3.58642	93.6	0.776	0.008
AIR FALL UNIT	90Z0915	7.70E-04	0.00872	0.00338	2.24E-14	0.53766	35.0	0.747	0.028
Normal	90Z0919	7.67E-04	0.00921	0.00621	1.71E-14	0.53340	22.5	0.738	0.037
79G14, 80G50a	90Z0920	7.65E-04	0.00814	0.00724	1.90E-14	0.57075	21.1	0.787	0.036
	91Z0436	7.20E-04	0.00672	0.00426	2.29E-14	0.58541	31.7	0.760	0.012
	91Z0942	4.55E-04	0.00703	0.00306	2.18E-14	0.94458	51.1	0.775	0.176
	91Z0943	4.55E-04	0.00670	0.00421	3.79E-14	0.93185	42.8	0.765	0.012
	91Z0945	4.55E-04	0.00705	0.00867	1.10E-14	0.91579	26.3	0.751	0.034
	91Z1116	4.60E-04	0.00876	0.00038	3.84E-14	0.92316	89.1	0.765	0.013
	91Z1117	4.60E-04	0.00910	0.00025	3.53E-14	0.92556	92.5	0.767	0.014
	92Z0246	3.97E-04	0.00660	0.00077	1.80E+25	1.06129	82.0	0.760	0.005
* RADIOGENIC					WEIGHTED MEAN			0.764 ± 0.005 Ma	

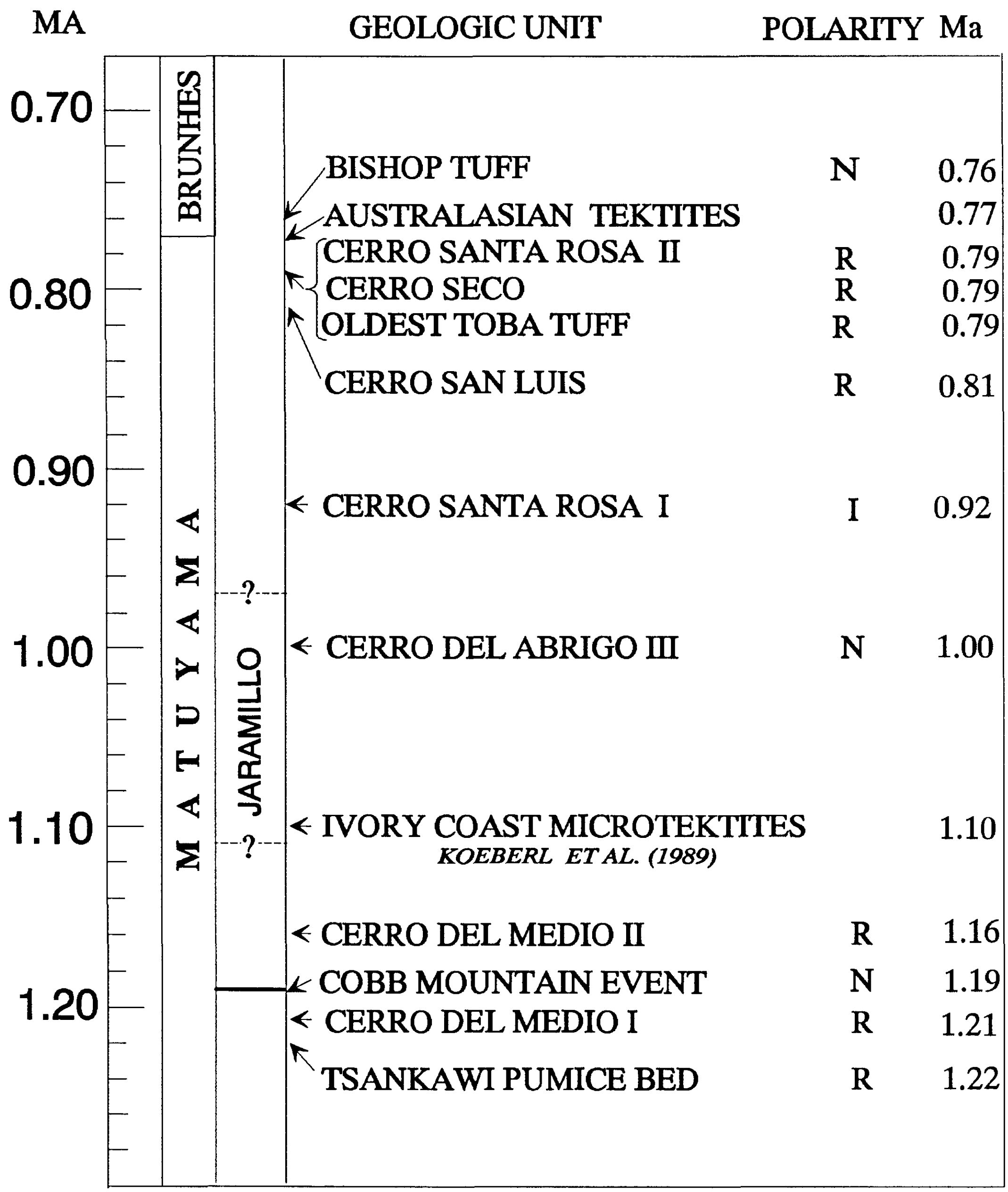

Figure 1 Diagram showing revised GPTS of This Paper