Online Supplementary Material for:

Gulf of Nuna: Astrochronologic correlation of a Mesoproterozoic oceanic euxinic event

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This file contains:

Supplementary methods

Supplementary figures (Figs. DR1-DR4)

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Data

The Velkerri Formation is composed of siliciclastic facies deposited in lower shoreface to offshore environments. This includes coarser-grained gravity flow deposits, finer-grained turbidite deposits, and highly organic-rich shales that records euxinic marine conditions. The Velkerri Formation is subdivided into three lithologic members, the Lower, Middle, and Upper Velkerri members. Grain-size variations are overwhelmingly dominantly siltstone and organic-rich siltstone, with occasional fine-to-medium grained sand in the Lower and Upper Velkerri members (Cox et al., 2016; Jackson and Raiswell, 1991; Munson, 2016; Warren et al., 1998). The high-resolution study focused on the upper portion of the Lower Velkerri Member that is exclusively mudstone with varying amounts of silt and organic matter. Close inspection of the portion of the TarlseeS3 core studied here depicts thinly laminated mudstone due to variable silt and organic matter content and subtle grain-size variations (Fig. 1C; Fig. DR1).

We conducted a cyclostratigraphic study of the Velkerri Formation as an independent test of its chronology, identifying potential astronomical cycles that should be internally consistent. Compared to geochemical and more sophisticated rock magnetic proxies, magnetic susceptibility is expedient and inexpensive to measure, commonly conducted in ODP/DSDP drilling and hydrocarbon exploration, and generally most effective. Magnetic susceptibility is one of the more successful proxies used in astrochronology (Bao et al., 2018; Mead and Tauxe, 1986; Park et al., 1993; Shackleton et al., 1999; Zhang et al., 2015). In the ca. 1.4 Ga Xiamaling Formation of North China, a Mesoproterozoic example of orbital forcing that has recently been demonstrated, magnetic susceptibility is the proxy (of 7 employed) to yield the most periodicities (Zhang et al., 2015).

Despite the empirical success of magnetic susceptibility as an astronomical chronometer, the mechanisms through which insolation changes are rectified as fluctuations in susceptibility are diverse. Although variability in susceptibility is likely in all cases due to that of magnetite content, the provenance of the magnetite is typically unknown. Several sources of magnetite have been documented and they vary in relative importance from basin to basin: (i) detrital magnetite varying due to changes in terrestrial influx and weathering patterns (Sinnesael et al., 2016), (ii) biogenic magnetite (e.g., magnetotactic bacteria) influenced by climate/environmental change (Kopp et al., 2007), (iii) authigenic magnetite (Lovley, 1990), and finally (iv) modulation of preserved magnetite due to variable dissolution

and/or pyritization of magnetite in anoxic sediments where sulfide content may vary with environmental conditions (Canfield and Berner, 1987; Karlin et al., 1987). In the Velkerri Formation, it is conceivable that all such sources of magnetic susceptibility variation apply. Our detailed magnetic mineralogy studies (Fig. DR4), paired with sedimentological observations (Fig. 1C; Fig. DR1), allow us to discern between these candidate sources of variation in magnetic susceptibility, which is most likely variable proportions of detrital magnetite plus/minus iron sulphides (see main text for details).

If measured carefully on flush, flat surfaces, magnetic susceptibility handheld meters (Terraplug KT-10) can be as satisfactory as laboratory measurements, and can allow for rapid and thus increased data collection. Core samples measured here provided ideal flat surfaces for accurate susceptibility measurements. A portion of the Velkerri Formation was measured on the TarleeS3 core at the core library in Darwin, Northern Territory, Australia (Figs. 1 and 2). Sample spacing was a compromise between regular spacing important for time series analysis and flat surfaces important for accurate measurements of the magnetic susceptibility meter. Precise stratigraphic heights of sampled levels were noted by correlating measured core intervals with high resolution images taken of the core. On average, sample spacing was ~5 cm, a more than sufficient sampling rate to resolve the ~60 cm precession band (Fig. 2). The data were detrended with a degree-2 polynomial in preparation for time series analysis (Fig. DR1).

Time series analysis

We conducted time series analysis on the magnetic susceptibility record using the Fast-Fourier transform (FFT; (Muller and MacDonald, 2000)) in order to test for the presence of any significant cycles. Spectral analyses were conducted in the stratigraphic domain, which yielded a set of spectral peaks representing cycles per stratigraphic meter. For the FFT, the spectral power used is the complex conjugate of the Fourier coefficients, normalized to unit mean power (Muller and MacDonald, 2000). We evaluated the significance of the FFT spectral peaks using a Monte Carlo routine to simulate noise (Muller and MacDonald, 2000). FFTs were performed on each of these 1000 randomly generated time series; a 95% confidence level was approximated for each frequency by calculating three times the mean power (Muller and MacDonald, 2000). We interpret spectral peaks rising above this 95% confidence level as statistically significant. Based on the FFT results, we ran bandpass filters with Gaussian windows to encapsulate the significant peaks identified. Bandpass filters detect both: (i) the bandwidth range of the significant signal and (ii) whether the signal is pure or whether it has a long-wavelength amplitude modulation. Although the goal is to make a bandpass as narrow as possible, one must be careful not to define the bandwidth so narrow so as to hide any significant (i.e., systematic and periodic) amplitude modulation. Details for how Milankovitch cycles were matched with identified cycles are discussed in the main text. Essentially identical statistically significant bandwidths were attained with multi-taper method (MTM) (Fig. DR5) spectral analysis as with FFT (Fig. 2).

Paleogeography

Euler rotation parameters of Figure 3A are as follows. All continents were first rotated to Laurentia into a fit of supercontinent Nuna, largely according to Evans and Mitchell (2011) with the following modifications: Congo/Sao Francisco was placed according to option B of Salminen et al. (2016); North China was rotated most closely to the position provided by Ding et al. (2020) and then adjusted slightly within paleomagnetic uncertainty to fit geologic correlations (Wang et al., 2019; Zhang et al., 2017). Nuna was then reconstructed in the paleomagnetic reference frame at 1.4 Ga.

Rock magnetic experiments

To obtain information on the magnetic carriers present in the material causing the magnetic susceptibility signal, we measured the susceptibility versus increasing temperature for representative samples from within, close and outside of the TOC peak events. An AGICO MFK-1 Kappabridge with attach CS-3 furnace was used at the University of Tübingen. Measurements were performed in air from room temperature up to 700°C.

Figure DR1. Photos of TarleeS3 core studied.

Figure DR2. Magnetic susceptibility of the TarleeS3 core. (Top) Raw data (Table DR1) with degree-2 polynomial trend (red). (Bottom) Detrended data prepared for time series analysis (Table DR2).

Figure DR3. Projected periods for precession (19 and 21 ka) and obliquity (41 and 54 ka) through geologic time, as a function of decreasing spin rate and increasing Earth-Moon distance, respectively (Berger and Loutre, 1994). Target astronomical values this used for our study ca. 1.4 Ga (Fig. 2) were interpolated along the slope between the triangles.

Figure DR4. Thermal susceptibility experiments of the Velkerri Formation from the Altree2 core. (A) Total organic carbon from the Altree2 core (as in [Figure 3](#)) indicating locations of samples. (B) Thermal susceptibility results. Red, heating; blue, cooling. See text for interpretation.

Figure DR5. Multi-taper method (MTM) spectral analysis. From left to right, the statistically significant bandwidths identified are (i) by frequency, 0.14241536, 0.48828125, 0.75276693, and 1.62760417 and (ii) by wavelength, 7.02 meters (short eccentricity), 2.05 m (?), 1.33 m (obliquity), and 0.619 m (precession). These bandwidths are thus essentially the same to those identified with the FFT method in [Figure 2](#).

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