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Evidence for a 27-Ma cycle in ocean hypoxia over the last 260 Ma

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Abstract

We find that spectral analyses of the ages of the ten recorded major ocean anoxic events of the past 260 Ma reveal a strong spectral peak at 26.9 My significant at the ~95% confidence level. This cycle matches the periodicities of ~26 to 36 My detected in fluctuations in tectonics, sea levels and climate, in flood-basalt eruptions, and in biotic extinctions. The ages of eight of these anoxic events are correlated with concurrent episodes of extinctions of marine organisms. All ten anoxic intervals are closely associated with the ages of flood-basalt eruptions, suggesting causal connections through volcanic release of greenhouse gases resulting in severe hyperthermal intervals and hypoxia in the oceans.

Introduction

Episodes of widespread hypoxia in the oceans have occurred from time to time during the last 260 My. These anoxic and euxinic intervals have been associated with hyperthermal climate events, and are suggested as a link between greenhouse gas emissions from flood-basalt volcanism and resulting marine-extinction episodes (e.g., Wignall et al., 2005; Wignall, 2015; Palfy and Smith, 2000; Palfy et al., 2001; Hotinski et al., 2001; Cao et al., 2009; Mehay et al., 2009; Bonis et al., 2010; Jenkyns, 2010; Ruhl, et al., 2011; Song et al., 2013; Sell et al., 2014; Tedeschi et al., 2017; B. Zhang et al., 2018; F. Zhang et al. 2018; Benton, 2018; Penn et al., 2018).

Large volumes of greenhouse gases (CO_2 and CH_4) derived from the flood-basalt eruptions and from intrusive magmatic (large sills and dikes) interactions with carbon-rich country rocks (creating thermogenic methane) have apparently led to episodes of extremely warm global temperatures (Retallack, 1999; McElwain et al., 2005; Svensen et al., 2007; Schaller et al., 2011; Sun et al., 2012; Brand et al., 2012; Ernst and Youbi, 2017; Davies et al., 2017; Benton, 2018), and to warm, sluggish, stratified and poorly oxygenated oceans, culminating in widespread ocean hypoxia (Wignall, et al., 2005; Kiehl and Shields, 2005; Wignall, 2015; Ruhl and Kurschner, 2011; Caruthers et al., 2014; Clarkson et al., 2015; Baroni et al., 2018; Penn et al., 2018).

The warming would have also accelerated continental weathering (Retallack, 1999; Sheldon, 2005; von Strandmann, et al., 2013; Sun et al., 2018; F. Zhang et al., 2018), and increased the supply of phosphates, nitrates and other nutrients to oceanic surface waters via river runoff. This could have triggered unusually high export productivity, leading to greater oxygen demand in the deep ocean, and the spread of anoxic and even euxinic ocean conditions, leading to mass extinctions of marine life (Weissert et al., 1998; Bellanca et al., 2002; Handoh and Lenton, 2003; Scopelliti et al., 2004; Erba, 2004; Mort et al., 2007; Meyer et al., 2008; Cao et al., 2009; Owens et al., 2013; Ohkouchi et al., 20015; Coccioni et al., 2016; Them et al., 2018).

As marine-extinction events have been found to show evidence of an underlying 26 to 30 My periodicity (e.g., Raup and Sepkoskii,1986; Rampino and Caldeira, 2015), and flood-basalt eruptions might follow a similar underlying cycle (Rampino and Stothers, 1988), we decided to test for periodicity in the record of anoxic intervals.

Ocean anoxic events

We compiled the record of major ocean anoxic events of the last 260 Ma from the literature (e.g., Jenkyns, 2010, 2018; Leckie et al., 2002; Handoh and Lenton, 2003; Sageman, 2009; Wignall, 2015; F. Zhang et al., 2018), re-dated to the latest timescale (Ogg et al., 2016) (Table 1). Ten well-defined episodes of widespread ocean anoxia are recorded (an average of one every 29 My) -- at 56 Ma (the Paleocene-Eocene Thermal Maximum); 66 Ma (the Cretaceous-Paleogene boundary); 93.9 Ma (OAE 2 – end-Cenomanian, the Bonarelli Event); ~122 Ma (OAE 1a – early Aptian, the Selli Event); 134.7 Ma (Valanginian, the Weissert Anoxic Event); 145 Ma (the end-

Jurassic anoxic event); 183.7 Ma (the Toarcian Anoxic Event); 201.4 Ma (the end-Triassic anoxic event); 251.9 Ma (the end-Permian “super-anoxic” event); and 259.8 Ma (the end-Guadalupian anoxic event) (Table 1). Eight of these ten anoxic events are correlated with concurrent episodes of extinctions of marine organisms (Table 1).

Major anoxic events may have lasted for more than a million years (Isozaki,.1997). The duration of OAE 2 (the Bonarelli Event) is estimated from several localities at up to 820 ka (Scopeletti et al., 2006; Li et al., 2017), and the duration of OAE 1a (the Selli Event) is roughly estimated at between 1 and 1.3 My (Li et al., 2008).

Several other brief (≤1 My) hypoxic intervals, associated with hyperthermal events, but not with significant extinction pulses, occurred during the mid-Cretaceous (from the Albian to the Coniacian Stges) at ~113 Ma (OAE 1b; Level 113, Jacob Event, Monte Nerone Event); ~102 Ma (OAE 1c), ~100 Ma (OAE 1d, Piale Level); ~97 Ma (MCE, the mid-Cenomanian Event); and ~87 Ma (OAE 3) (Handoh and Lenton, 2003; Ingram et al., 1994; Coccioni and Galeotti, 2003; Mitchell et al., 2008) (Table 1). The earlier Faraoni Event in the latest Hauterivian Stage (~130 Ma) represents a brief dysoxic interval originally seen in the Italian Umbria-Marche Apennines (Coccioni et al., 1998; Baudin et al., 2002), but apparently found as far away as the central and northwestern Pacific (Follmi et al., 2012).

Time-series analysis of ocean anoxic events

In order to evaluate the potential periodic nature of the major hypoxic events of the last 260 My (Table 1), we utilized the circular spectral analysis method first developed by Schuster, 1875) and von Mises (1918), and refined by Stothers (1991). The method was designed to test for cycles in a time series of discrete events without amplitude information (effectively, a time series of Dirac delta-functions), where at least some of the events in the time series are thought to represent an underlying periodic process with some superimposed noise, but where some of the events could be spurious and not related to the periodic process. This method effectively measures the degree of clustering of events when the dates of the events are mapped to a data modulus of the test period under consideration. It produces a normalized distance metric, which should be minimized at the preferred cycle. The method works well for time-series like ocean anoxic events, which lack amplitude information, may be a mixture of periodic and non-periodic events, and consist of unevenly spaced data.

For circular spectral analysis, a timeline is 'wrapped' around a circle, the circumference of which represents a trial period (Stothers, 1991). For each occurrence, we calculate a unit vector from the origin. A series that is not periodic will tend to plot randomly around the circle, regardless of trial period selected. A periodic series, however, will tend to form a cluster at one point on the circumference when the correct trial period P is selected. The angular location of the cluster relative to 0° (the present) gives the phase (t_0).

The event times t_i are mapped onto a circle by conversion to angles a_i and b_i :

$$a_i = \sin 2\pi/P\,(t_i)$$

$$b_i = \cos 2\pi/P\,(t_i)$$

$$S = 1/N\sum_{i=1}^{N} (a_i) \qquad (1)$$

$$C = 1/N\sum_{i=1}^{N} (b_i)$$

$$R = (S^2 + C^2)^{1/2}$$

where i ranges from 1 to N (the number of events), and P is the trial period. S and C are the summations, $S = (\sum \sin a_i)/N$ and $C = (\sum \cos b_i)/N$.

Application of circular statistics leads to a mean vector magnitude, $R = (S^2 + C^2)^{1/2}$ (a normalized measure of goodness of fit). The direction of the vector that minimizes the dispersion at the trial period P indicates the phase, which can be computed: $t_0 = (P/2\pi) \tan^{-1} (S/C)$, if $C > 0$, or as $t_0 = (P/2) + (P/2\pi) \tan^{-1} (S/C)$, if $C < 0$. If R is plotted against P, then maximal values of R would correspond to periods in the series, $t_1, t_2, \ldots, t_N$. If, however, $t_1, t_2, \ldots, t_N$ are randomly distributed, then (a_i, b_i) would define a random walk, and the sum R will be small.

In this method, the normalized distance metric does not have a direct interpretation in terms of statistical significance. To assess statistical significance, we address the question: What is the likelihood that a time series drawn at random from the universe of possible time series would have a smaller normalized distance metric at the test period than does the actual time series?

To ensure that our results are a consequence of true periodicity and not of a characteristic recurrence interval, we constructed the set of test time series as follows. First, we calculated the length of time between each of the N events in the test time series, giving $N - 1$ intervals. We then took a random permutation of these $N - 1$ intervals and generated a time series of N events by taking the cumulative sum of this random permutation. Thus, we are testing against a universe of time series that contain the same set of intervals as the test time series, but permuted in a different order. This makes it clear that the periodicity is a consequence of the ordering of the intervals and not the statistical distributions of the intervals themselves.

We compared the Stothers (1991) normalized distance metric calculated at each test period with the normalized distance metric computed for 100,000 pseudo-time series generated by the permutation approach described above, each having 10 events over an interval of 260 My (Fig. 1). This significance test is powerful because the same set of intervals is present in the test time series and every one of the pseudo-time series, and the total length of the all of the pseudo-time series is identical to that of the test time series, eliminating artifacts associated with varying record lengths (Lutz, 1985) This significance test thus ascertains the likelihood that a random permutation of the same set of intervals would produce as strong evidence of periodicity as the time series being tested. The 0.95, 0.99, and 0.999 confidence lines in Figure 1 represent the 95th, 99th and 99.9th percentile result of 100,000 random pseudo-data sets.

The most significant spectral peak in the spectrum of anoxic events for periods from 15 to 50 My falls at 26.9 My (~95% confidence) (Figure 1). *P*-values in Figure 2 represent the number of cases out of 100,000 Monte Carlo simulations that had higher scores in Stothers' test. The *P*-value of 0.05 means that of 100,000 Monte Carlo simulations only 5,000 cases had higher scores in Stothers' method. A high-frequency` peak occurs at 12.6 My (relative power = 0.75) (Fig. 1). This is similar to a spectral peak seen in other geologic time series at about the same period, and may represent an independent climatic cycle (Boulila, 2019). It is, however, close to ½ the 26.9 My cycle.

Flood-basalt eruptions, ocean hypoxia and extinction episodes

The link between ocean hypoxia and marine extinctions may come from the severe reduction of habitats for benthic and pelagic organisms as anoxic waters spread, from increases in toxic trace metals in sulfidic waters, (e.g., Hg, As, Cr) (Leary and Rampino, 1990; Sanei et al., 2012), and/or by release of poisonous H_2S (Kump et al., 2005; Grice et al., 2005; Meyer et al., 2008; Penn et al., 2018) into the oceans and atmosphere. Release of H_2S could also have damaged the ozone layer (Lamarque et al., 2007) affecting non-marine fauna and flora as well.

The 27 My cycle seen in anoxic events is similar to the periodicity reported in marine extinction events (Raup and Sepkoskit,1986; Rampino and Caldeira, 2015), in episodes of flood-basalt volcanism (Rampino and Stothers, 1988; Rampino and Prokoph, 2013), and in tectonically-induced oscillations of sea level (Boulilla, 2018). It is notable that all ten of the anoxic intervals in Table 1 are coincident with the ages of flood-basalt episodes. This suggests that periods of flood-basalt volcanism, and resulting hyperthermal-hypoxic ocean conditions are related to global tectonic episodes that affect global sea levels (Embry et al., 2018) and also climate through pulses of release of volcanic greenhouse gases (Muller and Dutkiewicz, 2018).

The apparently ubiquitous underlying ca. 30-My cycles in geologic, climatic and biotic events are most likely driven by internal Earth processes (Sheridan, 1987), perhaps modulated by astrophysical factors such as pulses of heating during encounters with dark matter as the solar system oscillates through the galactic plane every ~30 Ma (Rampino, 2015; Abbas and Abbas, 1998). A similar underlying ~30 My periodicity has been reported in the ages of terrestrial impact structures, possibly from comet showers from the Oort Cloud generated from the same encounters with disc dark matter (Randall and Reece, 2014).

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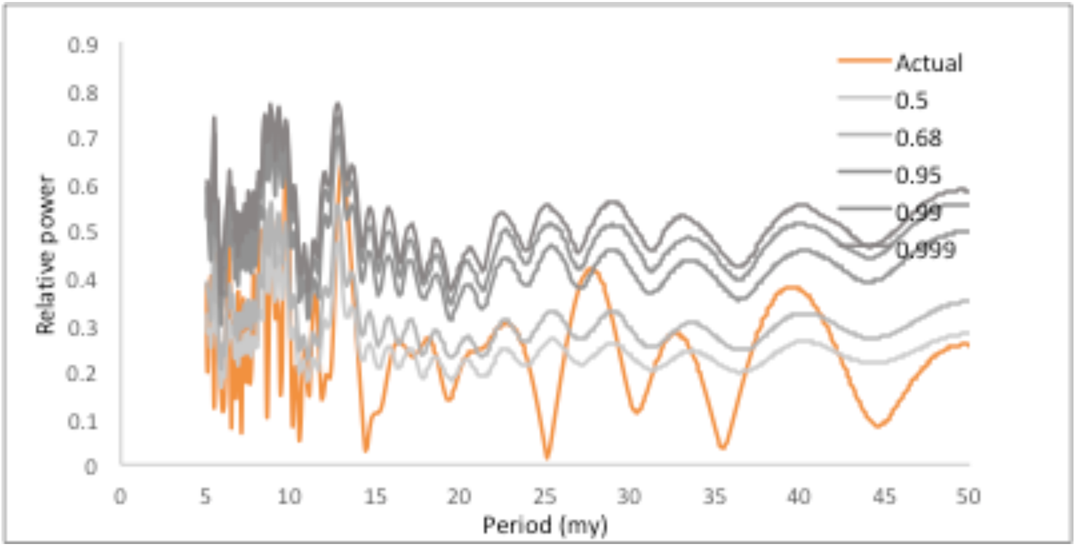
Figure Captions

Figure 1. Power spectrum of 10 major anoxic intervals of the past 260 My (Table 1) for periods of 5 to 50 My based on the circular spectral analysis method of Stothers (1991). A significant (95% confidence) occurs at 26.9 My.

Figure *2. P*-values for 10 major anoxic intervals over the past 260 My (Table 1) for periods from 5 to 50 My using the statistical method of Stothers (1991). The peak at 26.9 My is statistically significant (<0.05).

Figure 1



0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Relative power
0
5
10
15
20
25
30
35
40
45
50
Period (my)
Actual
0.5
0.68
0.95
0.99
0.999

Figure 2

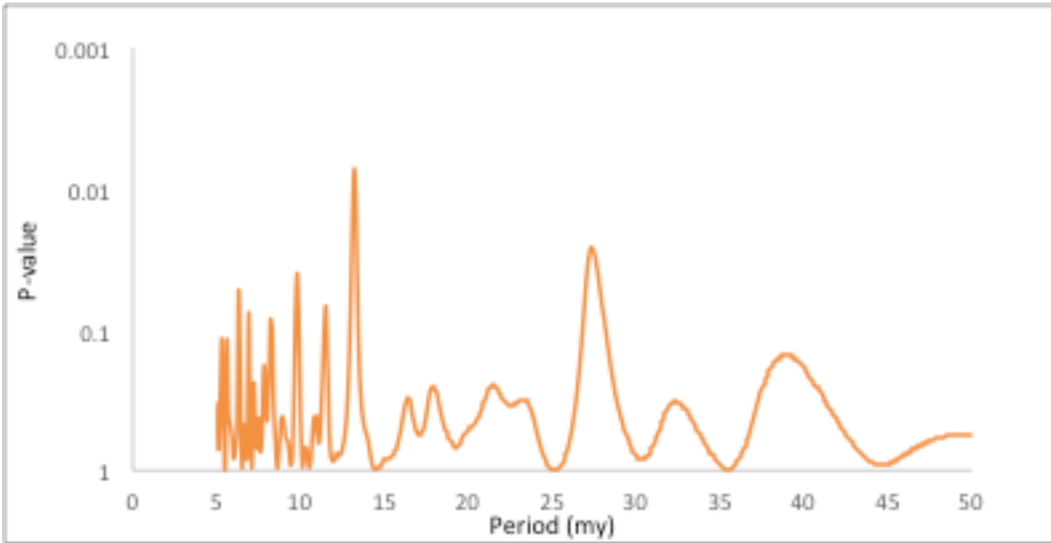


TABLE 1. Ocean anoxic events of the last 260 Ma, episodes of marine extinctions, flood-basalt eruptions, and stratigraphic Hg anomalies (for references see text).

Ocean Anoxic Events	Age (Ma)	Marine Extinction Episode	Flood Basalt	Age (Ma)	Hg Anomaly
PETM	56	PETM	NAIP	55.6, 61.9	Yes
K-Pg	66	Yes	Deccan	66.3 ±0.03	Yes
End-Cenomanian (OAE 2)	93.9	Yes	Madagas/Carib	92 to 94	Yes
Early Aptian (OAE 1a)	~120	Yes	Rajmahal/ OJP/Ker	~120	Yes
End-Hauterivian (Weissert)	134.7	----	Parana/Etendeka	134.3 ±0.8	Yes
End-Jurassic	145	Yes	Shatsky Rise	144.4 ±1.0	----
Toarcian	183.7	Yes	Karoo/Ferrar	183 ±1	Yes
End-Triassic	201.4	Yes	CAMP	201.5 ±0.05	Yes
End-Permian	251.9	Yes	Siberian	251.9 ±0.07	Yes
End-Guadalupian	259.8	Yes	Emeishan	259.6 ±0.5	Yes
Minor OAEs					
OAE 1b	113	No	Kerguelen (?)	?	Yes
OAE 1c	102	No	No		----
OAE 1d	100	No	No		----
Mid-Cenomanian Event (MCE)	97	No	No		----
OAE 3	87	No	No		----
Faraoni	130	No	Comei-Bunbury	131.5 ±0.8	----