Age of Matuyama-Brunhes boundary constrained by U-Pb zircon dating of a widespread tephra

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ABSTRACT

The youngest geomagnetic polarity reversal, the Matuyama-Brunhes boundary (MBB), provides an important datum plane for sediments, ice cores, and lavas. Its frequently cited age of 780 ka is based on orbital tuning of marine sedimentary records, and is supported by $^{40}Ar/^{39}Ar$ dating of Hawaiian lavas using recent age calibrations. Challenging this age, however, are reports of younger astrochronological ages based on oxygen isotope stratigraphy of high-sedimentation-rate marine records, and cosmogenic nuclides in marine sediments and an Antarctic ice core. Here, we present a U-Pb zircon age of 772.7 ± 7.2 ka from a marine-deposited tephra just below the MBB in a forearc basin in Japan. U-Pb dating has a distinct advantage over $^{40}Ar/^{39}Ar$ dating in that it is relatively free from assumptions regarding standardization and decay constants. This U-Pb zircon age, coupled with a newly obtained oxygen isotope chronology, yields an MBB age of 770.2 ± 7.3 ka. Our MBB age is consistent with those based on the latest orbitally tuned marine sediment records and on an Antarctic ice core. We provide the first direct comparison between orbital tuning, U-Pb dating, and magnetostratigraphy for the MBB, fulfilling a key requirement in calibrating the geological time scale.

INTRODUCTION

Geomagnetic polarity reversals, including the Matuyama-Brunhes boundary (MBB), are critical markers for calibrating the age of sedimentary sequences and volcanic rocks. Most age determinations for the MBB use marine, astronomically tuned, benthic and planktonic foraminiferal oxygen isotope records to date the midpoint of the transition. During the MBB and other reversals, Earth's magnetic field intensity dropped significantly, resulting in increased production of cosmogenic radionuclides, including ^{10}Be, in the upper atmosphere (Beer et al., 2002). Hence, the MBB has also been recognized as a positive spike in the ^{10}Be flux recorded in an Antarctic ice core (Raisbeck et al., 2006) and in marine sediments (e.g., Suganuma et al., 2010).

The MBB has a frequently cited age of 780 ka, which derives from astronomically tuned benthic and planktonic oxygen isotope records from the eastern equatorial Pacific Ocean (Shackleton et al., 1990). This age is supported by $^{40}Ar/^{39}Ar$ dating of lavas from Maui (Hawaii) at 781–783 ka, following revisions to the reference age of Fish Canyon Tuff sanidine (FCTs) standard for $^{40}Ar/^{39}Ar$ geochronology (Kuiper et al., 2008; Renne et al., 2011). However, post-depositional remanent magnetization (PDRM) lock-in of the geomagnetic signal occurs below the sediment-water interface in marine sediments (e.g., Roberts et al., 2013; Suganuma et al., 2011), which then yields ages for geomagnetic events that are too old. This age offset is influenced by sedimentation rate, as records with higher sedimentation rates should minimize the temporal offset caused by PDRM lock-in. Indeed, younger astrochronological MBB ages of 772–773 ka are given for high-sedimentation-rate records (Channell et al., 2010; Valet et al., 2014), with no PDRM lock-in delay being detected by Valet et al. (2014). These MBB ages are consistent with records of cosmogenic nuclides in marine sediments (e.g., Suganuma et al., 2010) and an Antarctic ice core (Dreyfus et al., 2008), although they are not supported so far by radiometric time scales.

The Kokumoto Formation, in the Kazusa Group, central Japan (Figs. 1A and 1B), is a well-exposed deep-sea sedimentary sequence deposited in a forearc basin open to the Pacific Ocean (e.g., Ito, 1998). A well-preserved and expanded MBB is clearly recognized immediately above a widespread rhyolitic tephra bed, the Byakubi-E. This geological setting offers a unique opportunity to apply SHRIMP-II (sensitive high-resolution ion microprobe) U-Pb dating to zircon crystals from the Byakubi-E tephra, in order to provide the first accurate U-Pb radioisotope age constraint on the MBB in a sedimentary sequence with a high-resolution oxygen isotope record.

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METHODS

Paleomagnetic Measurements and Oxygen Isotope Analysis

In total, 125 paleomagnetic samples were collected from a 12.3-m-thick interval at the Chiba composite section (Fig. 1B). Remanence measurements were made using a three-axis cryogenic magnetometer. Stepwise thermal demagnetization of the natural remanent magnetization was performed on all samples, and characteristic remanent magnetization directions were obtained at temperatures above 300 °C. A suite of rock magnetic experiments revealed the main magnetization carrier to be magnetite (titanomagnetite) (see the GSA Data Repository[1]). For oxygen isotope stratigraphy, we collected 68 samples from a 100.2-m-thick interval at the Chiba composite section (Fig. 1B). We used *Bolivinita quadrilatera* and *Cibicidoides* spp., which are the dominant benthic foraminifera throughout the section (see the Data Repository for details).

U-Pb Dating

Zircons were separated from the Byakubi-E tephra and then mounted in epoxy together with reference zircons. The U-Th-Pb analyses were made using SHRIMP-II at the National Institute of Polar Research, Japan. Correction of $^{206}Pb/^{238}U$ dates based on the Th/U of zircon (Th/U [zircon]) and of the magma (Th/U [magma]) from which the zircon crystallized are required because the zircons have a deficit of ^{206}Pb due to the initial Th/U disequilibrium caused by ^{230}Th exclusion (Schärer, 1984). We used Th/U values from the volcanic glass of the Byakubi-E tephra for the Th/U [magma] of the eruption, determined as 5.82 ± 0.03 (1σ) for five analyses. The Th/U was measured using an inductively coupled plasma–mass spectrom-

[1]GSA Data Repository item 2015173, geologic setting, methods, Tables DR1–DR3, and Figures DR1–DR6, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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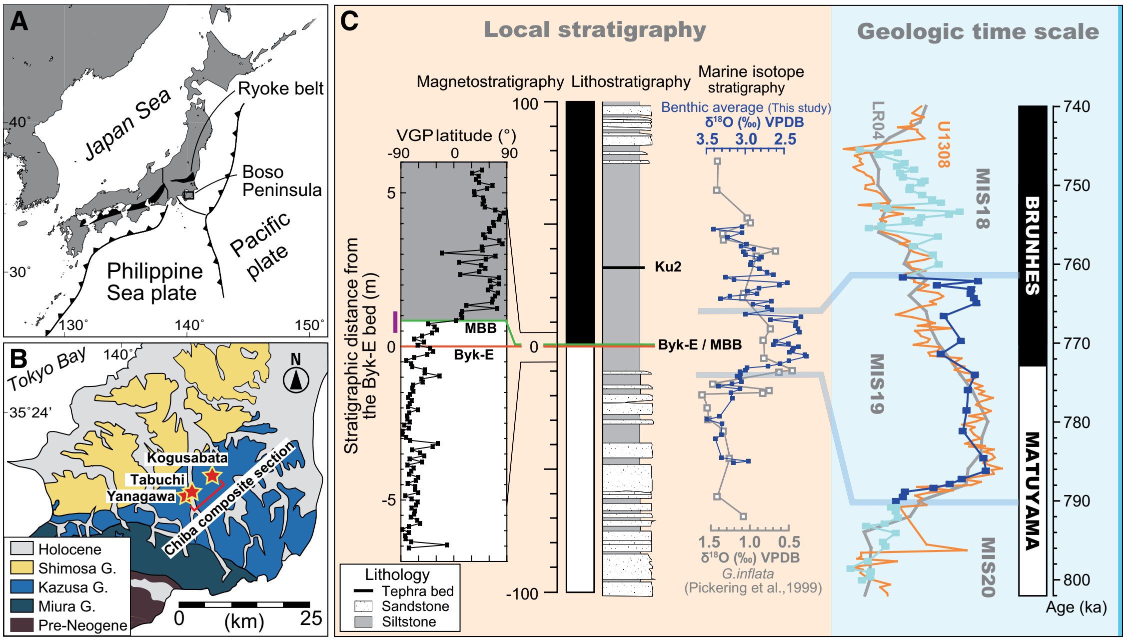

Figure 1. Location and stratigraphy of study site, Japan. A: Tectonic setting. B: Distribution of Kazusa Group (Kanto Basin) and position of Chiba composite section (Tabuchi, Yanagawa, and Kogusabata sections, shown by stars). C: Matuyama-Brunhes boundary (MBB) (green) and Byakubi-E (Byk-E) tephra (red) along with newly obtained high-resolution oxygen isotope stratigraphy in addition to that of Pickering et al. (1999) visually tuned to that of Integrated Ocean Drilling Program (IODP) Site U1308 (Channell et al., 2010) with LR04 benthic stack (Lisiecki and Raymo, 2005) shown for comparison. VPDB—Vienna Peedee belemnite; *G. inflata*—*Globorotalia inflata*; MIS—Marine Isotope Stage. Geologic time scale (with polarity log on right-hand side) uses MBB age of Channell et al. (2010). Correlation to Site U1308 is based on visual comparison of major oxygen isotope features. Purple bar beside magnetostratigraphic column indicates Matuyama-Brunhes directional transition (–45°–45° virtual geomagnetic pole [VGP] latitude); MBB is placed at its midpoint. Ku2 is another widespread tephra bed in the section. Light blue (MIS 20 and MIS 18) and dark blue (MIS 19) lines are the benthic δ¹⁸O average based on this study (local stratigraphy).

eter (ICP-MS) at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (see the Data Repository for details).

MAGNETO- AND OXYGEN-ISOTOPE STRATIGRAPHY

A detailed virtual geomagnetic pole (VGP) path for the Kokumoto Formation at the Chiba composite section was established at 10 cm resolution across the MBB, clearly identifying the reversal (Fig. 1C). The midpoint of the VGP transition occurs at ~0.8 m above the Byakubi-E tephra. High-resolution benthic foraminiferal oxygen isotope stratigraphy ($\delta^{18}O$) locates the MBB in the middle of Marine Isotope Stage (MIS) 19 (Fig. 1C). A sedimentation rate of 32.0 ± 9.3 cm/k.y. (with uncertainty in orbital tuning) for the section gives a VGP midpoint stratigraphic age 2.5 ± 0.9 k.y. younger than the depositional age of the Byakubi-E tephra. Based on this age model, the duration of the Matuyama-Brunhes directional transition is estimated to be 3.1 k.y., which is consistent with that given by high-resolution marine sedimentary records from the North Atlantic Ocean (2.9–6.2 k.y.) (Channell et al., 2010). The MBB "precursor," a preceding geomagnetic event characterized by a paleo-intensity low often with excursional directions (Hartl and Tauxe, 1996), that predates the MBB by ~18 k.y. (e.g., Valet et al., 2014), is absent from our Chiba record, which only extends 12.5 k.y. below the MBB based on the oxygen isotope chronology.

SHRIMP U-Pb Zircon Age

U-Pb dates from 63 zircons (65 spots) vary from Proterozoic to Quaternary (Fig. 2A). Three major groups are recognized in the age distributions: ca. 1.9–1.8 Ga, 75–60 Ma, and younger than 1.0 Ma. The mean ages of the two older groups correspond to the timing of abrupt growth of continental crust in the Proterozoic (Iizuka et al., 2010) and in the Late Cretaceous (Ishihara and Chappell, 2007). The old zircons appear to have been reworked from basement rocks that either contaminated the magma chamber producing the Byakubi-E tephra or were otherwise incorporated during deposition. In particular, a

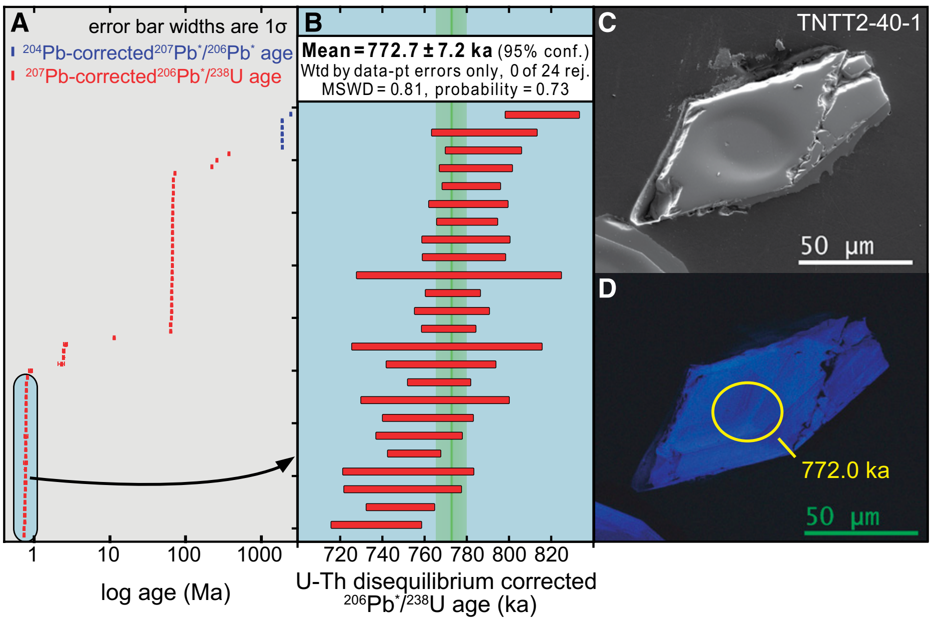

Figure 2. U-Pb ages and scanning electron microscope images of zircons. A,B: U-Pb dates for all analyzed zircons (A) and for Byakubi-E tephra (B). conf.—confidence; Wtd—Weighted; data-pt—data point; rej.—rejected; MSWD—mean square of weighted deviates. C,D: Secondary electron image (C) and cathodoluminescence image (D) for zircon from Byakubi-E tephra. SIMS pits and location of analysis for U-Pb date are shown in D.

large Cretaceous volcano and associated plutonic activity formed the Ryoke belt that rests on the much older Paleozoic metamorphic terrane in central Japan (Isozaki et al., 2010). The eruption conduit of the Byakubi-E tephra is unknown but may have passed through this belt. The Ryoke belt and Paleozoic terrane are also the sedimentary source units for the Kazusa Group. Additional older zircons have U-Pb ages of ca. 15 Ma and 2 Ma, and are distinct from the population of youngest zircons (Fig. 2A). All these reworked zircons are excluded from our age calculations. From the 24 youngest zircons, we obtain a weighted mean of 772.7 ± 7.2 ka (mean square of weighted deviates [MSWD] = 0.81) for the eruption/deposition age of the Byakubi-E tephra (Figs. 2B–2D).

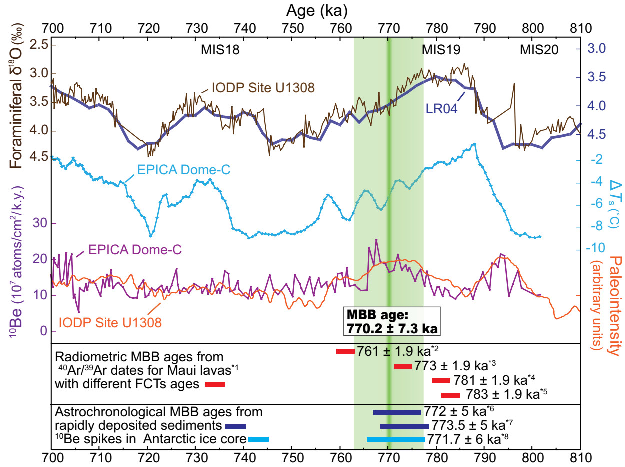

Figure 3. U-Pb age of Matuyama-Brunhes boundary (MBB) compared with $^{40}Ar/^{39}Ar$ ages, ^{10}Be flux, and paleoclimatic proxies. $^{40}Ar/^{39}Ar$ ages for Maui (Hawaii) lavas (Coe et al., 2004) are recalculated with different Fish Canyon Tuff sanidine (FCTs) ages. Oxygen isotope stratigraphy ($\delta^{18}O$) is from Integrated Ocean Drilling Program (IODP) Site U1308 (Channell et al., 2010) and LR04 benthic stack (Lisiecki and Raymo, 2005), and temperature change (ΔT_s) is from deuterium content of European Project for Ice Coring in Antarctica (EPICA) Dome C ice core (Jouzel et al., 2007). ^{10}Be flux and paleointensity (inverted) data are from EPICA Dome C ice core (Raisbeck et al., 2006; Dreyfus et al., 2008) and IODP Site U1308 (Channell et al., 2010), respectively. EPICA Dome C data are corrected to Antarctic Ice Core Chronology 2012 (Bazin et al., 2013). MIS—Marine Isotope Stage. Sources: *1—Coe et al. (2004); *2—Mochizuki et al. (2011); *3—Channell et al. (2010); *4—Kuiper et al. (2008); *5—Renne et al. (2011); *6—Valet et al. (2014); *7—Channell et al. (2010); *8—Raisbeck et al. (2006) and Dreyfus et al. (2008).

DISCUSSION

U-Pb dates from zircon in felsic volcanic rocks can predate the eruption age because the closure temperature for the diffusion of radiogenic Pb in zircon is higher than typical magmatic temperatures (Cherniak, 2010). Nonetheless, Crowley et al. (2007) reported that Bishop Tuff (eastern California) zircon crystallized rapidly, with most grains growing within 5 k.y. in $^{206}Pb/^{238}U$ age. In either case, the U-Pb age should represent the maximum age limit of the Byakubi-E tephra, and hence that of the MBB in the sedimentary section.

The U-Pb zircon age of 772.7 ± 7.2 ka for the Byakubi-E tephra gives an age of 770.2 ± 7.3 ka for the MBB based on the depositional time from the tephra to the MBB (the uncertainty of the MBB age is estimated by integration of errors in these data). This MBB age is younger than the frequently cited astrochronological age of 780–781 ka based on marine records with low deposition rates (e.g., Shackleton et al., 1990; Lisiecki and Raymo, 2005; Pillans and Gibbard, 2012). In contrast, the U-Pb age is consistent with astrochronological ages obtained from high-sedimentation-rate records from the North Atlantic Ocean (773.1 ka; Channell et al., 2010) and a record from the equatorial Indian Ocean (772 ka; Valet et al., 2014). Dating of the ^{10}Be flux anomaly from marine sediments in the equatorial Indian (772 ka; Valet et al., 2014) and Pacific (770 ka; Suganuma et al., 2010) oceans is also consistent with our U-Pb age (Fig. 3). VGP records from high-sedimentation-rate sections should be less affected by PDRM lock-in (Suganuma et al., 2010, 2011), which suggests that the younger MBB ages are the most reliable. In addition, the U-Pb age implies that the MBB corresponds to mid–MIS 19 and not its peak at 780 ka (Lisiecki and Raymo, 2005) (Fig. 3). This result is consistent with the findings of Liu et al. (2008) who compiled MBB data with foraminiferal oxygen isotope records in similar hydrographic settings to avoid effects of ocean circulation and regional temperature variations. They concluded that the MBB occurs late in MIS 19.

The ^{10}Be flux record in the European Project for Ice Coring in Antarctica (EPICA) Dome C ice core from Antarctica contains two broad peaks at ca. 770 and 795 ka (Fig. 3). The younger peak represents a weakening of the geomagnetic field intensity associated with the MBB, and the preceding smaller peak is thought to be a "precursor". A recently revised ice core chronology (Antarctic Ice Core Chronology 2012 [AICC2012]; Bazin et al., 2013) places the point of highest ^{10}Be flux for the MBB peak at 767.7 ± 6.0 ka, and the midpoint of this peak at 771.7 ± 6.0 ka (Fig. 3). The AICC2012 chronology for this age range is constructed with physics-based models (ice flow and accumulation models) owing to weak orbital (atmospheric $\delta^{18}O$) constraints (Bazin et al., 2013). Nonetheless, the ice core record supports a "young" MBB as inferred from the zircon U-Pb age of the Byakubi-E tephra (Fig. 3).

VGP records from lavas have the advantage that $^{40}Ar/^{39}Ar$ geochronology can be used to date the MBB directly, and the thermal remanent magnetization of lavas is also free from PDRM lock-in delays. Four lava piles that record transitional VGPs across the MBB have been dated by $^{40}Ar/^{39}Ar$ geochronology, with two age peaks statistically recognized (Singer et al., 2005). Only one of these piles, represented by six lavas on Maui at 775.6 ± 1.9 ka (2σ analytical), records the MBB (Coe et al., 2004) judging by consistency with the astrochronological age from sedimentary records. A peak that is 18 k.y. older must then correspond to the "precursor" (Singer et al., 2005). However, recent revisions to the reference age of the FCTs standard for $^{40}Ar/^{39}Ar$ geochronology require a systematic shift of the $^{40}Ar/^{39}Ar$ ages to 781–783 ka for the MBB (Kuiper et al., 2008; Renne et al., 2011). These ages, if real, place the MBB at the peak of MIS 19, in contrast to the mid–MIS 19 position indicated by high-resolution records and ^{10}Be peaks (Fig. 3). Uncertainty in ice volume models for the astronomical tuning of oxygen isotope records gives an error for the age of Termination IX (MIS 20–MIS 19 boundary) within 4 k.y. (Channell et al., 2010). Similarly, the ^{10}Be peak in the EPICA Dome C ice core cannot shift to the peak of MIS 19 because uncertainty for the AICC2012 age model is thought to be ±6 k.y. (Bazin et al., 2013; Fig. 3). Thus, the discrepancy between $^{40}Ar/^{39}Ar$ geochronology and astrochronology is unlikely to stem from uncertainty in the astronomical tuning.

Standardization of $^{40}Ar/^{39}Ar$ geochronology with recently proposed FCTs ages (28.201 Ma, Kuiper et al., 2008; 28.294 Ma, Renne et al., 2011) may explain the discrepancy. It has been shown that the recalibrated $^{40}Ar/^{39}Ar$ ages relative to the new FCTs age are systematically older, not only for the astrochronological MBB age, but also for other astronomically tuned reversal and excursion ages back to 1.2 Ma (Channell et al., 2010). However, Singer (2014) reported that a reanalysis of Maui lavas using improved analytical protocols and the FCTs age of Kuiper et al. (2008) yielded an age consistent with the astrochronologic age of Channell et al. (2010), implying that $^{40}Ar/^{39}Ar$ geochronology could yet prove consistent with a younger MBB age. On the other hand, Sagnotti et al. (2014) recently reported a MBB age of 786.1 ± 1.5 ka with a remarkably brief directional transition (<100 yr) based on $^{40}Ar/^{39}Ar$ dates from tephras within a lacustrine succession in central Italy. However, an apparently longer transition recorded from a core drilled through the same lacustrine sediments but at a slightly higher (1–2 m) stratigraphic position (Giaccio et al., 2013) suggests that the magnetic stability and/or sediment magnetization processes may require reexamination. Overall, further investigations of suitable stratigraphic sequences are still needed to understand the exact timing and nature of the geomagnetic field reversal.

CONCLUSIONS

SHRIMP U-Pb dating of zircons from a marine-deposited tephra close to the MBB is reported here alongside new paleomagnetic and $\delta^{18}O$ measurements from the Kazusa Group, central Japan. Our results yield a radiometric age for this important boundary, given that the U-Pb time scale is relatively free from assumptions about standardization and decay constants. Dating the Byakubi-E tephra at 772.7 ± 7.2 ka yields an age of 770.2 ± 7.3 ka for the MBB, which is consistent with astrochronological MBB ages from high-resolution oxygen-isotope records and ^{10}Be peaks in marine sediments, and an Antarctic ice core, and affirms correlations between astrochronology and the U-Pb radiometric time scale with respect to magnetic reversal stratigraphy.

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Notes

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