Cyclostratigraphic Calibration of the Upper Ordovician (Sandbian–Katian) Pagoda and Linhsiang Formations in the Yichang Area, South China

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1 Introduction

The Sandbian–Katian is a critical period for the transition from "hot-house" in the Lower Ordovician to "ice-house" in the end-Ordovician (Trotter et al., 2008). During this interval, the South China Block was located in the equatorial region (Torsvik and Cocks, 2016), with the widespread accumulation of Pagoda and Linhsiang formations (Zhan and Jin, 2007). Although these strata have been investigated for decades and their biostratigraphic correlation is almost established (e.g., Chen et al., 2011), their duration is ambiguous due to the lack of radioisotopic ages. Cyclostratigraphy provides an opportunity to solve this problem via the identification of Milankovitch cycles (eccentricity, obliquity, and precession) which could be used as geological "metronome". Astronomical forcing in the sedimentary record is a well-established phenomenon for the Phanerozoic (Hinnov, 2013) and has been proposed to affect the Ordovician climate (e.g., Fang et al., 2016, 2019; Zhong et al., 2018). In this paper, we conduct a detailed cyclostratigraphic analysis on the Pagoda and Linhsiang segments of the Yihuang-1 (YH-1) core. The main objectives are to detect the astronomical cycles and use them to constrain the timing of the Pagoda and Linhsiang formations.

2 Material and Method

The YH-1 core (Fig. 1A, 30°52′50.05″N, 111°24′0.94″E) was drilled at Huanghuachang, Yichang City, Hubei Province in 2014. The total thickness is 78 m with a recovery rate of 99.64%, covering the Miaopo, Pagoda, Linhsiang, Wufeng, and Lungmachi formations of the uppermost Middle Ordovician through to Lower Silurian in ascending order. The Pagoda and Linhsiang formations together are 28.19 m thick (45.81–74 m), characterized by light grey limestone interbedded with purplish red limestone (Fig.1B). Three proxy series were used in the time-series analysis of cyclostratigraphy (Fig. 1B), including magnetic susceptibility (MS), natural gamma-ray intensity (GR), and stable oxygen isotope (δ^{18}O). The MS data were measured on the core using an SM-30 magnetic susceptibility instrument at~0.01 m intervals. GR log data were measured in the borehole immediately after drilling with a sampling rate of 0.09 m. A dentist's drill was used in order to get the powders for the δ^{18}O measurements with ~0.1 m intervals in the State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences. A total of 2862, 310, and 285 samples were acquired for in the MS, GR, and δ^{18}O measurements, respectively.

The time-series analysis was conducted in three steps.

1) The MS, GR, and δ^{18}O series were resampled at 0.01 m, 0.09 m and 0.1 m, respectively, and then detrended by removing a 8-m "rLOESS" trend in the software ACycle v 0.2.6 (https://github.com/mingsongli/acycle).

2) To detect significant stratigraphic frequencies, MTM spectral analysis was performed on the detrended series with classical red noise modeling reported at the 85%, 90%, 95%, and 99% confidence levels through Matlab scripts (http://mason.gmu.edu/~lhinnov/cyclostratigraphytools.html). Evolutive harmonics analysis (EHA) was performed to identify the frequency shifts of the same component due to variable sedimentation accumulation rates (SARs) throughout the succession. Since temporal constraints are unavailable, correlation coefficient (COCO) and evolutionary correlation coefficient (eCOCO) (Li et al., 2018) procedures in ACycle v 0.2.6 were applied to evaluate the correlation coefficient between the power spectra of astronomical targets and paleoclimate proxy series across a range of plausible SARs; the target frequencies used here are 1/405 (E1), 1/135 (E2), 1/95 (E3), 1/33.3 (O1), 1/20.3 (P1), and 1/17.15 (P2) cycles/kyr for the Late Ordovician (450 Ma) based on Waltham (2015).

3) Gauss bandpass filtering was carried out to extract the interpreted long eccentricity sedimentary cycles using the *bandpass* routine of the Astrochron package (Meyers, 2014) in R. Subsequent 405-kyr calibration was executed in Matlabusing *depthtotime.m* (Kodama and Hinnov, 2015).

3 Results

The EHA and eCOCO results for the MS series (Fig. 2)

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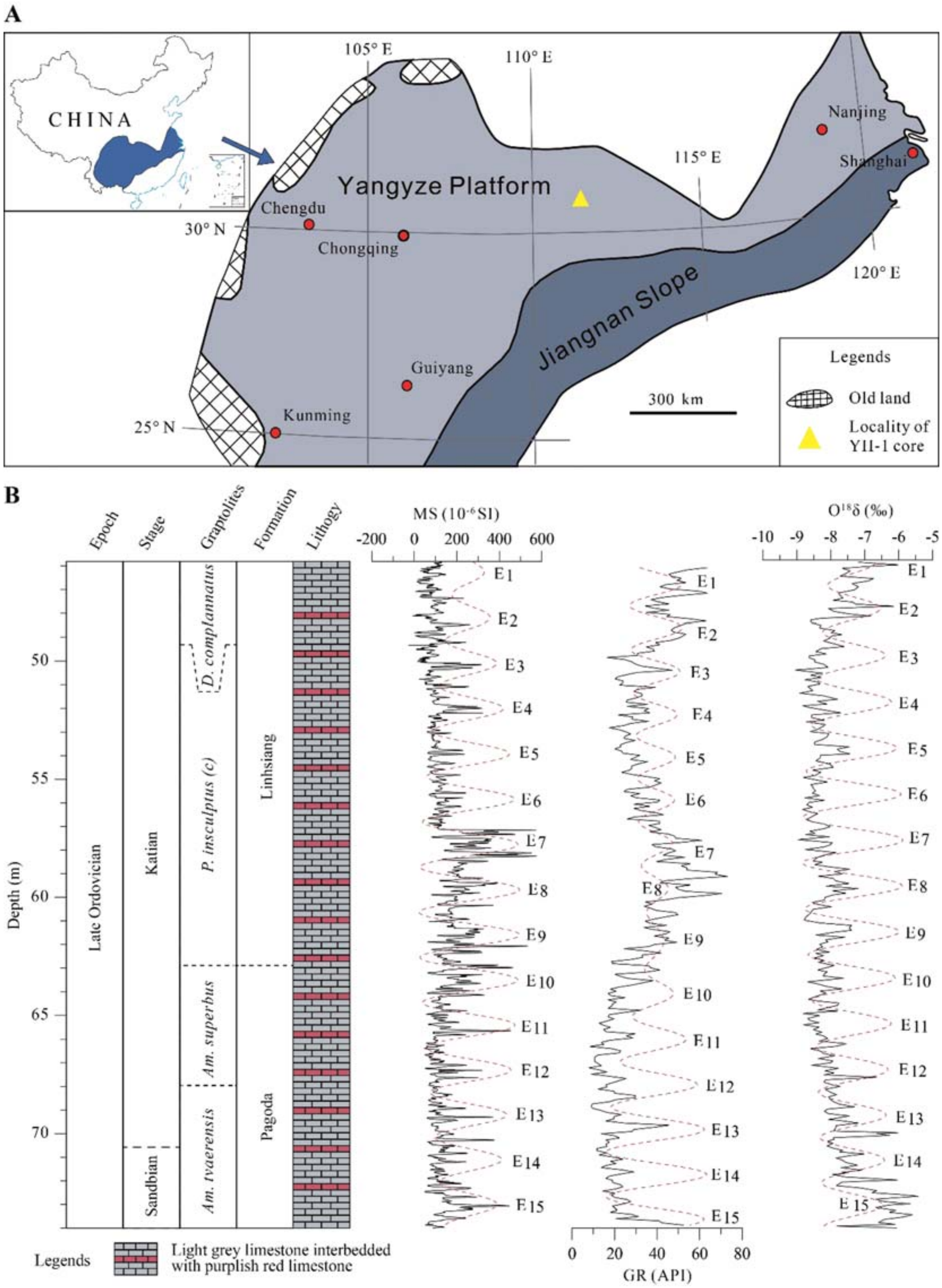

Fig. 1. Location map and the data for the present study.
A**.** Paleogeography of South China during the deposition of Pagoda Formation (revised from Zhan et al., 2016).**B.** The chrono-, litho-, bio- and cyclostratigraphy of the Pagoda and Linhsiang formations. The dashed red lines represent the interpreted 405-kyr eccentricity cycles.

indicate that the Pagoda and Linhsiang formations were deposited in a nearly constant SAR. The optimal SAR is 4.9 cm/kyr according to the outcome of COCO, with a H_0-SL of 0.05% and correlation coefficient of 0.3865 (Fig. 3). That is to say, the MS series is influenced by astronomical forcing with a 99.95% probability. Given the SAR of 4.9 cm/kyr, the significant wavelengths in the MTM spectra of the MS, GR, and O18δseries in the depth domain are converted into the time domain (Fig. 3), which conform well with the predicted astronomical target periodicities of Waltham (2015). The sedimentary cycles of ~2 m, 0.62–0.47 m, 0.22–0.16 m, 0.12–0.08 m are interpreted as the 405-ky long eccentricity (E), ~100-kyr short eccentricity (e), obliquity (O), and precession (P) cycles, respectively (Fig. 3).

Based on the interpreted E cycles, we carried out Gauss

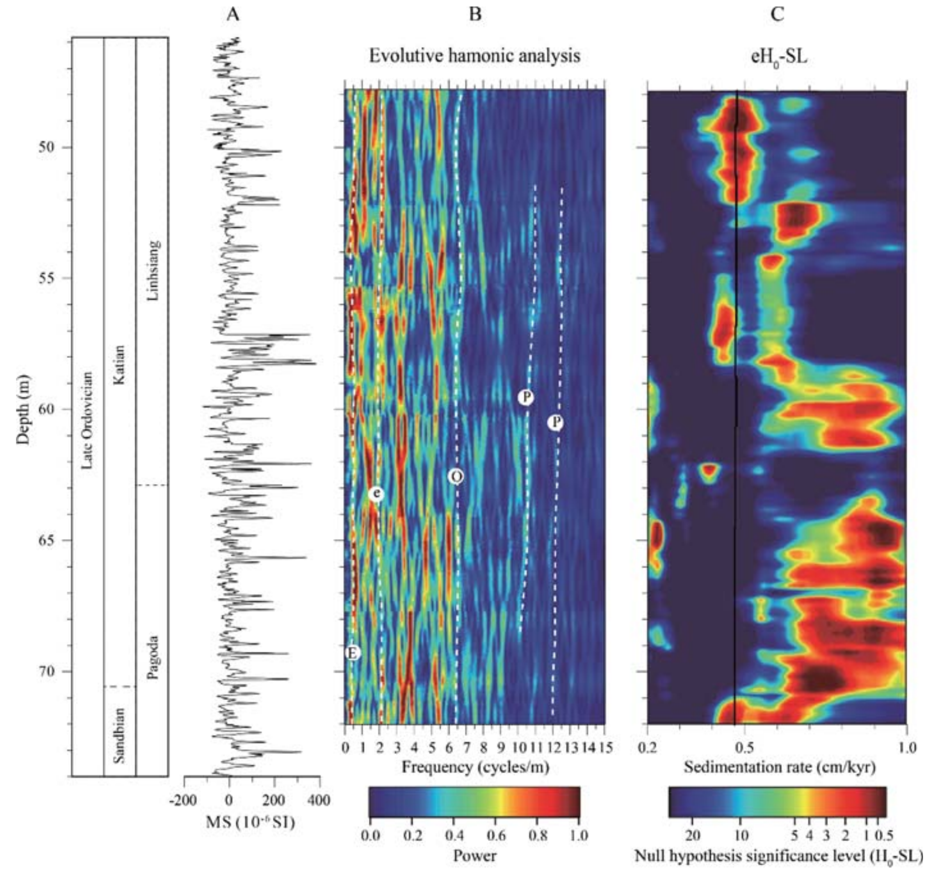

Fig. 2. Evolutive hamonic analysis (EHA) and Evolutionary correlation coefficient (eCOCO) analysis of the ARM series.
A. MS series after removing a 8-m 'rLOESS' long-term trend. B. EHA, the white dashed lines labeled E, e, O, and P represent the long-eccentricity, short-eccentricity, obliquity, and precession cycles, respectively. C. eCOCO with 405-kyr calibration derived SAR curve (black line). Both EHA and eCOCO were calculated with a 4-m sliding window.

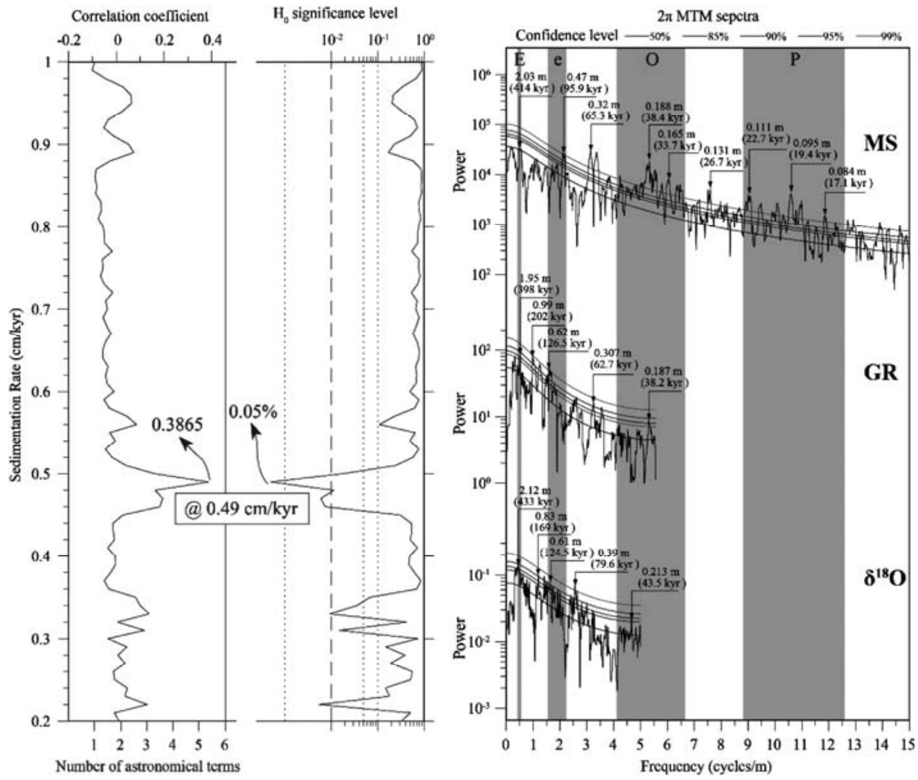

Fig. 3. The correlation coefficient (COCO) results of the MS series, and 2πMTM spectra of the the MS, GR, and $\delta^{18}O$ series.

bandpass filtering on the MS, GR, and $\delta^{18}O$ series using the same passbands of 0.525±0.075 cycles/m. All of the filter outs show 14.76 E cycles, although the GR series exhibits a slight phase lag behind the MS and $\delta^{18}O$ series. In the following 405-kyr calibration, each minimum of the extracted E cycles of the MS series was assigned a grid of ages with 405 kyr intervals (e.g., 0 kyr, 405 kyr, 810 kyr …) in order to construct a depth-time age model, through which the MS, GR, and $\delta^{18}O$ series in the spatial domain were all converted into the temporal domain and a "floating" astronomical time scale (ATS) was established. The ATS gives an estimated duration of 5976 kyr for the whole Pagoda and Linhsiang formations.

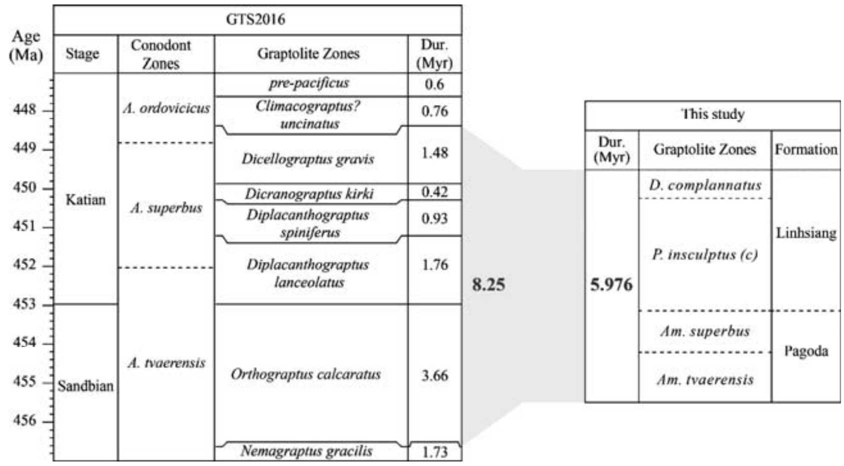

Fig. 4. The astronomically calibrated durations of Pagoda and Linhsiang formations and their comparison with the GTS2016.

According to the standard classification of the Upper Ordovician formations in the Yichang area (Chen et al., 2011), the Pagoda and Linhsiang formations are equivalent with the interval of *Orthograptus calcaratus* Zone to *Dicellograptus gravis* Zone (Fig. 4), which has a total duration of 8.25 Myr in the Geological Time Scale (GTS) 2016 (Ogg et al., 2016). However, our ATS with high statistical significance gives a shorter duration of 5976 kyr for the same interval, indicating that the durations of these graptolite zones should be shorter. In contrast, the upper Katian graptolite zones corresponding to the Wufeng Formation which overlylie the Linhsiang Formation have longer durations.

Key words: cyclostratigraphy, time-series analysis, astronomical time scale, duration

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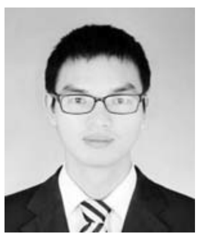

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