REFINING CHRONOLOGY FOR THE BRUNHES-MATUYAMA GEOMAGNETIC BOUNDARY

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Abstract The geomagnetic polarity reversals, including the Matuyama–Brunhes boundary (MBB), provides an invariant datum plane for sediments and lavas. However, geomagnetic synchronization has complications despite its potential. Its popular age of 780 ka for the MBB is based on astrochronologically-tuned marine sedimentary records, and is supported by $^{40}Ar/^{39}Ar$ ages of 781–784 ka from Hawaiian lavas using a recent age calibration. Challenging this age, however, younger astrochronological ages using oxygen isotope stratigraphy of high-sedimentation-rate marine records, and records of cosmogenic nuclides in marine sediments and an Antarctic ice core have been reported. Moreover, a high-precision U-Pb zircon age of 772.7 ± 7.2 ka is reported from a marine-deposited tephra near the MBB in the Chiba composite section in the Kokumoto Formation, Kazusa Group. 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. In addition, a high-resolution oxygen isotope chronology is also obtained in this section through the MBB. Therefore, the Chiba composite section will provide a basis for the first direct comparison between astrochronology, U-Pb dating, and magnetostratigraphy for the MBB, fulfilling a key requirement for calibrating the geological timescale. In this paper, I report these recent achievements according to the MBB.

Key words: Brunhes–Matuyama boundary, post-depositional remanent magnetization (PDRM), ^{10}Be, Chiba composite section, U-Pb zircon dating

1. Introduction

The Matuyama–Brunhes boundary (MBB), and preceding the other geomagnetic polarity reversals constitute critical markers for calibrating the age of sedimentary sequences and volcanic rocks. Therefore, knowing the age of this polaritychron (reversal) boundary is very important to a wide range of geological studies. Most age determinations for the MBB are based on marine astronomically-tuned benthic and planktonic foraminiferal oxygen isotope records to date the mid-point of the transition of virtual geomagnetic pole (VGP). However, an understanding of post-depositional remanent magnetization (PDRM) processes shows that lock-in of the geomagnetic signal occurs below the sediment–water interface in marine sediments, which adds uncertainty to geomagnetic synchronization of marine sedimentary records (Fig. 1). Because this

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uncertainty (age offset) is thought to be a function of sedimentation rate (e.g. Suganuma *et al*. 2010; Suganuma 2014), those records with higher sedimentation rates should minimize the PDRM lock-in problem. On the other hand, fluxes of cosmogenic radionuclides such as ^{10}Be provide an alternative tool to decipher the astrochronological MBB age. The Earth's magnetic field intensity dropped significantly during the MBB and other reversals, 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 popular 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 marine astronomically-dated MBB age is supported by ^{40}Ar/^{39}Ar ages of Maui lavas at 775.6 ± 1.9 (Coe *et al*. 2004; Singer *et al*. 2005), revised to 781–783 ka by recent revisions to the reference age of Fish Canyon Tuff sanidine (FCTs) standards for ^{40}Ar/^{39}Ar geochronology (Kuiper *et al*. 2008; Renne *et al*. 2010). However, younger astrochronological MBB ages of 772–773 ka are given for high sedimentation rate records (Channell *et al*. 2010; 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 timescales.

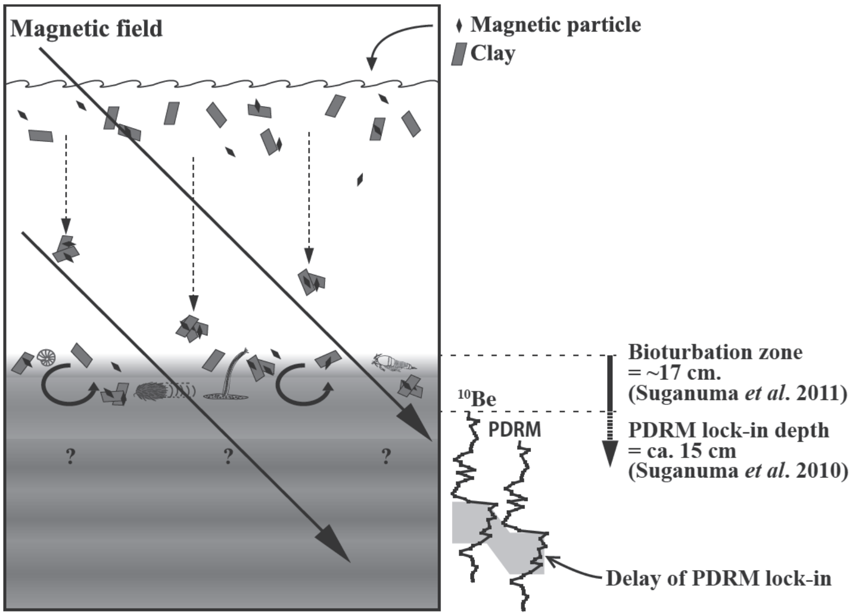

Fig. 1 Schematic figure depicting the current understanding of the PDRM process. Suganuma *et al.* (2010) has reported clear evidence of a deeper PDRM lock-in (~15 cm) based on the downward offset of the paleointensity minimum relative to the ^{10}Be flux anomaly at the MBB. However, the lock-in process (function) of PDRM remains unclear and topic of debate. The benthos illustrations were made by Dr. Nomaki. This figure is modified from Suganuma (2011).

2. PDRM Lock-in Problem

It is widely considered that sediments become permanently magnetized through a PDRM mechanism (Irving and Major 1964; Kent 1973). Immobilization of magnetic particles is thought to occur during sediment dewatering and compaction, which causes vertical offsets between the sediment/water interface and the zone where the paleomagnetic record is fixed (Verosub 1977). This offset is called the PDRM lock-in depth, and the magnitude of this depth has long been debated (e.g. deMenocal *et al*. 1990; Tauxe *et al*. 1996; Sagnotti *et al*. 2005; Tauxe and Yamazaki 2007; Liu *et al*. 2008). Suganuma *et al.* (2010) estimated the PDRM lock-in depth for marine sediments based on an offset between high-resolution ^{10}Be flux and paleomagnetic records through the MBB, and then they demonstrated that acquisition of the paleomagnetic record is delayed relative to the ^{10}Be record (Fig. 1). The delayed PDRM acquisition has been modeled by a so-called lock-in function (e.g. Suganuma *et al*. 2011; Egli and Zhao 2015). These studies suggest that the PDRM is not simply locked as a result of progressive consolidation and dewatering of marine sediments, and that mechanisms such as microbial activity, changes in sediment composition, and particle (flocculation) sizes, changes in chemical conditions, etc., are likely to be relevant.

3. Chiba Composite Section and Single Zircon U-Pb Dating of Byk-E Tephra

The Chiba composite section in the Kokumoto Formation, in the Kazusa Group, central Japan (Fig. 2a and 2b), is a well-exposed deep-sea sedimentary sequence across the Lower–Middle Pleistocene boundary deposited in a forearc basin open to the Pacific Ocean (e.g. Kazaoka *et al*. 2015). The Chiba composite section comprises the adjacent and contiguous Tabuchi (35˚17.66'N; 140˚08.79'E), Yanagawa (35˚17.15'N; 140˚07.88'E), and Kogusabata (35˚18.52'N; 140˚11.89'E) sections (Fig. 2b). Detailed magnetostratigraphy and oxygen isotope stratigraphy for this formation are newly established at 10 cm and 100 cm sample spacing, respectively (Suganuma *et al*. 2015) (Fig. 2c). A transition in the VGP records across the MBB is clearly identified in the section. The high-resolution oxygen isotope stratigraphy shows the midpoint of the VGP transition located between Marine Isotope Stage (MIS) 19 and 18, postdating the peak of MIS 19. A widespread rhyolitic tephra bed named Byk-E occurs ca. 80 cm below the midpoint of the VGP transition. This geological setting offers a unique opportunity to apply SHRIMP-II (sensitive high-resolution ion microprobe) U-Pb dating to zircon crystals from the Byk-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.

The U–Th–Pb analyses of separated zircons from the Byk-E tephra 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 the magma (Th/U [magma]) from which the zircon crystallized, are carried out by Th/U values from the volcanic glass of the tephra, determined as 5.82 ± 0.03 (1σ). From the 24 youngest zircons, we obtain a weighted mean of 772.7 ± 7.2 ka for the eruption/deposition age of the Byk-E tephra (Suganuma *et al*. 2015).

4. Discussion and Conclusion

The U-Pb zircon age for the Byk-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 uncertainity of the MBB age is estimated by integration of errors in these data). This MBB age is younger than the popular astrochronological age of 780–781 ka based on marine records with low sedimentation rate (e.g. Shackleton *et al*. 1990; Lisiecki and Raymo 2005). 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. 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).

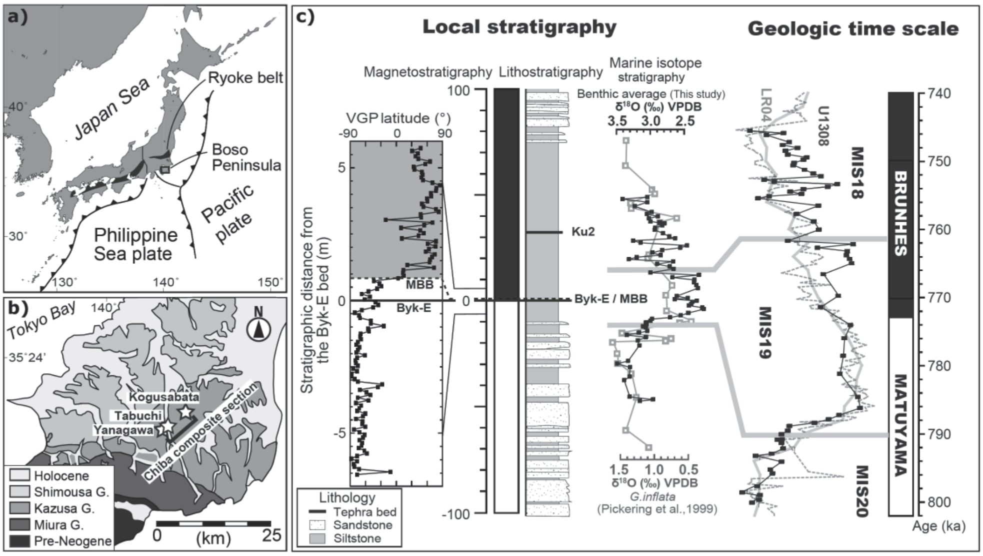

Fig. 2 Location and stratigraphy of the Chiba composite section. (a) Tectonic setting. (b) Distribution of Kazusa Group (Kanto Basin) and position of Chiba composite section, shown by stars. (c) MBB and Byk-E tephra along with newly obtained high-resolution oxygen isotope stratigraphy in addition to 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. Assigments of MIS 20 ~ 18 are the benthic δ^{18}O average based on this study (local stratigraphy). This figure is modified from Suganuma *et al*. (2015).

The ^{10}Be flux record in the EPICA Dome C ice core from Antarctica contains two broad peaks at about 770 and 795 ka. 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 (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. The AICC2012 chronology for this age range is constructed with physics-based models (ice flow and accumulation models) owing to weak orbital (atmospheric δ^{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 Byk-E tephra (Fig. 3).

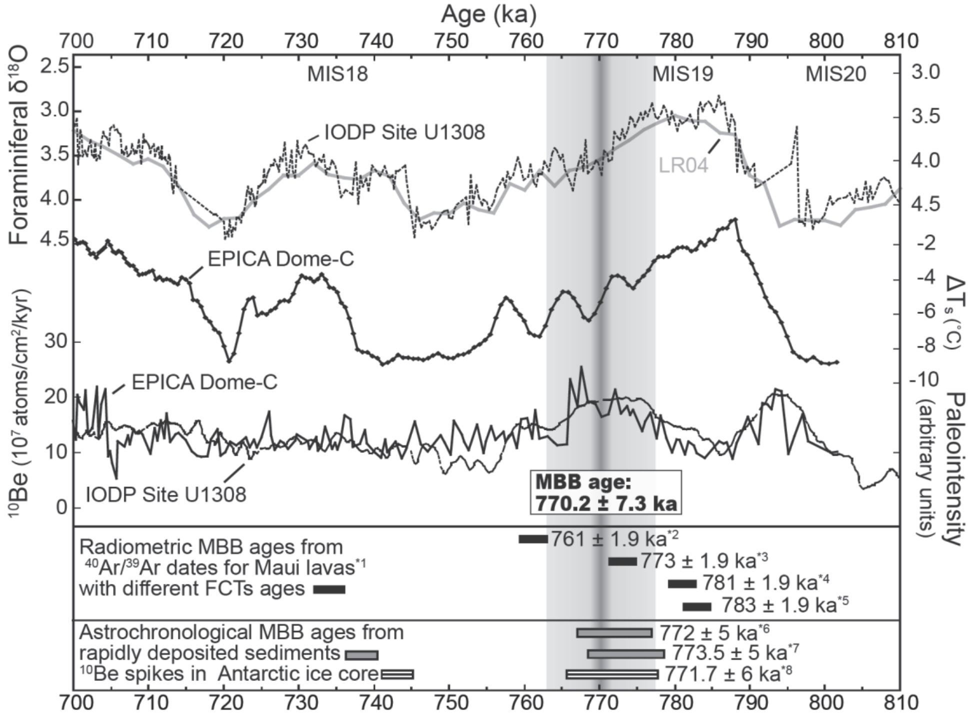

Fig. 3 U-Pb age of the MBB in comparison with ^{40}Ar/^{39}Ar ages, ^{10}Be flux, and paleoclimatic proxies. ^{40}Ar/^{39}Ar ages for Maui lavas (Coe *et al*. 2004) are recalculated with different FCTs ages. The oxygen isotope stratigraphy is from IODP U1308 (Channell *et al*. 2010) and LR04 (Lisiecki and Raymo 2005), and the temperature change is inferred from the deuterium content of the EPICA Dome C ice core (Jouzel *et al*. 2007). ^{10}Be flux and paleointensity (inverted) data are from the EPICA Dome C ice core (Raisbeck *et al*. 2006; Dreyfus *et al*. 2008) and IODP U1308 (Channell *et al*. 2010), respectively. The EPICA Dome C data are corrected to the AICC2012 ice-core chronology (Bazin *et al*. 2013). Asterisk numbers: [*1] Coe *et al*. (2004), [*2] Mochizuki *et al*. (2011), [*3] Channell *et al*. (2010), [*4] Kuiper *et al*. (2008), [*5] Renne *et al*. (2010), [*6] Valet *et al*. (2014), [*7] Channell *et al*. (2010), [*8] Raisbeck *et al*. (2006), Dreyfus *et al*. (2008). This figure is modified from Suganuma *et al*. (2015).

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 kyr 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*. 2010). 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 20/19 boundary) within 4 kyr (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 kyr (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.

The standardizations of $^{40}Ar/^{39}Ar$ geochronology with the recently proposed FCTs ages (28.201 Ma: Kuiper *et al*. 2008; 28.294 Ma: Renne *et al*. 2010) may explain the discrepancy. It has been shown that the recalibrated $^{40}Ar/^{39}Ar$ ages relative to the new FCTs 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). Based on the best fits to these geomagnetic reversals and excursions during 700–1250 ka, a new FCTs standard age of 27.93 Ma has been proposed (Channell *et al*. 2010). If our U-Pb age of MBB of 770.2 ± 7.3 ka is reliable, this suggests recalibration of the FCTs age to 27.824 ± 0.265 Ma, based on the same reasoning made for the ages of the Maui lavas. Considering the error, this age is consistent with the suggested age of 27.93 Ma (Channell *et al*. 2010). Singer (2014) recently reported that the reanalysis of Maui lavas using the FCTs age of Kuiper *et al*. (2008) but introducing exceptionally low, stable blanks yielded an age consistent with the astrochronologic age of Channell *et al*. (2010), suggesting that the recent $^{40}Ar/^{39}Ar$ geochronology is also consistent with the 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 higher 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.

In summary, the SHRIMP U-Pb dating of zircon grains from a marine-deposited tephra close to the MBB are provided alongside new paleomagnetic and $\delta^{18}O$ measurements of the host section. Results yield the first highly-accurate radiometric age constraint for this important boundary, given that the U-series timescale is relatively free from arguments of standardization and decay constant. Dating of the Byk-E tephra in the Chiba composite section 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 spikes in marine sediments and an Antarctic ice core, affirming correlations between astrochronology and the U-series radiometric timescale with respect to magnetic reversal stratigraphy.

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