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Astronomical cycles of Middle Permian Maokou Formation in South China and their implications for sequence stratigraphy and paleoclimate

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A B S T R A C T

High-resolution (930 samples) magnetic susceptibility (MS) and anhysteretic remanent magnetization (ARM) analyses were conducted on the ~49 m thick Middle Permian Maokou Formation at Dukou, South China. Spectral analysis of covariant MS and ARM series reveal Milankovitch cycles with eccentricity, obliquity, and precession. A 5.7 myr floating 405 kyr eccentricity cycle-calibrated astronomical time scale was constructed and used as a geochronometer for estimating the durations of the conodont zones. The results indicate that the durations of the *Jinogondolella postserrata*, *J. altudaensis*, *J. prexuanhanensis*, and *J. xuanhanensis* conodont zones were 490 kyr, 560 kyr, 820 kyr, and 750 kyr, respectively. The 405 kyr-calibrated MS and ARM series also show prominent ~1 myr cyclicity, which may correspond to the secular frequencies of Earth and Mars, s_4–s_3, in the Middle Permian. The early Capitanian time interval was synchronous with the Kamura cooling event, and the accentuated obliquity cycling may signal ice-sheet expansion. The modulations of the obliquity have a close relationship with third-order eustatic sequences of the Wordian and Capitanian stages, suggesting a glacioeustatic origin during the Middle Permian.

1. Introduction

It is well known that the Earth's orbital eccentricity, obliquity, and precession strongly influence insolation, global climate, and sea-level changes (Zachos et al., 2001a,b; Strasser et al., 2006; Naish et al., 2009). Boulila et al. (2011) noted that astronomically driven sea-level changes control the third-, fourth-, fifth-, and sixth-order depositional sequences; they also suggested that the third-order eustatic sequences have been controlled by 1.2 myr and 2.4 myr modulations of the obliquity and eccentricity cycles in the Cenozoic icehouse and Mesozoic greenhouse eras, respectively. These modulations originate from the secular frequencies of Earth (g_3 and s_3) and Mars (g_4 and s_4), which have been in secular resonance 2.4 myr $= g_4 - g_3 = 2(s_4 - s_3) =$ 2(1.2 myr) for the past 50 million years (Laskar et al., 2004, 2011). However, chaotic behavior of the Solar System during the more remote Mesozoic is thought to have led to unstable ~1.2 and ~2.4 myr periodicities (Herbert, 1999; Olsen and Kent, 1999; Boulila et al., 2010; Huang et al., 2010; Ikeda et al., 2010; Hüsing et al., 2011; Ikeda and Tada, 2013; Wu et al., 2013a), which might have induced astronomically forced third-order eustatic sequences to vary accordingly (Boulila et al., 2014). Unfortunately, this uncertainty greatly hinders investigation of the relationship between long-period astronomical terms and third-order eustatic sequences in the Paleozoic Era (Fang et al., 2015).

The Earth's paleoclimate system drifted from extremes of cold with massive continental ice sheets to mild climates with sparse and sporadic alpine-style glaciations in eastern Australia from the Early to Middle Permian (Isbell et al., 2003; Fielding et al., 2008). Though not apparent in the oxygen isotope curve, faunal evidence indicates a cooling bipolarity during much of the Middle Permian (Henderson et al., 2012). Dramatic fluctuations in atmospheric CO_2 levels (Montañez et al., 2007), as well as the lowest sea level (Haq and Schutter, 2008) and $^{87}Sr/^{86}Sr$ ratio (McArthur et al., 2012; Kani et al., 2013) in the Phanerozoic indicate climatic and tectonic upheavals during the late Middle Permian. A cyclostratigraphic study of the Middle Permian will provide a compelling glimpse into the astronomical forcing of a mild world with oscillating ice sheets and third-order eustatic sequences during a major climate transition.

Middle Permian marine strata are well developed in South China. Here, we conducted cyclostratigraphic research on the magnetic susceptibility (MS) and anhysteretic remanent magnetization (ARM) series

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of a ~49 m Middle Permian Maokou Formation at the Dukou section, Sichuan Province, South China. The main scientific objectives of this study are as follows: 1) to identify astronomical forcing of climate change in the Middle Permian, South China; 2) to construct a floating astronomical time scale (ATS) and calibrate the durations of conodont zones in the upper Maokou Formation; and 3) to investigate long-period astronomical terms during the Middle Permian and their possible relationship with third-order eustatic sequences.

2. Geological setting

During the Guadalupian epoch of the Permian, the South China Block (SCB) was located in the equatorial region at the eastern margin of the Paleotethys (Fig. 1A; Scotese and Langford, 1995). Shallow marine fossiliferous carbonate developed extensively on the South China Block (Fig. 1B; Feng et al., 1996). Global regression (Haq and Schutter, 2008) and regional Dongwu uplift (Editing Committee of Stratigraphy (ECS), 2000) in the late Capitanian resulted in the disappearance of carbonate platforms; some carbonates in the southwestern part of the SCB are overlain by the rocks generated by the basaltic Emeishan large igneous province (LIP) (Chung et al., 1998). Most of the carbonate platform of the northern SCB was truncated by clastics, comprising the so-called Wangpo Bed, which may have been derived from erosion of the Emeishan LIP (He et al., 2010).

The Dukou section of Xuanhan County (31°41′46″ N, 108°18′02″ E), Sichuan Province, one of the best-exposed Middle Permian sections, is located at the northeastern margin of the South China Block (Fig. 1B). The strata in Dukou section are comprised of the Guadalupian Maokou Formation, and the Lopingian Wuchiaping and Changhsing formations in ascending order (Fig. 1C). The Middle Permian sequence was deposited in a slope zone between the upper Yangtze Block Platform and the North Yangtze Basin (Fig. 1B). We focused on the continuously exposed upper part of the Maokou Formation with well developed conodont biostratigraphic constraints. In the studied interval, five conodont biozones: *Jinogondolella aserrata*, *J. postserrata*, *J. altudaensis*, *J. prexuanhanensis*, and *J. xuanhanensis* zones were identified from bottom to top (Mei et al., 1994). The upper Maokou Formation is visually cyclic (Fig. 1D) and mainly contains thinly bedded limestones with chert beds and siliceous nodules (Fig. 2).

3. Methods

3.1. Paleoclimate proxies

MS is a concentration indicator of magnetizable materials in rock samples (Ellwood et al., 2000). Its variations can reflect climatically or eustatically controlled weathering inputs via changes in the detrital component of sediments, and is widely applied in cyclostratigraphy (Ellwood et al., 2013; Wu et al., 2013a,b,c; Boulila et al., 2014; Fang et al., 2016). However, the response of MS values to eustatic changes varies among different depositional environments (Da Silva et al., 2009), and the origins of MS variations can be rather complicated (Ellwood et al., 2000). ARM is a measurement of the concentration of fine-grained (<20 μm) low-coercivity ferromagnetic minerals (Latta

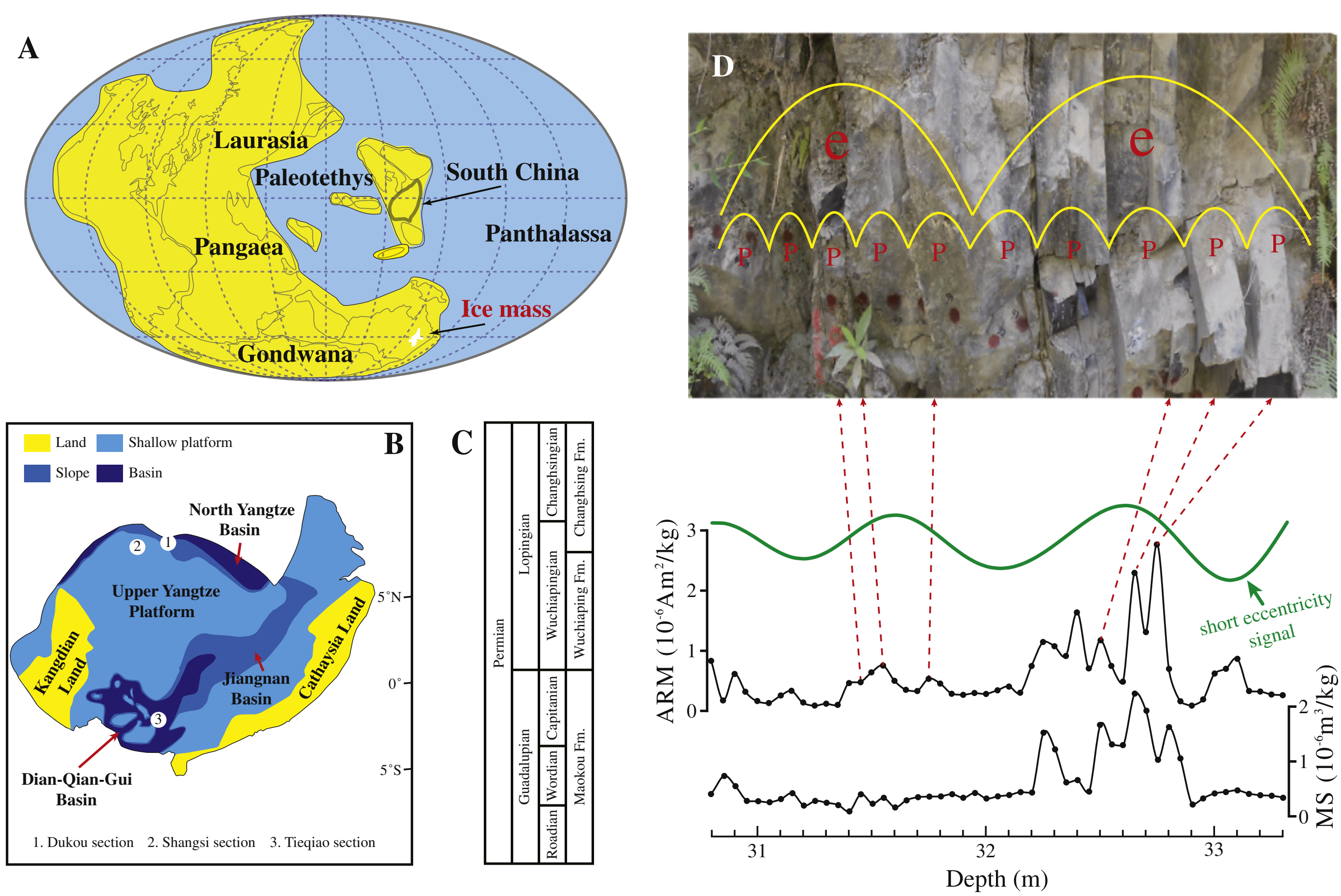

Fig. 1. (A) Guadalupian global paleogeography. The geographic base map is modified after Angiolini et al. (2013). The location, size, and shape of the ice sheets are from Isbell et al. (2012). (B) Guadalupian–Lopingian paleogeographic configurations of South China (Wang and Jin, 2000). (C) Chronostratigraphic division of the Dukou section based on Mei et al. (1994) and Shen et al. (2013). (D) Relationship between lithological cycles and magnetic susceptibility (MS) and anhysteretic remanent magnetization (ARM) series from the Maokou Formation at Dukou. The green line is the interpreted short eccentricity extracted by Gaussian band-pass filters with a frequency of 1.172 ± 0.4 cycles/m from the ARM series.