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Tracking variable sedimentation rates and astronomical forcing in Phanerozoic paleoclimate proxy series with evolutionary correlation coefficients and hypothesis testing

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ABSTRACT

This paper addresses two fundamental issues in cyclostratigraphy and paleoclimatology: identification of astronomical forcing in sequences of stratigraphic cycles, and accurate evaluation of variable sedimentation rates. The technique presented here considers these issues part of an inverse problem and estimates the product-moment correlation coefficient between the power spectra of astronomical solutions and paleoclimate proxy series across a range of test sedimentation rates. The number of contributing astronomical parameters in the estimate is also considered. Our estimation procedure tests the hypothesis that astronomical forcing had a significant impact on proxy records. The null hypothesis of no astronomical forcing is evaluated using a Monte Carlo simulation approach. The test is applied using a sliding stratigraphic window to track variable sedimentation rates along the paleoclimate proxy series, in a procedure termed "eCOCO" (evolutionary correlation coefficient) analysis. Representative models with constant and variable sedimentation rates, and pure noise and mixed signal and noise series are evaluated to demonstrate the robustness of the approach. The method is then applied to Cenozoic, Mesozoic and Paleozoic paleoclimate series. The Cenozoic case study focuses on a high-resolution Paleocene–Eocene iron concentration series from ODP Site 1262 (Leg 208) covering the Paleocene–Eocene Thermal Maximum and Eocene Thermal Maximum 2 events. The eCOCO time-calibrated iron series confirms previous findings of a role for long-term astronomical forcing of these Eocene events. The Mesozoic case study applies eCOCO to the classic Late Triassic Newark depth rank series of eastern North America. The estimated high-resolution sedimentation rate map in this case demonstrates a causal link between variations in depositional environment and sedimentation rate. Finally, the Paleozoic case study supports the cyclostratigraphic interpretation of a Devonian magnetic susceptibility series at La Thure, Belgium and provides new insights into changes of the depositional setting at this location. Taken together, eCOCO is a powerful tool for simultaneously evaluating sedimentation rates and astronomical forcing for paleoclimate series throughout the Phanerozoic.

1. Introduction

Construction of the geological time scale includes multiple sources and methods, radioisotopic dating, biostratigraphy, magnetostratigraphy, chemostratigraphy, cyclostratigraphy, and mathematical modeling. Among these techniques, the cyclostratigraphic analysis of Milankovitch cycles is the only method that can provide continuous, high-resolution age models (Gradstein et al., 2012). Numerous sedimentary records are evidently impacted by Milankovitch forcing at timescales of tens to hundreds of thousands of years (Hinnov, 2013). The leading present-day astronomical parameters include long orbital eccentricity (405 kyr), short orbital eccentricity (128 kyr and 95 kyr), obliquity (41 kyr), and precession (23 kyr and 19 kyr) cycles (Berger et al., 1992; Laskar et al., 2004, 2011). These parameters affect the timing and geographic distribution of insolation thus acting as a long-term paleoclimatic forcing. Geologists read these cycles using paleoclimate proxy records and link the recognized sedimentary oscillations to the astronomical cycles (Hinnov and Hilgen, 2012). However, this involves multiple ongoing scientific challenges: the uncertain nature of linkages between astronomical forcing and paleoclimate proxies (Hinnov, 2013; Weedon, 2003), potentially low signal to noise ratios in paleoclimate proxy series (Kemp, 2016; Meyers, 2012; Mann and Lees, 1996), confirmation of an astronomical origin in

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successions of stratigraphic oscillations (Malinverno et al., 2010; Meyers, 2015; Meyers and Sageman, 2007), distortion of the astronomical signal due to variable sedimentation rates (Sinnaesel et al., 2016; Lin et al., 2014; Weedon, 2003; Yu and Ding, 1998), and integration of cyclostratigraphy with other dating tools (Kuiper et al., 2008; Westerhold et al., 2012), among others.

Here we jointly test the astronomical origin of stratigraphic cycles as measured by paleoclimate proxy data, and estimate the evolution of sedimentation rates along a stratigraphic succession. Our approach employs the correlation coefficient between the power spectra of a proxy series and that of an associated astronomical forcing series, converting the proxy series to time for a range of "test" sedimentation rates. The number of astronomical parameters contributing to the estimated sedimentation rates is taken into account. The null hypothesis of no astronomical forcing is tested using a Monte Carlo simulation approach. A sliding window is applied to the proxy series in order to track changes in sedimentation rate along the stratigraphic succession; thus, we call this the "eCOCO" (evolutionary correlation coefficient) method. The eCOCO method is inspired by the average spectral misfit (ASM) method of Meyers and Sageman (2007), the Bayesian Monte Carlo method of Malinverno et al. (2010) and the TimeOpt method of Meyers (2015); similarities and differences among these methods are discussed below.

The eCOCO method is demonstrated using three synthetic series, and three Phanerozoic paleoclimate proxy series. The transition of the late Paleocene through the early Eocene is characterized by a sequence of significant climate events, including the Paleocene–Eocene Thermal Maximum (PETM) and the Eocene Thermal Maximum 2 (ETM2) events. Cyclostratigraphy of ODP Site 1262 (Leg 208) at Walvis Ridge, South Atlantic Ocean has led to the hypothesis of astronomically forced pacing of the PETM and ETM2 events (Lourens et al., 2005), although this hypothesis has been shown to be complicated in follow-on cyclostratigraphic studies by others (Meyers, 2015; Westerhold et al., 2007, 2008). Differing sedimentation rates for the late Paleocene–early Eocene interval have been proposed (Westerhold et al., 2007, 2008) and only an average sedimentation rate for the PETM-ETM2 interval at Site 1262 has been independently tested (Meyers, 2015). An astronomically tuned time scale of the depth-rank series of continental deposits in the Newark Basin, eastern North America, provides the fundamental basis for the age model of the current Late Triassic time scale (Gradstein et al., 2012; Kent et al., 2017). The late Norian–Rhaetian part of the Newark time scale has been recently supported by the global correlation between cycle calibrated magnetic polarity patterns from the Late Triassic Xujiahe Formation and those from the Newark Supergroup (Li et al., 2017). Cyclostratigraphic study of the Givetian–Frasnian magnetic susceptibility series from the La Thure section of Belgium provides a high-resolution astronomical time scale for the Givetian of the Middle Devonian (De Vleeschouwer et al., 2015). The interpretation of astronomical cycles has been further corroborated by Martinez et al. (2016).

In all three of these Phanerozoic cases, eCOCO-derived high-resolution sedimentation rate results provide new insight into the associated paleoclimatic and paleoenvironmental changes. The eCOCO analysis of our three case studies confirms published sedimentation rates at a high degree of confidence (exceeding 99% significance, i.e., rejection of the null hypothesis at levels of $p < 0.01$). Application of eCOCO in cyclostratigraphy thus has the potential more generally to enhance the reproducibility of astrochronological timescales and contribute to establishing more robust geological age models throughout Earth history.

2. Evolutionary correlation coefficient (eCOCO)

2.1. Correlation coefficient

The correlation coefficient used here is the Pearson product-moment correlation coefficient (Mudelsee, 2014), calculated in MATLAB™ (https://www.mathworks.com/help/matlab/ref/corrcoef.html) as

$$\rho(T, D) = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{\overline{T_i - \mu_T}}{\sigma_T}\right)\left(\frac{\overline{D_i - \mu_D}}{\sigma_D}\right) \quad (1)$$

where N is a number of observations of the target (T) or data (D) time series, μ_T and σ_T are the mean and standard deviation of the target, and μ_D and σ_D are the mean and standard deviation of the data series. The correlation coefficient measures the linear correlation between the target (T) and data (D) series, where the target series is the power spectrum of the astronomical solution, and the data series is the power spectrum of proxy time series at a given sedimentation rate. The periodogram is a useful metric of agreement because the associated spectral estimates have a narrow resolution bandwidth compared to common procedures such periodogram smoothing or Multi-Taper Method (MTM) spectral estimation (Thomson, 1982). The periodograms of both astronomical target series and data time series are calculated using MATLAB function *periodogram.m* with a zero padded length of 10,000. The red noise background of the data series is modeled using an AR(1) autoregressive fit to the series using MATLAB function *RedConf.m* by Husson (2014) and is employed so as to only retain spectral features that exceed the estimated red noise background; if the spectral amplitude is less than the estimated mean red noise background at a given frequency f, it is set to 0. The range of $\rho$is between -1 and $+1$, where 1 is a perfect positive correlation, 0 is no correlation, and -1 is a perfect negative correlation.

The highest frequency Milankovitch cycle during the past 249 Ma corresponds to the precession index term at 1/(17 kyr) (Laskar et al., 2004), thus we estimate the correlation coefficient of the periodograms of the target and data series over the frequency range 0 to 0.06 cycles/kyr for Cenozoic and Mesozoic series. The highest frequency of the precession index is 1/(16.4 kyr) at 440 Ma according to Berger and Loutre (1994), and so for the Devonian case study (∼384 Ma) we estimate the correlation coefficient over the frequency range 0 to 0.07 cycles/kyr.

For paleoclimate series younger than 249 Ma, both data and target series are obtained using periodograms of paleoclimate series and Laskar astronomical solutions, respectively. For paleoclimate series older than 249 Ma, a target series is constructed as the sum of harmonic functions whose frequencies are given by Berger and Loutre (1994) using an original MATLAB script *period2spectrum.m*.

2.2. Significance level

In this step, we adopt as a null hypothesis (H_0) the existence of no astronomical frequencies in the data series and all spectral peaks higher than an AR(1) background occur by chance. Since the periodogram is not Gaussian-distributed (it is Chi-Squared), standard parameteric distributions for the correlation coefficient ρ are not valid. We instead use a non-parametric Monte Carlo approach to produce a null distribution and to test the null hypothesis of no significant astronomical frequencies, as follows:

(1) The number of peaks of the periodogram higher than an AR(1) background for the paleoclimate data series is counted as n, and the sampling frequency (df) of data is

$$df = 1/(N * dt) \quad (2)$$