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GEOLOGICAL NOTES

An ~60-Million-Year Periodicity Is Common to Marine $^{87}\text{Sr}/^{86}\text{Sr}$, Fossil Biodiversity, and Large-Scale Sedimentation: What Does the Periodicity Reflect?

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ABSTRACT

We find that the marine $^{87}\text{Sr}/^{86}\text{Sr}$ record shows a significant periodicity of 59.3 ± 3 m.yr. The $^{87}\text{Sr}/^{86}\text{Sr}$ record is $171^\circ \pm 12^\circ$ out of phase with a $62 (\pm 3)$ -m.yr. periodicity previously reported in the record of marine animal diversity. These periodicities are close to $58 (\pm 4)$ -m.yr. cycles found for the number of gap-bounded sedimentary carbonate packages of North America. We propose that these periodicities reflect the operation of a periodic “pulse of the earth” in large-scale earth processes. These may be linked to mantle or plate-tectonic events, possibly uplift, which affects the earth’s climate and oceans and, thus, the geochemistry, sedimentation, and biodiversity of the marine realm.

Online enhancements: appendix, figures.

Introduction

It has frequently been suggested that large-scale geological phenomena may be the driver for large-scale evolutionary change that is revealed in the fossil record, for example, that the emplacement of large igneous provinces may drive mass extinctions (e.g., Courtillot et al. 1996). Possible connections between large-scale tectonic phenomena, the fossil record, and the record of marine $^{87}\text{Sr}/^{86}\text{Sr}$ (a proxy for continental weathering) have been noted before by casual allusion (e.g., McArthur et al. 2001), minimal discussion (Prokoph et al. 2008), discussion that lacked quantification (Halverson et al. 2007; Purdy 2008), and plots presented at Geology Society of America meetings (R. A. Rohde, personal communication, 2007). Here we provide a time series analysis of an independent signal of the geological record in an attempt to reveal more about large-

scale geological events as potential drivers of biodiversity change.

We note that a 62 ± 3 -m.yr. periodicity exists in the record of marine animal diversity (Rohde and Muller 2005; Cornette 2007; Lieberman and Melott 2007; Melott 2008; Melott and Bambach 2011a). This periodicity is present in three independent sets of data that we have examined that document Phanerozoic marine diversity (details in Melott and Bambach 2011a and references therein). A periodicity of 58 ± 4 m.yr. is present in the temporal and area-weighted number of gap-bound sedimentary carbonate in the United States (Melott and Bambach 2011b, using data from Peters 2008a). Peters (2008b) initially noted that, on the basis of his data, the Sloss Sequences—as Peters had redefined them—averaged 67 m.yr. in length, and he observed that this was similar to the periodicity of diversity fluctuation observed by Rohde and Muller (2005). Using a now much expanded set of North American data, Meyers and Peters (2011) have found a $56 \pm$

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3-m.yr. periodicity in the total sediment area coverage of the continent, similar to the 58 ± 4 -m.yr. periodicity Melott and Bambach (2011*b*) found in Peters's older compilation of the number of gap-bound units. Both periodicities are significant and in phase with the biodiversity periodicity (Melott and Bambach 2011*b*). Error bars (\pm) on periods given in this work signify the bandwidth of the spectral peak, that is, an estimate of one standard deviation in the frequency distribution of power as observed on a spectral plot.

Other reported periodicities include an ~ 60 -m.yr. periodicity in the timing of emplacement of continental large igneous provinces over the past 320 m.yr. (Prokoph et al. 2004), which we discuss later. In passing, an ~ 60 -m.yr. periodicity was noted in the record of marine $^{87}\text{Sr}/^{86}\text{Sr}$ by Prokoph et al. (2008) and McArthur (2010). Neither observation was supported by significance levels of the detection, phase angle, or extended discussion.

Methods

We examine periodicity using the amplitude peaks of the Fourier coefficients of time series, a widely used method (Muller and MacDonald 2002; Press et al. 2007). Virtually any mathematical function can be decomposed into a sum of sinusoids, but a significant indication of periodicity exists when the amplitude of some frequency stands out significantly above the others.

Developing the arguments of Melott and Bambach (2011*a*, 2011*b*), here we tested for periodicity in marine $^{87}\text{Sr}/^{86}\text{Sr}$ using the LOWESS fit of McArthur and Howarth (2004) for the Phanerozoic and the number of short-lived genera (those that endure less than 45 m.yr.), given by Rohde and Muller (2005), which are reduced from the database of Sepkoski (2002). Both sets of data use are adjusted to the timescale of Gradstein et al. (2004).

The LOWESS fit of McArthur and Howarth (2004) is based on 3875 pairs of published data, unevenly spread through Phanerozoic time. The uncertainty of positioning of peaks and troughs in the Sr curve within the timescale used (Gradstein et al. 2004) matches the quality of age given by the timescale used and is ± 2 m.yr. for the Palaeozoic and Mesozoic and typically < 0.3 m.yr. for the Cenozoic. Because the residence time of Sr in the world's oceans is today around 2 m.yr., marine $^{87}\text{Sr}/^{86}\text{Sr}$ is buffered against rapid change (i.e., timescales < 1 m.yr.; Richter and Turekian 1993), it is certain that no major excursions remain unidentified.

In line with standard methods, to facilitate our

Fourier analysis, we use a LOWESS curve that was detrended by fitting a cubic regression, calculating residuals about the fitted line, and normalized by dividing each value of $^{87}\text{Sr}/^{86}\text{Sr}$ by the relevant standard deviation (for details, see the appendix, available in the online edition or from the *Journal of Geology* office). Detrending is standard in time series analysis and has no effect on inherent periodicity in time series signals other than at the period of the fit. Normalization (as defined earlier) is a mathematical convenience that permits better comparison between different sets of time series data. To compare periodicity and phase between time series results from different data sets, we use cross-spectral analysis. The $^{87}\text{Sr}/^{86}\text{Sr}$ curve was sampled at 1-m.yr. intervals (an interval 10 times the 0.1-mA intervals that constitute the fit), as are the biodiversity data (interpolated between adjacent data points only). This approach was checked against Lomb-Scargle methods (no interpolation) elsewhere (Cornette 2007; Melott and Bambach 2011*a*). We note that our spectral analysis is restricted to periods longer than 25 m.yr. Interpolation and sampling effects are significant only for periods much shorter than this (see, e.g., Melott and Bambach 2011*a*). All data are resolved to timescales considerably smaller than 25 m.yr. We use AutoSignal (ver. 1.7) for power spectra, but cross-spectra were computed with software written by A.L.M. The appendix contains more background discussion of cross-spectra.

Results

In figure 1, we show the residuals of marine $^{87}\text{Sr}/^{86}\text{Sr}$ and short-lived genera over most of the Phanerozoic. Their oscillations are visibly anticorrelated; the correlation coefficient is -0.53 and is significant at the level $P < 0.0000001$ against the possibility that noise in uncorrelated series could have given rise to the measured correlation coefficient. A value of -0.44 ($P \sim 0.005$) results when the same quantity is computed from the count of all marine genera in the independent Paleobiology Database biodiversity (Alroy 2008; Alroy et al. 2008).

Figure 2*A* shows the power spectrum (computed with AutoSignal 1.7) of the detrended $^{87}\text{Sr}/^{86}\text{Sr}$ fluctuations. The highly significant ($P < 0.001$) peak (frequency highlighted on all plots by an arrow marker) appears at 59.3 ± 3 m.yr., that is, within less than one joint standard deviation (the two standard deviations added in quadrature [the total is the square root of the sum of the squares] from the

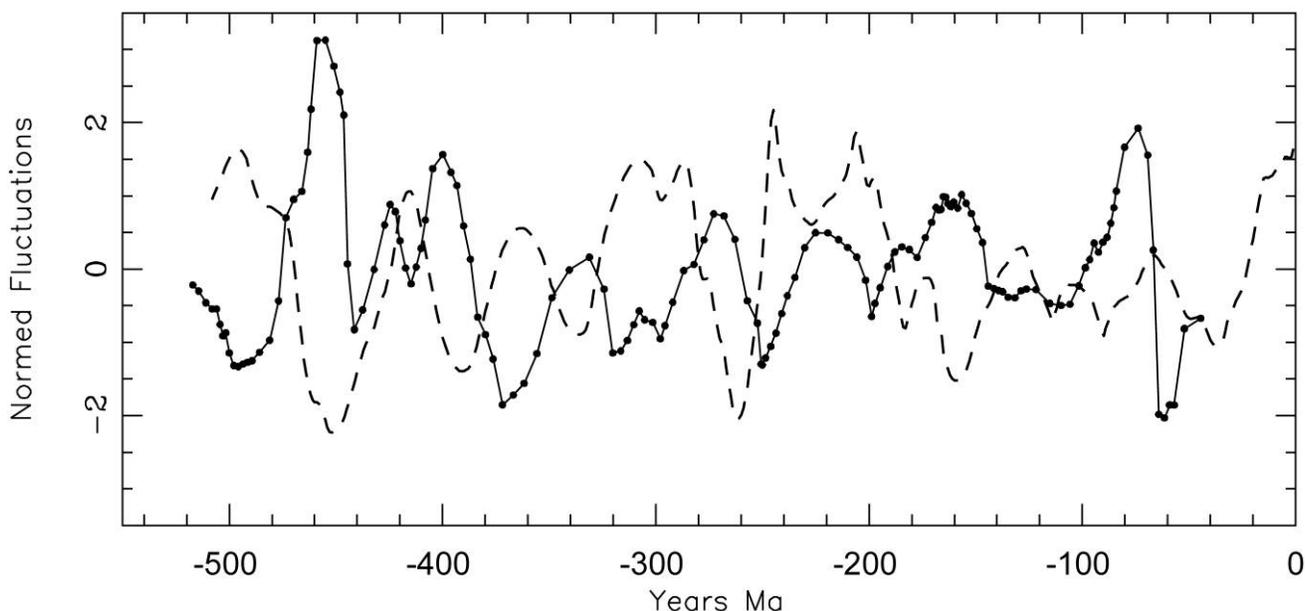


Figure 1. Diversity of genera that lasted less than 45 m.yr. and marine $^{87}\text{Sr}/^{86}\text{Sr}$ values. All curves have been detrended and divided by their standard deviation to put them on a common Y-axis range. The dashed line is the best fit to the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, and the solid line with points is the number of genera of short-lived fauna.

period of the biodiversity fluctuation; Rohde and Muller 2005; Melott and Bambach 2011a and references therein). Significance levels include taking account of the length of the record; end effects are removed by zero padding, detrending, and checking with the alternate method of tapered-cosine windows (Muller and MacDonald 2002; Press et al. 2007). The peak at about 60 m.yr. even appears in the power spectrum of the nondetrended curve.

In figure 2B–2D, we show the real part of (complex) cross-spectra, since all quantities are nearly in perfect phase or antiphase with one another (see appendix). Figure 2B displays the cross-spectrum of $^{87}\text{Sr}/^{86}\text{Sr}$ with biodiversity. The strong negative peak at ~61 m.yr. (X -axis value $0.0165 \text{ m.yr.}^{-1}$) is another representation of the anticorrelation seen clearly in figure 1. The components at the cross-spectral peak are 171° out of phase, where 180° would be perfectly so. The coherent fluctuation of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and marine biodiversity suggests that geological events with a period of ~60 m.yr. influence both and probably share a common cause. Note that the anticorrelation seen in figures 1 and 2B does not extend to all frequencies. For example, the $^{87}\text{Sr}/^{86}\text{Sr}$ curve (seen in fig. A1, available in the online edition or from the *Journal of Geology* office) has a long-term trend that is concave downward over the Phanerozoic. Biodiversity, on the other hand, appears to

rise, pause, and then rise some more over the same period. This means that the process that drives these variables in opposite directions is specific to a period of ~60 m.yr.

We next consider the periodicity in the number of sedimentary rock packages mentioned earlier. In an earlier article (Melott and Bambach 2011b), we found that carbonate packages exhibit a much stronger periodicity than do siliciclastic packages, so we regard this analysis of segregated lithologies as more robust than the analysis of Meyers and Peters (2011). The combined standard deviation of the biodiversity result and our carbonate package result, adding in quadrature, is 5 m.yr. At a 4-m.yr. difference in period, the two signals are less than one standard deviation apart in frequency. In figure 12 of Melott and Bambach (2011b), the two best-fit sinusoids are plotted together. It can be seen that they coincide closely in the mid-Permian. They are therefore most out of phase at the Cambrian (possibly as a result of dating ambiguity) and near the present (short-lived genera are undefined after 45 Ma).

In figure 2C, we show the cross-spectrum between $^{87}\text{Sr}/^{86}\text{Sr}$ and the number (area and temporal discreteness weighted) of gap-bound sedimentary packages documented from the United States (Peters 2006, 2008a). The data represent 541 composite

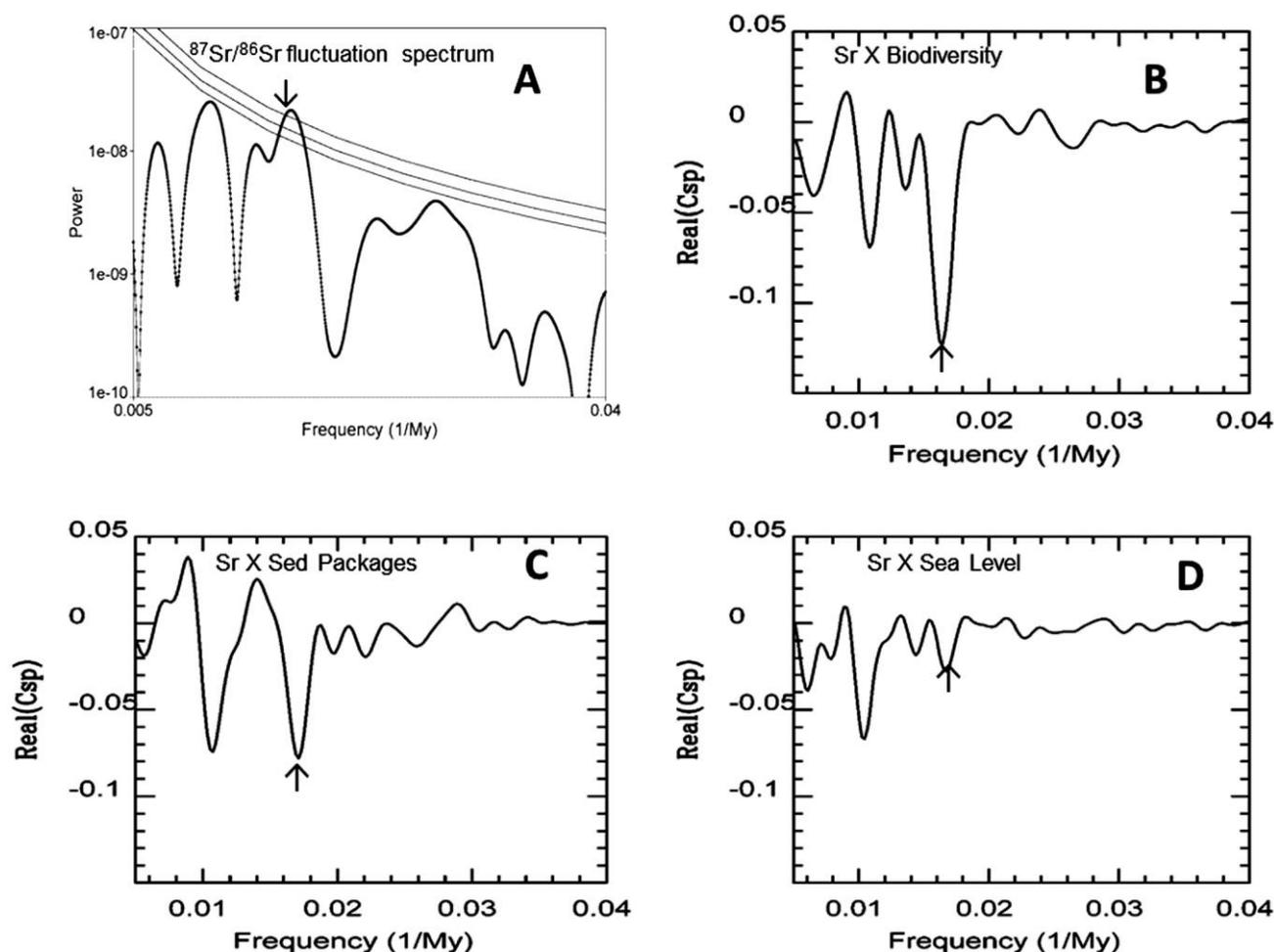


Figure 2. All four plots have semilog axes. *A*, Power spectrum of the fluctuations in detrended marine $^{87}\text{Sr}/^{86}\text{Sr}$ values. The *X*-axis label units are frequency, the inverse of the cycle time, as is customary with spectra. The parallel lines indicate significance levels of $P = 0.05$, 0.01 , and 0.001 , respectively. The peak at 59.3 ± 3 m.yr. is significant at $P < 0.001$ and is responsible for 28% of the variance in the detrended data. *B*, Real part of the cross-spectrum between detrended biodiversity of short-lived genera (62 ± 3 m.yr.) and $^{87}\text{Sr}/^{86}\text{Sr}$, showing a strongly negative peak at ~ 61 m.yr., which implies that biodiversity and the isotopic ratio oscillate out of phase on these timescales. *C*, Cross-spectrum between the detrended $^{87}\text{Sr}/^{86}\text{Sr}$ and the (area-weighted) number of marine gap bound sedimentary packages (period 58 ± 4 m.yr.). Note the existence of strong negative peaks at 58 and 92 m.yr., which are, again, out of phase between the two signals. More sedimentary packages being deposited at a given time means lower $^{87}\text{Sr}/^{86}\text{Sr}$ for variations on these timescales. *D*, Cross-spectrum of the $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios with sea level (Ogg and Lugowski 2010). The power spectrum of the sea level data alone has a broad peak at a period of 58–67 m.yr., but it is far too low to be considered significant (Melott and Bambach 2011*b*, their fig. 11). Some insignificant inverted phase oscillation occurs at a frequency of 60 m.yr., which may reflect contamination of the eustatic signal by correlated tectonic uplift effects. Stand-alone power spectra for biodiversity are shown by Melott and Bambach (2011*a*), and those for sedimentary packages (*C*) and sea level (*D*) are shown by Melott and Bambach (2011*b*, their figs. 10, 11; not repeated here).

stratigraphic columns covering the 48 contiguous United States and Alaska. They define 3221 sedimentary packages that are bounded by unconformities. It is the most complete continent-wide compilation of stratigraphic data available; see es-

pecially Peters (2006) for details of his compilation method. Additionally, he discusses the COSUNA (correlation of stratigraphic units of North America) charts used as a source of data (Peters 2006, p. 396–398). The numbers of these packages oscillate

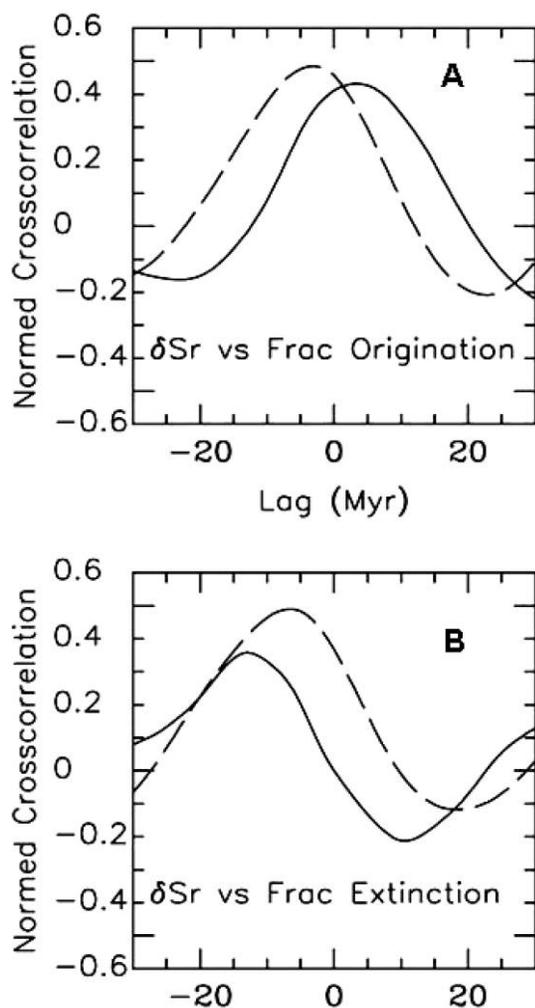


Figure 3. Cross-correlation as a function of lag in millions of years between detrended and normalized variables $^{87}\text{Sr}/^{86}\text{Sr}$ and fractional origination and extinction (origination or extinction divided by the total number of genera extant at a given stage) in our two paleontological data sets. Positive lag is defined as having the isotopic ratio change precede the biodiversity change. The solid lines represent the fraction of origination and extinction of short-lived genera in the Sepkoski (2002) data, as plotted in figure 1 of Melott and Bambach (2011a). The dashed lines represent similar analysis of the variables λ and μ , which describe extinction and origination rates in the Paleobiology Database, as specifically defined elsewhere (Alroy 2008; Alroy et al. 2008). *A* is origination, and *B* is extinction. Similar patterns are exhibited between the two independent and different data sets, confirming the robustness of the relationship with $^{87}\text{Sr}/^{86}\text{Sr}$. The common pattern confirms that the interaction of origination and extinction is needed to establish large swings in biodiversity and that both are correlated with $^{87}\text{Sr}/^{86}\text{Sr}$ fluctuations. The lines are shown over a lag interval of ± 30 m.yr. and are nearly periodic over the plot-

at 58 ± 4 m.yr. in-phase with biodiversity counts (Melott and Bambach 2011b; see also Meyers and Peters 2011) and is out of phase with $^{87}\text{Sr}/^{86}\text{Sr}$. For figure 2C, we combine carbonate and siliciclastic package data, since both are predominantly marine, but separate analysis of each (Melott and Bambach 2011b) shows that the former shows a larger amplitude peak at the same period. A peak near 0.01 m.yr. $^{-1}$ is also present and much more prominent than in figure 2B, suggesting that there may be a periodicity around 100 m.yr., which does not have a strong effect on biodiversity, in contrast to the one at 58 m.yr., which is prominent in figure 2B and 2C.

In figure 2D, we show the cross-spectrum of eustatic sea level with $^{87}\text{Sr}/^{86}\text{Sr}$. A peak at ~ 60 m.yr. is present but weak, because the peak for eustasy at this frequency is insignificant, although the one for the $^{87}\text{Sr}/^{86}\text{Sr}$ spectrum is strong. The eustasy data (from Ogg and Lugowski 2010) shows only a minor peak in phase with the strong periodicity in marine diversity (Melott and Bambach 2011b).

In figure 3, we show the cross-correlation with $^{87}\text{Sr}/^{86}\text{Sr}$ of fractions of origination and extinction in the two very different paleontological data sets we have used here. They exhibit very similar patterns, confirming that the correlation is robust and not dependent on any particular features of either data set. The data sets have different intervals. Since the Paleobiology Database has longer intervals, its curves are displaced as expected with respect to the Sepkoski data—we assigned originations to the beginnings of intervals and extinctions to the ends. Therefore, this timing is more accurate in Sepkoski data-based curves. Changes in the rate of both origination and extinction contribute to the correlation between biodiversity and $^{87}\text{Sr}/^{86}\text{Sr}$. A peak means a positive correlation, and a trough means a negative correlation. A positive lag means that the isotope ratio precedes the biodiversity. A negative lag means the opposite.

Figure 3A implies that origination is peaking at or just after the isotope peak, which is when biodiversity is a minimum. Figure 3B implies that extinction peaks 10–15 m.yr. before the isotope ratio

ted domain, further confirming the centrality of the ~ 60 -m.yr. periodicity in marine $^{87}\text{Sr}/^{86}\text{Sr}$. Extinctions were assigned to the ends of intervals in which the data were binned, and origination was assigned to their beginnings. This results in a time displacement of about 7 m.yr. between the curves on the basis of the two sets of data, since the Paleobiology Database data has a much longer mean interval.

peak (when biodiversity is on the way down). These results are fully consistent with our previous analysis (Melott and Bambach 2011*b*) of the role of origination and extinction in the biodiversity curves. It does not, however, imply that whatever causes these processes drives both origination and extinction directly. It is possible, for example, that the driver affects extinction rates and that extinction drives origination, since it opens a niche for new species.

Since diversity has a periodicity, it is important to see how the processes that generate diversity and diversity change (origination and extinction) relate to the Sr isotope pattern. The cross-correlation in figure 3 documents that both origination and extinction have a role in the periodicity. The relationship of the timing of origination peaks and extinction peaks with the timing of Sr isotope peaks (which negatively correlate with peaks of biodiversity) relate directly to determining the changes in biodiversity with origination peaks at or just after the isotopic peaks (which is when biodiversity is at a minimum) and extinction peaks 10–15 m.yr. before the isotope peaks (which is during the interval when diversity is decreasing). This pattern also of course connects to the record of number of gap-bound sedimentary packages (which is positively correlated to diversity) too, in that extinction is highest as that pattern is heading for a minimum. Although the last appearances of given genera may simply be timed with a loss of record, the fact that these genera never reoccur indicates that the actual extinctions occur during the low point in the record. Originations peak at the time when the record is poorest rather than when it is best.

Discussion

Variations in values of marine $^{87}\text{Sr}/^{86}\text{Sr}$ reflect the interplay of two major—and several minor—influences. The two strongest are continental weathering, which drives marine $^{87}\text{Sr}/^{86}\text{Sr}$ to higher values, and hydrothermal circulation at mid-ocean ridges, which drives it to lower values. The hydrothermal flux of Sr from mid-ocean ridges circulation is about half that of continental weathering (Elderfield and Schultz 1996, their table 9). The value of marine $^{87}\text{Sr}/^{86}\text{Sr}$ is therefore commonly taken as a proxy for the rate of continental weathering, either through glacial action (Armstrong 1971) or increased tectonism (Raymo et al. 1988; for dissenting views, see Halverson et al. 2007; Li et al. 2007). Our finding of a link between $^{87}\text{Sr}/^{86}\text{Sr}$ and the temporal variation in the number of marine sedimentary packages appears to favor the view

that the marine $^{87}\text{Sr}/^{86}\text{Sr}$ reflects mostly continental weathering, since changes in relative sea level would cause variation in the area of continent exposed to weathering and the deposition of marine sediments. Indeed, McArthur et al. (2001, their fig. 9) noted an overall correspondence between the volume of sedimentation through the Phanerozoic and the major features of the marine $^{87}\text{Sr}/^{86}\text{Sr}$ curve: both show Cambrian and Cenozoic maxima and a Mesozoic minimum.

When continental freeboard is high (and relative sea level is low), epeiric seas are absent or reduced in size, and fewer packages of marine sediments can accumulate on continental basement. Because the area of shallow seas can vary over time by an order of magnitude or more (Ogg and Lugowski 2010), and because of the low correlation with eustasy, we suggest that long-term tectonic processes, which are a likely source of the periodic fluctuation in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in seawater, are also responsible for the periodic waxing and waning in the number of sedimentary packages (Peters 2008*a*), with low $^{87}\text{Sr}/^{86}\text{Sr}$ at times of low continental freeboard and high numbers of sedimentary packages and vice versa (fig. 2*C*).

We further suggest that times of high continental freeboard and diminished areas of shallow shelf habitat (in which most of the fossil record is deposited) would increase the vulnerability of shallow water marine faunas to stress, especially taxa of limited geographic extent, limited environmental tolerances, or limited species richness. Since short-lived genera would include most of the genera with limited species numbers and limited geographic and/or environmental distribution (Jablonski 1989; Miller 1997), they would include the genera most likely to be vulnerable to regional uplift. Genera endemic to a region would be the most vulnerable, since large-scale regional uplift could encompass their entire geographic range. Although some bias in the diversity data may be from temporal fluctuation in the volume of the sedimentary record (more sediments mean more opportunity to find fossils), we have demonstrated (in Melott and Bambach 2011*b*) that the diversity pattern is real and is not an artifact of variable quality of the geologic record (see also Peters 2006, 2008*a*, 2008*b*).

The fact that equivalent periodic patterns of fluctuating characterize diversity of short-lived genera, numbers of marine sedimentary packages, and the value of marine $^{87}\text{Sr}/^{86}\text{Sr}$ reflects a signal we could call “the pulse of the earth.” The 171° phase angle difference means that $^{87}\text{Sr}/^{86}\text{Sr}$ is low when biodiversity and the number of sedimentary packages are both high. (The difference between 171° and

180° is well within about one standard deviation of the common timing.) As we will discuss, this may represent the “press” aspect of the press-pulse model (Arens and West 2008) of mass extinctions (Bambach 2006)—the idea that they result from periodic background stress combined with catastrophic events (Feulner 2011). Such a combination of forcings can explain the clustering of mass extinction events in the declining diversity phases of the 62-m.yr. periodicity pattern of fluctuating diversity shown by Melott and Bambach (2011*b*).

Uplift sufficient to cause significantly enhanced erosion of continental rocks is a regional tectonic phenomenon (e.g., mountain building). In addition, glaciation at lower elevations in high-latitude regions can pulverize old cratonic cores and enhance weathering of radiogenic basement (Montañez et al. 2000). Plate-tectonic closure of ocean basins eliminates marine habitats along the colliding coasts (Kearey et al. 2009). Similarly, major regional uplift of continental crust, associated with either crustal thickening or large-scale intrusions (e.g., Karoo sills and dykes; Jourdan et al. 2007), drains shallow seas from the uplifted region. The small signal found in eustatic sea level estimates (fig. 2*D*) may be due to contamination of the data by effects such as local or regional tectonism (Petersen et al. 2010).

We cannot rule out regional tectonism as a cause. The periodicity in the number of sedimentary carbonate packages shown by Melott and Bambach (2011*b*) and here in figure 2*C* is based on North American data. Could this explain a global signal? The $^{87}\text{Sr}/^{86}\text{Sr}$ signal is global not because the flux of Sr into the oceans is global but because Sr has a long residence time in seawater relative to the mixing time of the oceans (Hess et al. 1986). Thus, large regional fluxes of Sr to the ocean—from the weathering of the Andes, for example—will produce a “global” response in the $^{87}\text{Sr}/^{86}\text{Sr}$ of seawater that is potentially indistinguishable from a more spatially uniform pulse of Sr from intensified climate-driven weathering of the continents. Potential processes that may be regional in extent should not be overlooked.

There is a reported ~60-m.yr. periodicity in dates on emplacement of large igneous provinces (LIPs) for a few cycles over the past 320 m.yr. (Prokoph et al. 2004). The multiple effects of increased volcanic activity (added supply of sulfur, carbon dioxide, etc.; Devine et al. 1984), which accompany the genesis of LIPs (Saunders 2005), could in principle create another stress system (e.g., Sobolev et al. 2011) that might affect the diversity of vulnerable genera as well as $^{87}\text{Sr}/^{86}\text{Sr}$ without much af-

fecting eustatic sea level, which would be consistent with the nearly absent signal in figure 2*D*. Unfortunately, neither the significance level nor the phase of the signal in LIP emplacement times was reported by Prokoph et al. (2004). We have examined the power spectrum of LIP emplacement times in three separate compilations (Prokoph et al. 2004; Arens and West 2008; results from TimeScale Creator [Ogg and Lugowski 2010]). We found no significant periodicity at any timescale and especially no hint of any near 60 m.yr. (see fig. A2, available in the online edition or from the *Journal of Geology* office).

DeCelles et al. (2009) proposed that periodicity exists in the timing of Cordilleran-type orogens. Their period of ~40–50 m.yr. was based on visual inspection of geological time series, including Nd isotopes, but the existence of the periodicity is debatable, and requests to release the data for analysis have not been met.

So what might be the reason these phenomena are periodic in behavior? One possible internal earth source of the driver for periodicity is large-scale convective circulation of the mantle. Computational models support the potential for a presence of periodicity in such mantle convection. Periodic upwellings may arise from steady heating (Ribe et al. 2007). Fluid dynamics equations predict recurrence times (with great uncertainty based on uncertain viscosity) of a few tens of millions of years (Davaille and Vatteville 2005; Ribe et al. 2007; Müller et al. 2008). There is some laboratory experimental support for this sort of behavior (Schaeffer and Manga 2001).

Other hints of periodic behavior of the earth’s interior include evidence for coincident variation of widely separated mantle upwellings with a period of 15 m.yr. (Mjelde and Faleide 2009). Small-scale, sublithospheric mantle convection will affect surface movement (Petersen et al. 2010) and so regionally control relative sea level and patterns of erosion and deposition. It has been argued that uplift due to mantle convection provides an alternative to eustatic mechanisms for relative sea level change on timescales up to 100 m.yr. (Lovell 2010). If the mantle convection were periodic, as claimed on the basis of the computational models, this would explain periodic uplift, changes in continental freeboard, and sedimentation, with the observed absence of a significant periodic signal in eustatic sea level (Melott and Bambach 2011*b*). Since the $^{87}\text{Sr}/^{86}\text{Sr}$ signal is a global one, a globally synchronized periodicity in mantle convection would suffice—an idea that finds some support in the observations of Mjelde and Faleide (2009) that there has

been a synchronization of events between Iceland and Hawaii. Gyüre and Jánosi (2009) show that whole-mantle convection (rather than isolated up- and downwellings) with a period of a few tens of millions of years is the expected behavior.

Hints of periodic behavior of production of oceanic sea floor and, therefore, eustatic variation from changes in oceanic basin volume have been described (Becker et al. 2009), but we have been unable to find the claimed ~60-m.yr. period in that data. Other evaluations of sea-floor spreading rate for the past 140 Ma (e.g., Seton et al. 2009) differ considerably, so no firm conclusions can be reached about any periodicity in sea-floor spreading rates, although this is another system that likely plays a role in the phenomena we discuss.

Climate is another possible common driver of biodiversity, $^{87}\text{Sr}/^{86}\text{Sr}$, and deposition of sedimentary packages, since it can affect erosion rates (e.g., Li et al. 2007). There is intense debate over the relative contributions of tectonics and other erosion to $^{87}\text{Sr}/^{86}\text{Sr}$ change (Molnar and England 1990; Egholm et al. 2009; Dowdeswell et al. 2010), but effects of increased erosion and subsequent uplift due to unloading by retreat of ice caps will affect both $^{87}\text{Sr}/^{86}\text{Sr}$ and continental freeboard. This driver is potentially interesting because there are possible climate drivers that have a built-in periodicity at ~62 m.yr. Medvedev and Melott (2007) have shown that the oscillation of the solar system normal to the galactic disc with a period of ~62 m.yr. should result in increased exposure to high-energy cosmic rays when the earth is north of the galactic disc (north taken as the maximum of galactic latitude, in the general direction of the Virgo Cluster). Atmospheric ionization caused by such cosmic rays has been proposed as a causal agent in changing ter-

restrial cloud cover (Melott et al. 2010) and in changing the frequency of lightning (Erlykin and Wolfendale 2010). Climate change particularly at high altitude may change erosion rates and the ^{87}Sr flux into the oceans. Calculations indicate that radiation propagating to the ground may be sufficient to significantly increase the radiation load from muons on organisms on the surface and the top ~1 km of ocean (Atri and Melott 2011a, 2011b). This is a speculative but physically reasonable mechanism to lower biodiversity that gives the right period and phase, based on solutions of the motion of the solar system in the galaxy (Gies and Helsel 2005).

The data and our analyses document that a highly regular periodic process affects both the evolution of life in the oceans and some geochemical and sedimentary systems. While we have hints that can connect tectonic systems (or possibly astronomical ones) to these earth surface phenomena, we are left with a theoretical challenge: we have no exclusive theory for periodic processes internal to the earth. What is the driving mechanism, and why is it periodic in effect?

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