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Timing of the Matuyama–Brunhes geomagnetic reversal: Decoupled thermal maximum and sea-level highstand during Marine Isotope Stage 19

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A B S T R A C T

Recent high-resolution magnetic and microfossil data from a long core penetrating the Osaka Group, Japan are astronomically tuned and reassessed to reveal detailed stratigraphic features across the Matuyama–Brunhes (MB) polarity transition during Marine Isotope Stage (MIS) 19. The sediments have a uniform and high average accumulation rate of 63 cm/ky. Astronomical tuning based on six calibration points, including a clear MIS 19.2 sea-level lowstand, dates the main MB boundary (MBB) to 777.6 ka, the sea-level peak of the MIS 19.3 highstand to 780.7 ka, and the climatic thermal maximum (TM) to 776.4 ka. The MB transition began with a short-lived normal polarity episode that occurred before the highstand at MIS 19.3, and terminated with multiple rapid reversals that occurred between highstand MIS 19.3 and lowstand 19.2. The TM just postdates the termination of the MB transition, and occurs about 4000 years after the sea-level peak. The delayed TM is also observed at Gesher Benot Ya'aqov, Israel and on the Mediterranean coast, and possibly at Lake Baikal. In high-resolution records from Chinese loess–paleosols and deep-sea sediments, the rapid reversal zone of the MBB has a very similar climatostratigraphic character. These magneto-climatostratigraphic features in MIS 19 are useful for correlating between terrestrial and marine sediments. The delay in warming relative to the sea-level highstand seems to have been due to a cloud-albedo effect induced by an increase in galactic cosmic ray flux during an extremely low magnetic field intensity interval.

1. Introduction

Reversal of the Earth's magnetic field polarity is recorded in various materials simultaneously on the Earth surface and provides a reliable temporal datum for the Quaternary. The Matuyama–Brunhes (MB) polarity boundary (MBB), occurring in Marine Isotope Stage (MIS) 19, is the primary guide for the Early–Middle Pleistocene boundary (Head and Gibbard, 2005; Head et al., 2008). Although the MBB is important in Quaternary stratigraphy, high resolution magnetic and climatic records across the MBB show complex features (Hyodo et al., 2006; Prokopenko et al., 2006; Wang et al., 2006; Kitaba et al., 2009, 2012, 2013; Yang et al., 2010). For example, the MB reversal just predates the thermal maximum in the continental interior of Siberia (Prokopenko et al., 2006), whereas it definitely postdates the MIS 19 sea-level highstand (Bassinot et al., 1994; Lisiecki and Raymo, 2005). The discrepancy in timing of the warmest air temperature and this sea-level highstand (ice volume minimum) causes a conflict in the correlation of marine and terrestrial sediments. Debate continues over the chronology for the MBB, as the astronomical age obtained from deep-sea cores is significantly younger than the mean $^{40}Ar/^{39}Ar$ date of transitionally magnetized lavas (Channell et al., 2010). There are, therefore, many important problems in the magneto-climatostratigraphy of MIS 19.

High-resolution magnetic and microfossil data from a long core penetrating the Osaka Group can solve these problems, because they simultaneously record 100–1000 year variations in the magnetic field, climate, and relative sea-level across the MB transition (Hyodo et al., 2006; Kitaba et al., 2013). In this study, we reassess the data stratigraphically comparing terrestrial and marine records, and produce a high-resolution magneto-climatostratigraphy of MIS 19. A new age model is constructed through the astronomical tuning of sea-level and climate proxies. New pollen assemblage data are incorporated in the latter.

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2. Astronomical tuning of sea-level and climate proxies from Osaka Bay

A Plio-Pleistocene sequence, >2500 m thick at maximum, lies in the Osaka Basin, which has been subsiding at a relatively uniform rate due to faulting caused by subduction of the Philippine Sea Plate (Biswas et al., 1999; Yoshikawa et al., 2000). The sequence mainly consists of lacustrine deposits in the lower part, and alternating marine and lacustrine layers in the upper part. The first marine invasion into Osaka Bay occurred during MIS 37 (Biswas et al., 1999), after which a fine marine clay layer was deposited every interglacial when the sea-level rose above the sill for Osaka Bay, which sits at −50 to −60 m in elevation at present. During glacial periods, the sea coast retreated southward toward the Pacific, and the basin contained a lake. The elevation of the sill has not changed since at least the first marine invasion (Kariya et al., 2010). Twenty-one marine layers have been recognized and are correlated with MIS numbers (e.g. Takatsugi and Hyodo, 1995; Yoshikawa and Mitamura, 1999). Tephrochronology, magnetostratigraphy, and climatostratigraphy show that sediments have accumulated at uniform rates in the basin (Uchiyama et al., 2001; Kariya et al., 2010; Kitaba et al., 2011). Sea-level proxies with diatom assemblage data show that a linear age model is valid for each marine clay layer (Kariya et al., 2010; Kitaba et al., 2013). A marine clay layer correlated with MIS 19, defined by diatom assemblage and sulfur content data, spans a depth range from 406.2 m to 390.8 m in a 1700-m core that is the focus of the present study (Kitaba et al., 2013). From the thick MIS 19 layer, 100–200 year resolution magnetic data have been obtained from the MB transition (Hyodo et al., 2006). Paleoclimate data with 100–200 year resolution based on pollen have also been obtained (Kitaba et al., 2013), in addition to 1000–2000 year resolution data (Hongo, 2007; Kitaba et al., 2009).

We construct a new age model for this 1700-m core based on the astronomical tuning of a sea-level proxy curve. Ice volume, a tuning target, is calculated using the model of Imbrie and Imbrie (1980), with insolation at 65°N for June 21 (Laskar et al., 2004). Ice volume variations, calculated at 15 ka for the mean time constant (T_m), and 0.6 and 0.4 for the nonlinearity parameter (b), are shown in Fig. 1a. The b = 0.6 curve, which is the value adopted for the global benthic oxygen isotope stack LR04 (Lisiecki and Raymo, 2005), is used in this study. The timing of the Holocene marine invasion of Osaka Bay is recorded in a core collected near the 1700-m northern Osaka Bay core (Masuda et al., 2000). The base of the marine layer dated at 11,000 years cal BP lies at −51 m in elevation, which is adjusted to −47 m on the assumption of a constant subsidence rate (Hyodo et al., 2006). The 11,000 years cal BP age is the time when post-glacial sea-level rise exceeded the sill for Osaka Bay and reached the northern area of the bay. This age is 1.7 ka after the mid-point (12.7 ka) between the adjacent ice volume maximum and minimum, which correspond to isotopic events 2.2 and 1, respectively. The same timing, a delay of 1.7 ka from the midpoint of adjacent ice volume maxima and minima, is applied to the beginnings of the marine layers of other interglacials. The depth versus age plots of astronomically-tuned marine layers show linear relations for many cores drilled in the Osaka Basin (Kariya et al., 2010) (Fig. 2a). A regression line for the 1700-m core provides a mean accumulation rate (a.r.) of 63.2 cm/ky (correlation coefficient R = 0.999).

One of our relative sea-level proxies, based on the percentage of marine and brackish diatoms shown by the solid line in Fig. 1b, reflects the degree of influence of freshwater, or distance from the Yodo River mouth, depending on changes in sea-level. Another sea-level proxy based on the percentage of benthic marine and brackish diatoms as shown by a dotted line in Fig. 1b reflects changes in water depth, or amount of light reaching the sea floor, depending upon changes in sea-level. This proxy is inversely correlated with

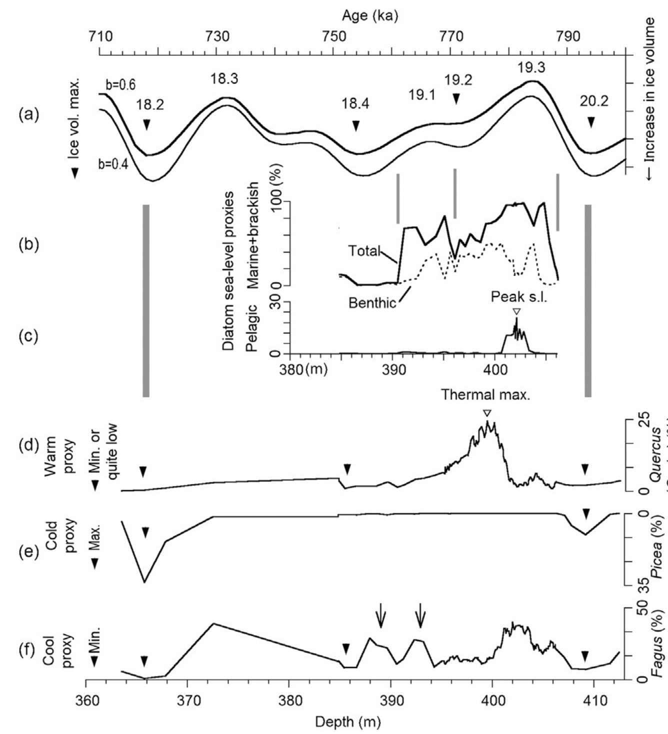

Fig. 1. Plots of sea-level and climate proxy data from the Osaka Bay 1700-m core. (a) Age plots of ice volume variations calculated with nonlinearity parameter b = 0.6 and 0.4 (see text for details). (b, c) Depth plots of proportions of (b) marine and brackish diatoms, (c) pelagic diatoms, (d) *Picea* pollen, (e) *Quercus* (*Cyclobalanopsis*), and (f) *Fagus*. Data for (b–f) are from Kitaba et al. (2013), except for new pollen data between 384.83 m and 363.49 m. Arrows at 389 m and 393 m in (f) show warming events.

sea-level depth. The two proxies show consistent variations except below a depth of 404.5 m, where the proportion of benthic diatoms remains nearly zero even during a low sea-level period (Fig. 1b). Marine bottom environments may have been unsuitable for benthic diatoms for some time just after the marine invasion. Sea-level rapidly rose in the earliest part of MIS 19, followed by a brief drop, and then continued rising. The highest sea-levels are from 403 m to 401 m. During the high sea-level interval, Osaka Bay expanded northeastward to the Kyoto Basin. The highest sea-level occurs at a depth of 402.1 m, where a maximum proportion of pelagic diatoms appears (Fig. 1c). Sea-level gradually decreased above 401 m, followed by a rise above 396.1 m. High sea-levels were maintained from 395 m to 391 m. The high sea-level intervals from 403 to 401 m and 395 to 391 m are correlated with highstands at MIS 19.3 and 19.1, respectively, and the sea-level drop at 396.1 m with the lowstand at MIS 19.2. The beginning of the marine layer is calibrated to 787.3 ka, an age delayed by 1.7 ky from the midpoint of neighboring ice volume maximum and minimum, and the end of the marine layer to 762.3 ka, an age preceded by 1.7 ky. The three calibration points including that for MIS 19.2 within the MIS 19 marine layer show a good linear relationship (Fig. 2b).

Astronomical calibrations can be made outside the marine interval using climate events. Fig. 1d, e and f show proportions of the boreal conifer *Picea*, a cold proxy, evergreen *Quercus* (*Cyclobalanopsis*), a warm proxy, and deciduous *Fagus*, a cool proxy, respectively. Data for the interval from 363.49 m to 384.83 m are new, combined with the pollen data of Kitaba et al. (2013), and using the same methods. The proportion of *Picea* shows cold maxima at depths of 409.1 m and 365.8 m, where both *Quercus* (*Cyclobalanopsis*) and *Fagus* show minimum or quite low values,