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Cycles in Fossil Diversity

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It is well-known that the diversity of life appears to fluctuate during the course the Phanerozoic, the eon during which hard shells and skeletons left abundant fossils (0-542 Ma). Using Sepkoski's compendium[1] of the first and last stratigraphic appearances of 36380 marine genera, we report a strong 62 ± 3 Myr cycle, which is particularly strong in the shorter-lived genera. The five great extinctions enumerated by Raup and Sepkoski[2] may be an aspect of this cycle. Because of the high stastical significance, we also consider contributing environmental factors and possible causes.

Sepkoski's posthumously published *Compendium of Fossil Marine Animal Genera*[1], and its earlier versions, has frequently been used in the study of biodiversity and extinction[3-4]. For our purposes, diversity is defined as the number of distinct genera alive at any given time, i.e. those whose first occurrence predates and last occurrence postdates that time. Because Sepkoski references only 295 stratigraphic intervals, the International Commission on Stratigraphy's 2004 time scale[5] is used to translate the stratigraphic records into a record of diversity vs. time, with details given in the supplement. Though Sepkoski's is the most extensive compilation available, it is known to be subject to certain systematic limitations due primarily to the varying availability and quality of geologic sections[6-7], the implications of this will be discussed where appropriate.

Fig. 1A shows diversity vs. time for all 36380 genera in Sepkoski's compendium. In Fig. 1B we show the 17797 genera that remain when we remove those with uncertain ages (given only at epoch or period level), and those with only a single occurrence. The smooth trend curve through the data is the third-order polynomial that minimizes the variance of the difference between it and the data. The overall shape of 1A and 1B is similar to those previously published for fossil families[2] and for genera[3]. It rises rapidly at the beginning of the Phanerozoic (right side), drops to a nadir near the Permian-Triassic boundary (251 Ma), and then rises steeply until the present. These variations may result from evolutionary and environmental drivers[8], observational biases[6], or changes in the number of available geologic sections[7]; for example, the sharp rise towards the present may be driven by the greater availability and study of recent sections.

Our focus is not on the trend but on the short-term variations shown in 1C, obtained by subtracting the trend from 1B. The Fourier spectrum of 1C is shown in 1E. It is dominated by a strong peak with period 62 ± 3 Myr (frequency 0.016 cycles/Myr). The sine wave corresponding to this cycle is also shown in Fig. 1C, where it accounts for 35% of the variance. Note that because steep drops in diversity are often followed by gradual recoveries, the peaks and valleys in the data don't precisely align with those of the sine curve. Also, some abrupt features may appear more gradual because of incomplete records.[9] We indicate the 5 major extinction events of Raup and Sepkoski[2] by dashed lines. They all occur during declining phases of the 62 Myr cycle, suggesting that the 62 Myr cycle may have influenced the timing or magnitude of these extinctions.

Fig. 1E has a second spectral peak, with period 140 ± 15 Myr (frequency 0.007 cycles/Myr). To show this cycle directly in the diversity data, we subtracted the 62 Myr sine wave from 1C; the result is shown in 1D. This procedure of subtraction and reanalysis follows the maximum likelihood approach advocated by MacDonald.[10]

To determine the statistical significance of the cycles, we estimated background in two ways. In model R, we assume that all diversity changes reflect a random walk, and simulate this using random permutations of the steps in Fig.1B. Thirty thousand Monte Carlo simulations were detrended (3rd order polynomial) and analyzed; their average spectral power is the red line R in Fig. 1E. For model W, we broke the detrended data from 1C into 20 groups and scrambled their order, thus preserving short-term correlations, but randomizing the placement of major events. Thirty thousand Monte-Carlo simulations yielded the flatter blue background W. This is a more appropriate background estimate than R if the fluctuations represent perturbations about an independently driven slow trend. Based on these backgrounds, the probability of observing peaks at least as strong as the 62 and 140 Myr spectral peaks were computed and are shown in Table 1. In doing so we considered both the significance of finding the indicated peak at the specified frequency and more generally the probability of finding a similar peak at any frequency. With no more than a 1% chance of a similar feature occurring anywhere in the spectrum, the 62 Myr peak is clearly significant. By contrast, the 140 Myr peak can plausibly result from purely random processes and this is likely if diversity dynamics reflect R-type behavior. Further technical details of this computation appear in the supplement.

The possible presence of an ≈ 60 Myr cycle in fossil data had been suggested by Thomson[11-12] and by Ager[13], but they performed no statistical analysis to confirm their qualitative observations. In fact, when we use the older 1989 time scales on the present fossil data, we find that the 62 Myr peak is not statistically significant. Different parts of the record shift in phase and cancel each other.

While unexpected, and of ambiguous significance, we do note that the 140 Myr cycle is consistent with the periods of other cycles reported in climate[14] and cosmic rays[15], and on those grounds may warrant further investigation. We also note that several authors[16-17] have reported cycles of 26-32 Myr in diversity or extinctions. While the 62 Myr cycle is the dominant cycle in Sepkoski's diversity data, the existence of secondary features in the middle of some cycles (Silurian, Upper Carboniferous, Lower Jurassic, Eocene) may have influenced previous reports of this ~30 Myr cyclicity.

A particularly simple way to enhance the 62 Myr cycle is to separate the diversity of the 13682 "short-lived" genera, those that endured ≤ 45 Myr, from the "long-lived" ones. This is shown, without detrending, in Figure 2. While the short-lived genera represent, on average, 44% of the diversity at any instant in the geologic record, they are responsible for 86% of the amplitude in Fig 1C. By contrast, the long-lived genera show few significant variations and only strongly participate in one extinction, the Permian-Triassic. We note from Fig 1C and 2A that the 62 Myr cycle is somewhat less regular and well-developed during the last ~150 Myr. It is unclear whether this represents a change in the cycle or merely an obscuring effect due to the large apparent increase in total diversity during this time.

To understand the 62 Myr cycle, it is necessary to consider environmental and causal factors that may be involved. However, given the large sampling biases affecting Sepkoski's work[6-7], we must also acknowledge that the cycle might be driven by a physical process affecting the fossil record, such as changes in sedimentation, rather than a process which directly impacts diversity. One potential concern is that the durations of several geologic periods (Carboniferous, Devonian, Ordovician + Silurian) are ~60 Myr, suggesting that the 62 Myr cycle might be an artifact of the choice of period boundaries. However, most period boundaries were defined by major biological and geological events long before their ages were known. This suggests that any regularity in period durations is likely to be a response to the periodic changes influencing the diversity, rather than its cause.

Other geophysical records

To help understand the cycles, we examined the following geophysical records:

1. **Glaciation.** Veizer et al.[14] found a strong cycle in $\delta^{18}O$, a proxy for glaciation and climate, with period of ~135 Myr, statistically indistinguishable from our 140 ± 15 Myr cycle. Cold periods in $\delta^{18}O$ precede our 140 Myr diversity maxima by 20 - 25 Myr. A 140 Myr cycle has been reported in other glacial indicators, although the results are disputed.[15,18,19]
2. **Geochemical cycles.** $\delta^{13}C$ is a proxy for biomass, and the $^{87}Sr/^{86}Sr$ ratio in marine fossils can reflect continental crust erosion (which in turn reflects climate change) and major vulcanism; however spectral analysis shows no statistically significant 62 or 140 Myr cycle.[20]
3. **Sea Level** changes[21] have been associated with extinctions[22]. Extreme sea-level states correspond to some extremes in our 62 Myr cycle, but not in a consistent way: low stands during the Quaternary, Permian-Triassic and Cambrian-Vendian boundary as well as the high stand during the middle Cretaceous fall on lows and highs of the 62 Myr cycle respectively. Spectra of sea level records[21] show peaks near the 62 and 140 Myr periods, but with low statistical significance.
4. **Vulcanism** is frequently invoked as a possible cause of mass extinctions. Wavelet analysis on the ages of large igneous provinces[23] shows a minor feature near 60 Myr but with marginal significance, and no cycle near 140 Myr.
5. **Impact records.** Ages of impact craters on Earth[24] show no significant periodicity at 62 or 140 Myr, though it is widely believed that many moderate size craters have never been discovered.
6. **Geologic Formations.** Records of the number of explored geologic formations[7] show no 62 or 140 Myr periodicity though poor resolution could obscure such cycles.
7. **Cosmic rays.** Shaviv[15] reported a 143 ± 10 Myr cycle in meteorite ages, and attributed it to variation in cosmic ray flux.

Our searches found no compelling match for the 62 Myr cycle; however, incomplete records and errors in time scales can obscure true periodicity. The match of our 140 Myr diversity cycle to the climate/glacial/cosmic ray cycle may be real, since having a peak at exactly that frequency is still relatively unlikely, however less ambiguous data would be needed to establish the connection and explain the relatively large lag between the diversity and climate cycles.

Possible causes

The 62 Myr cycle is strong. It might be an intrinsic effect of evolution or a variation in preservation; in either case, it is worth considering other geophysical processes that could be driving it:

1. **Galactic mass regions**. Long period comets are deflected into the inner solar system primarily by gravitational tides from galactic mass concentrations[25]. Thus, periodic passage of the solar system through molecular clouds, galactic arms, or other structure could cause periodic variations in impacts on the Earth. Shaviv[15] has argued that a 140 Myr period between spiral arm crossings is consistent with existing astrophysical constraints.
2. **Mantle Plumes**. Laboratory simulations of mantle plumes, under idealized conditions, show relaxation oscillator modes in which plumes reach the surface at regular intervals for 6 to 9 cycles[26]. Similar behavior in the Earth could cause periodic vulcanism.
3. **Oscillations in the Galactic Plane**. The sun currently oscillates up and down across the galactic plane every 52-74 Myr[27] but the mid-plane crossings occur every 26-37 Myr, and plausible responses would seem to have this shorter period[25]. Moreover, the period is not constant, but drops to half when we pass near higher density galactic arms.
4. **Solar cycles** could affect climate, but solar theory[28] predicts that long period oscillations do not occur.
5. **Earth Orbital Oscillations** could affect climate. Using an orbital integration package[29] and 9 point-mass planets, we found no significant cycles with periods of 62 or 140 Myr. Changes in obliquity were not included in our calculations.
6. **A companion star(s) to the Sun** could trigger periodic comet showers. However a 62 Myr orbit is unstable to perturbations from passing stars. The interaction of two or more short period companions could generate a longer periodicity (e.g. through beats), but our simulations showed that mutual perturbations would likely destroy any regularity.
7. **Planet X** is a hypothesized large planet that perturbs the Kuiper Belt and could yield periodic comet showers on the right time scales.[30] No evidence for it exists.

Though no explanation exists, the 62 Myr cycle is not a subtle signal. It is evident even in the raw data (Fig 1A), dominant in the short-lived genera (Fig 2), and strongly confirmed by statistical analysis. We don't know if this cycle is a variation in true diversity or only in observed diversity, but either case requires explanation and implies that an unknown periodic process has been having a significant impact on Earth's environment throughout the Phanerozoic. Most models seem to make testable predictions, so we are hopeful that the cause of this behavior will not remain a mystery for long.

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Figure captions

Figure 1. Genus Diversity. Plot A (green) shows the number of known marine animal genera vs. time from Sepkoski's compendium[1], converted to the 2004 Geologic Time Scale[5]. Plot B (black) is the same with single occurrence and poorly dated genera removed. The trend line (blue) is a 3rd order polynomial fit to the data. Plot C is B with the trend subtracted and a 62 Myr sine wave superimposed. Plot D is the detrended data after subtracting the 62 Myr cycle and with a 140 Myr sine superimposed. Dashed vertical lines indicate the times of the five major extinctions enumerated by Raup and Sepkoski[2]. The Fourier spectrum of B is shown in E. Curves W (in blue) and R (in red) are estimates of spectral background. Conventional symbols for major stratigraphic periods appear at the bottom.

Figure 2. Diversity of Short and Long Lived Genera. This plot shows, with no detrending, the diversity of all genera that have both a first and last appearance resolved at the stage or substage level, and either persisted for ≤ 45 Myr (plot A) or > 45 Myr (plot B). Genera with only single occurrences were excluded. Vertical dashed lines indicate the times of maxima of the 62 Myr sine wave of Fig. 1C. Conventional symbols for major stratigraphic periods appear at the top.

Table caption

Table 1. Likelihood of Similar Cycles. The probability of observing the 62 and 140 Myr cycles given the R or W background models as described in the paper. These are stated both in relation to finding the spectral peak in its current position and as the probability of finding a similar peak anywhere in the spectrum. Details appear in the supplement.

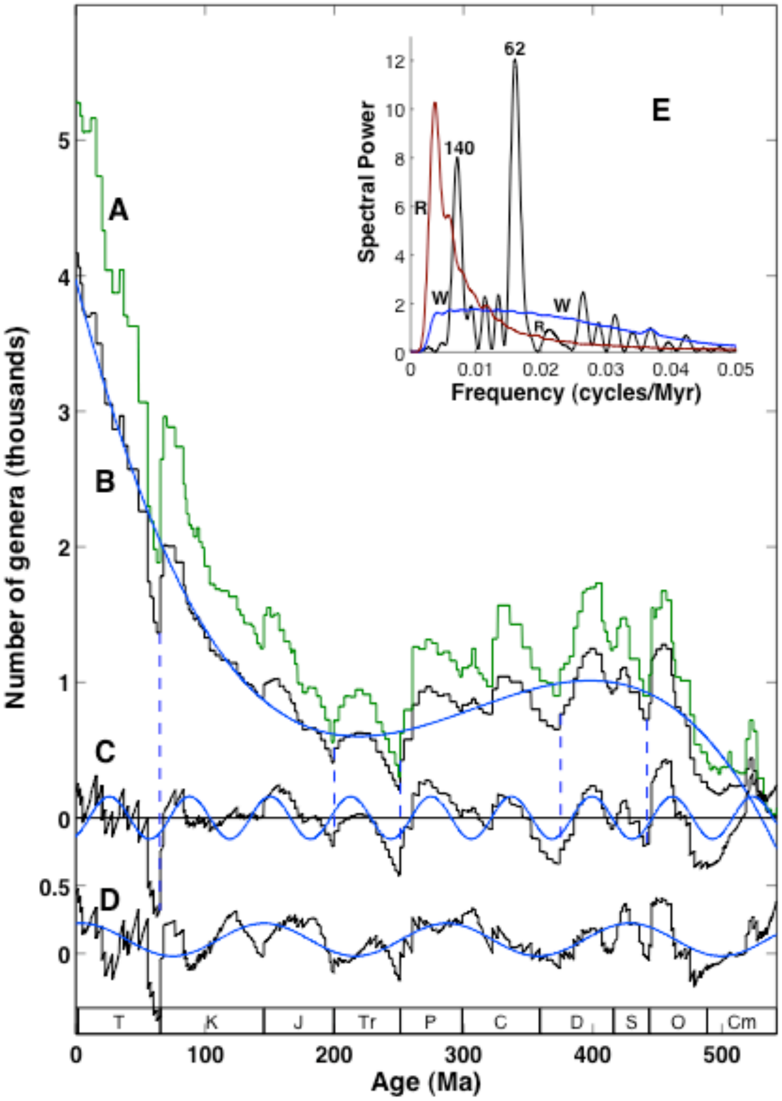
A
B
C
D
E
Number of genera (thousands)
5
4
3
2
1
0
0.5
0
Spectral Power
12
10
8
6
4
2
0
62
140
R
W
W
R
0
0.01
0.02
0.03
0.04
0.05
Frequency (cycles/Myr)
T
K
J
Tr
P
C
D
S
O
Cm
0
100
200
300
400
500
Age (Ma)

Figure 1.

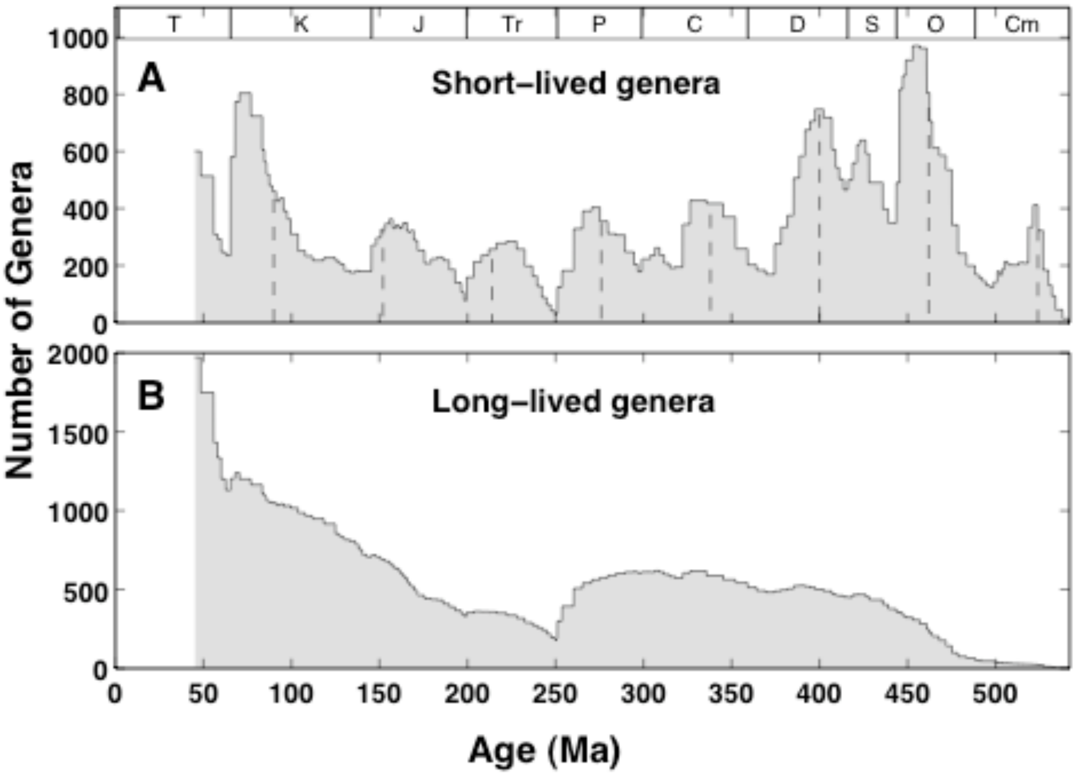
T
K
J
Tr
P
C
D
S
O
Cm
A
Short–lived genera
B
Long–lived genera
Number of Genera
0
200
400
600
800
1000
0
500
1000
1500
2000
0
50
100
150
200
250
300
350
400
450
500
Age (Ma)

Figure 2.

Probability of Peaks	At this frequency		Anywhere in spectrum	
	R	W	R	W
62 Myr	< 5E-5	3.6E-4	< 0.0013	0.010
140 Myr	0.12	0.0056	0.71	0.13

Table 1