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Research Paper

A pulse of the Earth: A 27.5-Myr underlying cycle in coordinated geological events over the last 260 Myr

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ABSTRACT

We performed spectral analyses on the ages of 89 well-dated major geological events of the last 260 Myr from the recent geologic literature. These events include times of marine and non-marine extinctions, major ocean-anoxic events, continental flood-basalt eruptions, sea-level fluctuations, global pulses of intraplate magmatism, and times of changes in seafloor-spreading rates and plate reorganizations. The aggregate of all 89 events shows ten clusters in the last 260 Myr, spaced at an average interval of ~ 26.9 Myr, and Fourier analysis of the data yields a spectral peak at 27.5 Myr at the ≥ 96% confidence level. A shorter period of ~ 8.9 Myr may also be significant in modulating the timing of geologic events. Our results suggest that global geologic events are generally correlated, and seem to come in pulses with an underlying ~ 27.5-Myr cycle. These cyclic pulses of tectonics and climate change may be the result of geophysical processes related to the dynamics of plate tectonics and mantle plumes, or might alternatively be paced by astronomical cycles associated with the Earth's motions in the Solar System and the Galaxy.

1. Introduction

There is a long history regarding the questions of temporal coordination among various geological events (e.g., Stille, 1924; Du Toit, 1937; Umbgrove, 1947), and of a long-term underlying cycle of about 30 Myr in the geologic record (e.g., Holmes, 1927; Grabau, 1936, 1940). Plate-tectonic theory implies that episodes of various regional geological events should be manifestations of global patterns of plate dynamics and mantle-plume activity (e.g., Lovell, 2010; Livermore, 2018). Early work on correlations and potential periodicity in the geological record was hampered by limitations in age-dating of geologic events that prevented quantitative investigations. It is also likely that the geologic record could be a mixture of periodic and non-periodic events, and that there could be leads and lags in the occurrences of various related geologic phenomena. Thus, statistical techniques are necessary to extract potential signals from the noise.

In the modern era, Fischer and Arthur (1977) proposed a 32-Myr cycle in marine climate and biotic change, most likely linked to tectonics, but their work lacked quantitative rigor. In 1984, Raup and Sepkoski provided rigorous time-series analysis of newly compiled fossil data, and reported a highly significant 26.4 Myr period in marine extinctions of the last 250 Myr (Raup and Sepkoski, 1984, 1986). An extinction period of ~ 26 Myr to 27 Myr was subsequently extended to the entire Phanerozoic (Rampino and Haggerty, 1995). These findings led to renewed interest in quantitative searches for ~ 30 Myr periods in geological events of various kinds that might lead to periodic extinction episodes.

For example, Rampino and Stothers (1984), using a similar linear time-series analysis technique (Stothers, 1991), reported a period of about 33 ± 3 Myr from records of the ages of sea-level lowstands (0–200 Ma), changes in seafloor-spreading rates (0–150 Ma), and tectonic episodes (0–570 Ma) compiled from the best contemporary sources. For oscillations of sea level, Rampino and Stothers (1984) analyzed the Mesozoic and Cenozoic sea-level data (stratigraphic sequence boundaries) of Vail et al. (1977) and reported the highest spectral peak at 33 ± 1 Myr. Negi et al. (1990) later reported a similar 33-Myr cycle over the last 200 Myr from spectral analysis of the updated sea-level curve of Haq et al. (1987). For tectonic events, using a compilation of about 700 radiometric age determinations (Rb-Sr, U-Pb and K-Ar dates) from the last 600 Myr, Liritzis (1993) reported a significant ~ 30-

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Myr tectonic cycle, and a less significant longer cycle of about 250 Myr.

In 1993, Rampino and Caldeira published the results of spectral analyses of the records of important geological events over the past 260 Myr. The data came from a compilation of the best-determined ages of 77 events from the geological literature up to that time (Rampino and Caldeira, 1992, 1993). These events included episodes of marine extinctions, paleoclimatic data (in the form of the ages of major ocean-anoxic intervals and large evaporite deposits), pulses of continental flood-basalt volcanism, changes in seafloor- spreading rates, fluctuations in sea level as expressed by stratigraphic sequences, and orogenic (tectonic) events.

They noted ten clusters of the geological events in the last 260 Myr, with an average spacing of ~ 26 Myr, and subsequently performed Fourier transform analysis of the entire data set of 77 events and found a statistically significant underlying periodicity of ~26.6 Myr at the 99.9% confidence level. Spectral analyses of the seven individual classes of events gave a dominant period in the range from 26.2 Myr to 30.6 Myr, with the phase of that period (t_0) varying between 8.4 Ma and 11.7 Ma (Rampino and Caldeira, 1993).

These studies were based on the best-dated geological events at the time of publication in the 1980s and early 1990s. In the past 25 years, however, there have been significant improvements in radio-isotopic dating techniques (e.g., U-Pb zircon and $^{40}Ar/^{39}Ar$ ages) (e.g., Renne et al., 2013; Jourdan et al., 2014; Burgess and Bowring, 2015), and changes in the geologic timescale (Cohen et al., 2013; Gradstein et al., 2020). With this in mind, we compiled updated records of geologic events by using the best age-data available from the recent literature pertaining to times of 89 recognized major geologic events over the last 260 Myr (Table 1), and have subjected these data to new tests of correlation and spectral analyses.

2. New data of the ages of geologic events

New age data for a number of the geologic events of the last 260 Myr (the best-dated part of the geologic record) (Table 1) were gathered from the recent published literature for 29 global sequence boundaries reflecting sea-level fluctuations (Embry et al., 2018); 12 marine-extinction episodes (Raup and Sepkoski, 1986; original data published in Sepkoski, 2002); 9 non-marine tetrapod extinction events (Rampino et al., 2020, 2021); 13 continental flood-basalt eruptions (Rampino et al., 2019); 10 major ocean-anoxic events (Rampino et al., 2019); 8 times of changes in seafloor spreading rates (Müller et al., 2016); and 8 global pulsations of intraplate magmatism (Mjelde et al., 2010), for a total of 89 events. In the case of marine- extinction events, we used the Sepkoski (2002) data set (see also Bambach, 2006), which has better resolution than the more recent fossil database of Alroy et al. (2008). We also note that the number of peaks of extinction events in the Alroy et al. (2008) data set is similar to the peaks in the Sepkoski (2002) data set. Wherever relevant, ages were slightly re-adjusted (only a few cases, mostly ≤ 1.5 Myr) in accordance with the latest geologic timescales for consistency (Cohen et al., 2013; Gradstein et al., 2020). Sources for the individual ages are given in the relevant references. Table 1 shows all of the age data in 10-Myr bins, and it is important to note that error bars in most cases are ≤ ± 1 Myr, so that the small uncertainties in the ages of the various events have little effect on the results of our spectral analyses, where we first rounded ages to the nearest Myr.

Table 1
Geological events of the last 260 Myr.

Interval (Ma)	Marine Extinction[1]	Anoxic Event[2]	Continental Basalt[3]	Sequence Boundary[4]	Non-Marine Extinction[5]	Changes in Spreading Rate[6]	Intra-Plate Volcanism[7]
0–9	2.6	–	–	5.33	7.25	–	3
10–19	11.6	–	16.6 ± 0.03	11.63	–	–	10, 15
20–29	–	–	–	23.03	–	–	23
30–39	36.5	–	30.4 ± 0.4	33.9	33.9	–	30
40–49	–	–	41.2	–	–	40	
50–59	–	56.0	56.6 ± 0.3	52.0	–	50, 58	–
60–69	66.04	66	61.9; 66.3	61.6; 68	66	–	60, 65
70–79	–	–	–	–	–	75	–
80–89	–	–	–	84.2	–	80	–
90–99	93.9	93.9	92.9 ± 3.8	93.9	–	–	–
100–109	–	–	–	100; 109	–	–	–
110–119	–	–	118 ± 1	–	–	–	–
120–129	124[8]	124	123.5 ± 1.5	124; 129.4	–	120	–
130–139	–	132.6	134.7 ± 1	132.6; 139.8	–	–	
140–149	143.1	–	–	149.2 ± 0.9	143.1	140	–
150–159	–	152	–	____	–	155	–
160–169	–	–	–	161.5 ± 1.0	–	–	–
170–179	–	–	–	170.3 ± 1.4	–	170	–
180–189	184.2 ± 0.7	184.2 ± 0.7	182.7 ± 0.03	184.2 ± 0.7	–	–	–
190–199	–	–	–	190.8 ± 1.0; 199	–	–	–
200–209	201.4 ± 0.2	201.4 ± 0.2	201.5 ± 0.05	205.7	201.4 ± 0.2	–	–
210–219	215	–	–	218	215	–	–
220–229–	–	–	228	227.3	–	–	
230–239	–	–	–	237	–	–	–
240–249	–	–	–	247	–	–	–
250–259	251.9 ± 0.02	251.9 ± 0.02	251.9 ± 0.07	252	251.9 ± 0.02	–	–
260–269	259.8 ± 0.5	259.8 ± 0.5	259.6 ± 0.5	260	259.8 ± 0.5	–	–

Sources: Marine-extinction events[1] (Raup and Sepkoski, 1986; Sepkoski, 2002); ocean-anoxic intervals[2] (Rampino et al., 2019); flood-basalt eruptions[3] (Rampino et al., 2019); stratigraphic sequence boundaries[4] (Embry et al., 2018); non-marine tetrapod extinction episodes[5] (Rampino et al., 2020); changes in sea-floor spreading rates[6] (Müller et al., 2016); and global pulses of intra-plate magmatism[7] (Mjelde et al., 2010). Error bars for most ages are ≤ ± 1 Myr, and ages were adjusted to the latest geological time scales (Gradstein et al., 2020; Cohen et al., 2013) where appropriate, but this did not significantly affect the results of our analyses.

[8]The age of the Barremian/Aptian boundary is given as 121.4 Ma in the Gradstein et al. (2020) time scale and 125 Ma in the Cohen et al. (2020) time scale. That boundary had an age of 126.3 Ma in the Ogg et al. (2016) time scale. We prefer the 125 Ma age, making the early Aptian event about 124 Ma, but this makes no difference in the results of the spectral analyses. The ages were rounded to the nearest Myr for the Fourier analyses in this study.

3. Statistical testing and results

3.1. Moving-window analysis

A 10-Myr moving-window, centered every 0.5 Myr, was applied to the combined age data of the 89 geological events (Table 1), and the number of dated occurrences that fell within the moving window was computed at 1-Myr intervals. The result of the moving-window analysis shows ten peaks or clusters in the number of dated events (peaks having 5 to 11 events) over the last 260 Myr (Fig. 1a). Between these 10 peaks, the number of events drops off sharply and commonly approaches zero. The peaks remained stable in position despite variations in the size of the moving window (5 Myr to 10 Myr). Peaks are centered at about 7, 35, 61, 95, 124, 140, 186, 196, 213, and 255 Ma, with an average interval between peaks of 27.5 Myr (Fig. 1a).

3.2. Gaussian smoothing

An independent statistical exercise was to treat each of the 89 dates in the record as a delta function (spike), and then to apply a Gaussian smoothing with a standard deviation of 5 Myr to the resultant function, centered at every 0.1 Myr (Fig. 1b). The Gaussian filter removed high-frequency noise components, again resulting in ten peaks (or clusters) centered at about 10, 34, 63, 95, 122, 141, 184, 201, 217, and 255 Ma. with a similar average interval between peaks of 26.9 Myr (Fig. 1b).

3.3. Fourier analysis

We computed a Fourier transform to derive the best-fitting period for the 89 geological events in the last 260 Myr. First, we rounded the original un-windowed data to the nearest million years and counted the number of events in each 1 Myr interval. We then applied a standard Tukey window with a window size of 6 Myr. We padded the smoothed time-series data and applied a Fourier transform (Gasquet and Witomski, 1999). We tried different combinations of Tukey window size (5–10 Myr) and number of paddings (0–40) in search of the pairing that gave the most characteristic spectrum.

The highest peak in the Fourier power spectrum occurs at a period of 27.5 Myr (Fig. 2). A relatively strong secondary signal occurs at a period of 8.9 Myr (Fig. 2). We computed the significance of the result by generating 100,000 test datasets and comparing the spectral power at 27.5 Myr. To simulate the test datasets, the intervals between each two consecutive events were calculated. After permuting the order of the intervals, a new time series was recalculated based on the new set of intervals. This method ensures that the test time series are between 0 and 260 Ma and the number of events remains at 89. Ultimately, only ~ 4% of the test datasets produced a higher spectral power at 27.5 Myr, indicating a confidence level of at least 96% for that period.

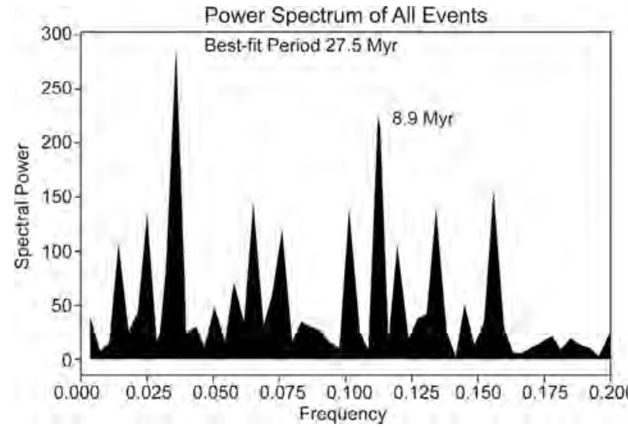

Fig. 2. Results of Fourier transform of the ages of all 89 geologic events (Table 1). The original un-windowed data was rounded to the nearest Myr, and a Fourier transform was applied with a standard Tukey window of 6 Myr. The highest peak in the Fourier power spectrum occurs at a period of 27.5 Myr (99% confidence). A strong secondary signal occurs at a period 8.9 Myr.

We also performed similar Fourier transform analysis of just the combined records of marine extinctions (12 events) and non-marine tetrapod extinctions (9 events) of the last 260 Myr, for a total of 21 extinction events (Table 1), and found a significant period of 27.5 Myr (Fig. 3). There was no significant peak at 8.9 Myr. This suggests that the periodicity of marine and non-marine extinctions plays a significant role in the 27.5 Myr cycle detected in the aggregate of all 89 geologic events, even though extinctions represent only ~23% of the 89 total events, and that the 8.9 Myr cycle comes largely from the other events. In support of this, Fourier analysis of the 68 non-extinction events gave the highest spectral peak at 8.9 Myr, with reduced power at 27.5 Myr (Fig. 4).

The 8.9 Myr cycle that we detected is similar to a ~ 8 Myr to 10 Myr cycle that shows up in spectral analyses of sea-level indicators (Boulila et al., 2012; Embry et al., 2018), the diversity of calcareous plankton, (Prokoph et al., 2004), records of marine $\delta^{18}O$

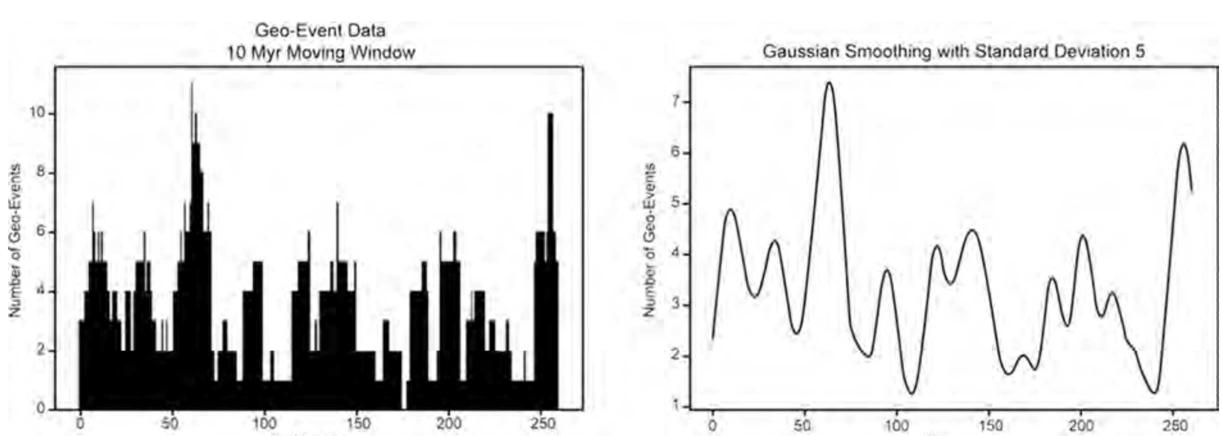

Fig. 1. Left: Results of moving-window analysis of the ages of 89 geologic events (Table 1) using a 10-Myr moving window centered every 0.5 Myr, with the number of occurrences that fell within the moving window computed at 1-Myr intervals. Ten clusters (peaks) are visible. Right: Ages of the 89 geologic events (Table 1) with a Gaussian smoothing with a standard deviation of 5 Myr centered at every 0.1 Myr. Again, ten clusters (or peaks) are visible.

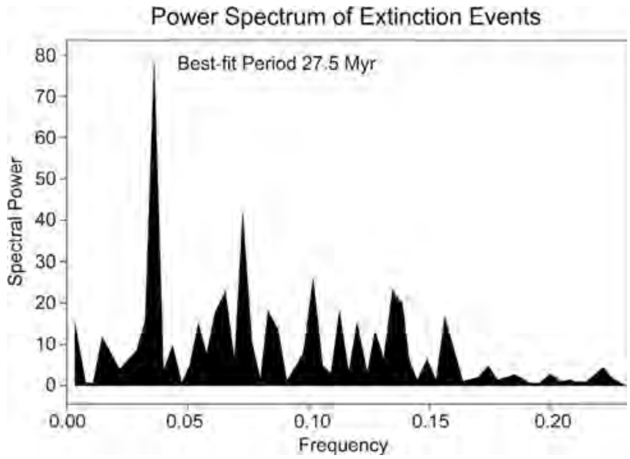

Fig. 3. Fourier power spectrum of a combination of marine and non-marine extinctions (21 events) (Table 1). Note the single high spectral peak at 27.5 Myr.

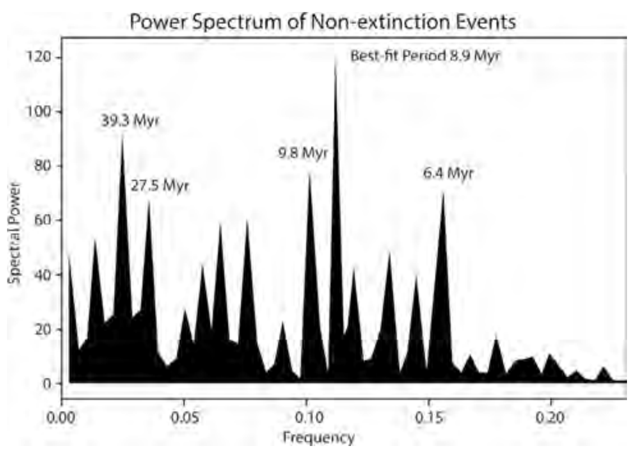

Fig. 4. Fourier power spectrum of the 68 remaining (non-extinction) events (Table 1). Note the high power at 8.9 Myr, and reduced power at 27.5 Myr.

and $\delta^{13}C$ (Boulila, 2019; Boulila et al., 2012; Prokoph et al., 2004), geologic carbon emissions (Martinez and Dera, 2015), and variations in dolomite abundance in marine sediments (Negi et al., 1996).

4. Discussion

In the last 25 years, a number of workers have reported an ~ 26-Myr to 36-Myr cycle in various geological events. For example, Clube and Napier (1996) utilized the same original geological data (77 events) from Rampino and Caldeira (1993), and applied periodogram analysis combined with circular spectral analysis (Stothers, 1991). Statistical significance was calculated by comparing the power spectra of the real data with synthetic random data having the same broad underlying probability distributions as the actual data. Clube and Napier (1996) separately analyzed the record of marine extinctions and reported a significant periodicity of ~ 26.3 Myr, with the most recent phase (t_0) of the cycle at ~ 12. 1 Ma, similar to other analyses of marine extinctions (e.g., Raup and Sepkoski, 1984, 1986; Melott and Bambach, 2014; Rampino and Caldeira, 2015). When Clube and Napier (1996) applied their methods to the remaining geological data (66 events) they found a statistically significant period (99.4% confidence level) of 26.3 Myr with a phase (t_0) at ~ 10.8 Ma.

Other individual data sets of geologic events have been analyzed with similar results. For example, Prokoph et al. (2004) applied time-series analysis to the sea-level curve of Hardenbol et al. (1998) along with the diversity of calcareous plankton and marine stable-isotope data ($^{87}Sr/^{86}Sr$, $\delta^{18}O$ and $\delta^{13}C$) (from Veizer et al., 1999) over the last 230 Myr, and reported a statistically significant (95% confidence) cycle of 26–33 Myr. Baker and Flood (2015) performed time-series analyses on up-dated sea-level data (from Kominz et al., 2008) from the Late Cretaceous to the Miocene (from ~ 110 Ma to 10 Ma), and found a statistically significant spectral peak (99% confidence level) at 31 Myr.

Boulila et al. (2018) (using the sea-level data from Haq et al., 1987; Haq and Al-Qahtani, 2005; and Haq and Schutter, 2008) reported a significant 36-Myr sea-level oscillation for the entire 541-Myr Phanerozoic, apparently modulated by a longer ~250 Myr cycle. They also detected a similar cycle of 36 Myr in climatic proxy data over the same interval (the marine carbonate $\delta^{18}O$ record of Veizer and Prokoph, 2015), and proposed a climatic driver for the 36-Myr sea-level cycle. Most recently, Rampino and Caldeira (2020) analyzed (with circular spectral analysis) the ages of the 57 dated major sequence boundaries (times of sea-level low stands) from the very complete Canadian High Arctic record of the past 545 Myr (Embry et al., 2018), and found a statistically significant (>99.9% confidence level) cycle of 32 Myr in the sea-level data. Oppo et al. (2020) reported a 26-Myr to 27-Myr cycle in deposition of methane-derived carbonates related to methane seepage on the seafloor, apparently controlled by sea-level changes and variations in organic carbon burial related to ocean-anoxic periods.

The connection between tectonics and sea-level oscillations may come from changes in directions and rates of seafloor spreading and subduction (Cogné and Humler, 2004; Coltice et al., 2013), intraplate stresses related to rearrangements of global plate motions (e.g., King et al., 2002; Müller et al., 2016; Embry et al., 2018; Müller and Dutkiewicz, 2018), and pulsations of convection (Lovell, 2010) or mantle-plume activity (e.g., Sheridan, 1987). Mjelde et al. (2010) reported evidence for major peaks in intraplate volcanism in the last 70 Myr (Table 1) that seem to be global in extent, and which have an average ~ 9-Myr to 10-Myr spacing similar to the spacing of stratigraphic sequence boundaries (e.g., the "10-Myr-flood" cycle of Embry et al., 2018).

Climate may be affected by changes in atmospheric pCO_2 from pulses of global volcanism (e.g., subduction-related and/or flood-basalt activity) (Müller and Dutkiewicz, 2018; Rampino et al., 2019), and by changes in land/sea distribution related to the sea-level fluctuations (Caldeira and Rampino, 1991). Müller and Dutkiewicz (2018) found a significant 26-Myr periodicity in a tectonically driven model of carbon emissions and resulting carbon-dioxide content of the atmosphere for the last 420 Myr. Shaviv et al. (2014) had earlier reported a significant 32-Myr cycle in global paleoclimate (marine $\delta^{18}O$ measurements) going back 540 Myr, modulated by a longer ~170 Myr periodicity.

More recently, Boulila (2019) reported prominent ~9 Myr and ~36 Myr periods in a record of ocean climate ($\delta^{18}O$ of benthic foraminifera) going back 115 Myr. Specific climatic events seem to have occurred preferentially at the extremes in the two cycles, suggesting that the climate excursions were paced by both cycles. Other more abrupt events were attributed to non-cyclical processes (e.g., large-body impacts) that may have interacted with the cyclical climatic forcing as triggers or feedbacks (Boulila, 2019).

Stothers (1989) found that the ages of Mesozoic and Cenozoic chronostratigraphic stage boundaries in the geologic timescales in use at the time showed a weak ~30-Myr periodicity. Using the recent Gradstein et al. (2020) time scale, we found a similar ~27-Myr periodicity in the ages of stage boundaries for the last 260 Myr. One might expect this situation, since the time scale is composed of stages that were first defined by changes in marine biota, which apparently exhibit the 26-Myr to 27-Myr cycle (Raup and Sepkoski, 1986; Rampino and Caldeira, 2015). The current biostratigraphically defined stage boundaries (Cohen et al., 2013; Gradstein et al., 2020) are commonly associated with stratigraphic sequence boundaries (evidence of correlative sea-level fluctuations) (e.g., Embry and Mørk, 2006; Embry et al., 2018) and with climatic events that show a ~ 32-Myr to 36-Myr cycle (Boulila, 2019; Boulila et al., 2012; Rampino and Caldeira, 2020; Shaviv et al., 2014). These correlations support a link among sea levels, climate and biotic changes.

In the case of the ages of 13 episodes of continental flood-basalt volcanism of the last 260 Myr, Rampino and Stothers (1988) reported a period or quasi-period of ~ 32 ± 1 Myr in an early dataset with errors as great as ±5 Myr to ±10 Myr. Rampino and Caldeira (1993) later found two strong spectral peaks at 23.1 Myr and 26.2 Myr in a continental flood-basalt record with better time control. More recently, Prokoph et al. (2013) considered a record of updated ages and volumes for 32 eruptions of Large Igneous Provinces (LIPs) (continental flood basalts and oceanic plateaus) using wavelet analysis. They reported a significant spectral peak at 28–35 Myr.

We note that 7 out of the 12 marine-extinction events and 6 out of the 9 non-marine tetrapod extinction episodes in the last 260 Myr are significantly correlated with the pulses of continental flood-basalt volcanism (Table 1) (Rampino et al., 2019; Rampino et al., 2020). It is also true, however, that 3 of the same marine/non-marine extinction co-events (end-Cretaceous event at 66 Ma, the end-Jurassic event at 143 Ma, and a Late Triassic event at 215 Ma), are also closely correlated with the ages of 3 of the 4 largest impact craters ($\geq$100 km in diameter) of the last 260 Myr (Chicxulub, Morokweng, and Manicouagan), each apparently capable of causing a mass extinction (Toon et al., 2016; Rampino, 2020). These co-occurrences suggest some causal connection, or synergistic effects between large impacts and flood-basalt volcanism.

The potential cause-and-effect relationships between the geologic activity and biotic changes may be complex, but there are several apparent causal chains. One proposed relationship links flood-basalt eruptions, increased volcanic CO_2 release, abrupt and severe climate warming, anoxic oceans and marine-extinction episodes (Ernst and Youbi, 2017; Rampino et al., 2019; Wu et al., 2021). There is also a potential chain of causation for tectonic episodes, related sea-level and pCO_2 oscillations, climate and biotic changes (Caldeira and Rampino, 1991; Müller et al., 2008; Rampino and Caldeira, 2020; Van Der Meer et al., 2014).

What could be driving the correlated cycles in geologic and climatic events? Explanations have long centered around potentially linked cycles of global tectonics and climate change (e.g., Fischer and Arthur, 1977). The dominant ~30 Myr pacing may be a result of strictly internal Earth processes (e.g., pulsation tectonics) (Sheridan 1987) including interactions among seafloor spreading, subducted slabs and mantle convection (Storey, 1995; Lovell, 2010; Mather et al., 2020).

Müller and Dutkiewicz (2018) found that atmospheric pCO_2 data for the last 420 Myr showed fluctuations with a 26–32 Myr cycle. They proposed a driving force for the cyclic oscillations of pCO_2 and resulting climate changes related to the workings of the global carbon cycle. Their model takes advantage of a large reservoir of carbon sequestered in oceanic crust as a result of hydrothermal carbon uptake in hot, young crust near spreading ridges, and with a strong dependence on ocean bottom-water temperatures.

In their analysis, Müller and Dutkiewicz (2018) combined a global plate model with estimates of paleo-ocean bottom-water temperatures to track the evolution of the oceanic crustal carbon reservoir over the past 230 Myr. Their modeling predicted that rates of seafloor spreading, as well as the storage, subduction, and emission of ocean crustal and mantle CO_2, fluctuate with a period of ~26 Myr to 32 Myr. They suggested a connection between pulses in seafloor spreading and equivalent cycles in subduction-zone rollback, with a similar periodicity, driven largely by the dynamics of subduction-zone migration. This mechanism provides a direct connection among cyclical tectonics, the carbon cycle and climate change.

The potential involvement of the Earth's orbital cycles is supported by the fact that $\delta^{13}C$ fluctuations in ocean sediments (Zachos et al., 2001, 2008; Cramer et al., 2009) show similar cycles (~27 Myr to 29 Myr and 8.3 Myr to 8.4 Myr) in the amplitude modulation of a shorter ~2.4 Myr $\delta^{13}C$ cycle (Boulila et al., 2012). In the orbital Milankovitch cycles, amplitude modulation of a similar 2.4 Myr orbital eccentricity cycle (Laskar et al., 2011), apparently leads to similar spectral peaks of ~27.5 Myr to 33 Myr, and about 8 Myr to 10 Myr (Boulila, 2019; Boulila et al., 2012). Boulila (2019) discussed a potential relationship where orbital-driven climate changes could be modulating tectonic processes through loading and unloading of water and ice. Loading and unloading of sediments through deposition and erosion also seems a possible driver (Rampino et al., 1979).

On the other hand, the main period of about 30 Myr is close to the Solar System's ~ 32 ± 3 Myr vertical oscillation about the midplane of the Galaxy (Rampino and Stothers, 1986). In the Galactic plane region, increased cosmic-ray flux might lead to significant climatic changes (Gies and Helsel, 2005; Svensmark, 2006; Shaviv et al., 2014), whereas encounters with concentrations of disk-dark matter might trigger comet showers from the Oort Cloud (Randal and Reece, 2014), as well as thermal and geophysical disturbances in the inner Earth (Abbas and Abbas, 1998; Rampino, 2015, 2017). We note that a 26 to 37 Myr cycle has been reported in the ages of terrestrial impact craters, using various statistical techniques and sets of crater ages (Rampino and Caldeira, 2015; Rampino and Prokoph, 2020) potentially connecting the terrestrial and extraterrestrial cycles.

One question that remains is: Are the nominal ~ 26 Myr to 27.5 Myr cycles and the longer ~ 32 Myr to 37 Myr cycles actually the same, with the difference in period being a result of problems in the intercalibration and accuracy of various dating techniques over time, the version of the geologic timescale in use at the time, differences in statistical techniques and data sets, potential actual irregularities in the cycle lengths, or some other factors?

For example, Rampino and Prokoph (2020) reported the results of 23 published (1984–2017) individual spectral analyses of marine extinctions that utilized various spectral methods, variable data and different geologic time scales. These 23 studies produced statistically significant cycles in marine extinctions in the range from 26 Myr to 33 Myr. This supports the idea that differences in methods and datasets may be partly responsible for variations in the lengths of the detected cycles.

5. Conclusions

We performed moving-window and spectral analyses on the record of 89 major geologic events of the last 260 Myr, including marine and non-marine extinctions, ocean-anoxic events, sea-level oscillations, continental flood-basalt eruptions, pulses of intra-plate magmatism, and changes in seafloor spreading rates. Moving window-analysis shows ten peaks (or clusters) in the number of dated events (peaks having 5 to 11 events) over the last 260 Myr centered at ~ 10, 34, 63, 95, 122, 141, 184, 201, 217, and 255 Ma, with an average interval between peaks of 27.5 Myr. Fourier analyses of the ages of the events produced spectra with significant peaks at 27.5 Myr and 8.9 Myr. Similar cycles of 26–36 Myr and 8–10 Myr have been reported in these and other aspects of geologic and climatic changes. The question of the precise lengths of the cycles, however, which may depend upon the statistical techniques utilized and differences in the various datasets, is still open.

The correlations and cyclicity seen in the geologic episodes may be entirely a function of global internal Earth dynamics affecting global tectonics and climate, but similar cycles in the Earth's orbit in the Solar System and in the Galaxy might be pacing these events. Whatever the origins of these cyclical episodes, their occurrences support the case for a largely periodic, coordinated, and intermittently catastrophic geologic record, which is quite different from the views held by most geologists.

Declaration of Competing Interest

The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

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