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MASS EXTINCTIONS OVER THE LAST 500 MYR: AN ASTRONOMICAL CAUSE?

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Abstract: A Fourier analysis of the magnitudes and timing of the Phanerozoic mass extinctions (MEs) demonstrates that many of the periodicities claimed in other analyses are not statistically significant. Moreover we show that the periodicities associated with oscillations of the Solar System about the Galactic plane are too irregular to give narrow peaks in the Fourier periodograms. This leads us to conclude that, apart from possibly a small number of major events, astronomical causes for MEs can largely be ruled out.

Key words: mass extinctions, periodicity, astronomical processes, Phanerozoic

INTRODUCTION

The cause (or causes) of mass extinctions (MEs) of marine and terrestrial biological genera has been debated for many decades (see Hallam 2004) and there is, not surprisingly, an extensive and impressive portfolio of research in this area (see for example, McLeod 2014, together with Bond and Grasby 2017 for more recent reviews). Insofar as the problem is germane to understanding the evolution of life on Earth, its solution is important.

The cause can either be firstly, astrophysical, such as the impact of asteroids, or secondly, terrestrial, due to changes in habitat together with drama induced by climate change and plate tectonic movements, or both. Our aim here is, specifically, to determine or not the astrophysical influence on MEs and the Earth's ecosystems through deep time.

Periodicity in fossil range data, in a loose sense, has been recognised for some time (Newell 1952). The initial quantification, however, of periodicity in marine mass extinctions (Raup and Sepkoski 1982) prompted a range of astronomical explanations: The Sun's oscillation about a Solar plane (Schwartz and James 1984), oscillation of the Solar System vertically about a galactic plane (Rampino and Strother 1984), the presence of a distant Solar companion, Nemesis (Davis *et al*. 1984; Whitmire and Jackson 1984), the existence of a tenth planet (Whitmire and Matese 1985), i.e. beyond the orbit of Pluto, and periodic comet showers (Alvarez and Muller 1984). To these can be added some earlier explanations, prior to the Raup and Sepkoski analysis, including periodic doses of cosmic rays (CR) controlled by reversals in the Earth's magnetic field (Hatfield and Camp 1970) and climate change based on fluctuating Solar energy and rhythms in mantle convection and associated processes (Fischer 1977). The concept of periodicity, however, has not received universal acceptance. In a critique of the flurry of astronomical papers, Hallam (1984) noted the many terrestrial causes of mass extinction including climate and sea-level changes together with volcanicity while emphasising the shortcomings of the Fossil Record at that time in providing an accurate time frame. Benton's (1993, 1995) updated analysis of the Fossil Record (Harland *et al.* 1967) indicated that only three of the ten peaks cited by Raup and Sepkoski (1984) were real mass extinctions and his data did not validate the other peaks. Many of these claims thus were dismissed due to inadequate data and poorly calibrated time scales (e.g. Patterson and Smith 1987). In a series of key studies Bambach (2006) and his colleagues (Bambach *et al.* 2004) re-evaluated the data, stating firstly there were only three major (or big) MEs in the Fossil Record (end Ordovician, end Permian and end Cretaceous) and secondly that ME events were not homogeneous, suggesting the lack of a common effect and causation. In addition palaeontological textbooks on both sides of the Atlantic (e.g. Benton and Harper 2009; Foote and Miller 2007) have paid scant attention to periodicity as a key pattern in the history of life. Thus the growing body of evidence suggested that each major ME was different and there was no common cause (e.g. Bambach *et al.* 2004; Bambach 2006; Brenchley and Harper 1998). Extinctions, moreover, were clearly episodic, a series of separate events, rather than periodic, occurring at regular intervals.

Within the last decade there has been a renewed interest in periodicity with better calibrated time-series data, larger databases of taxon-range information at the genus level and more sophisticated analytical techniques. Periodicities in fossil-range data have been re-established by a number of author groups predicting causality from coincident periodic processes, some astronomical. For example, Rohde and Muller (2005) demonstrated a 62 ± 3-million-year cycle, which is particularly evident in the shorter-lived genera. More recently, Melott *et al.* (2010) similarly described a 62±3 myr cycle, associated with cosmic rays (CR); Melott and Bambach (2011a) noted a 62 myr cycle with the signal strength decreasing in time due to the accumulation of long-lived genera; Melott and Bambach (2011b) favoured periodic sea-level change or astronomical causes to explain that cycle; Melott *et al.* (2012) linked the biotic data to a 59.3±3 myr cycle in the strontium isotope record that may be associated with mantle or plate tectonic events; Melott and Bambach (2010) calculated a 27 myr cycle that ruled out the influence of the distant Nemesis; finally in a recalibrated dataset with reference to the most recent geological timescale (Gradstein and Ogg 2012), 27 and 62 myr cycles have been detected shifting in and out of phase (Melott and Bambach 2013,2014). The causes are unknown. In addition a 56-myr rhythm has been identified in sedimentary cycles during the Phanerozoic in North America (Meyers and Peters 2011) and developed in terms of marine biodiversity change and its relationship to ocean redox conditions and long-term sea-level fluctuations driven by plate tectonics (Hannisdal and Peters 2011). Two areas, however, have particularly enlivened the debate: Firstly, Rampino (2015) and Rampino and Caldeira (2015) have re-introduced the coincidence of asteroid craters with mass extinction events, noting a 26-30 myr cycle for extinctions and 31±5 myr for cratering. Secondly, this apparently matches the Sun's vertical oscillations through the galactic disc (32-42 myr) between crossings, invoking the influence of the mid-plane Oort Cloud and a dark matter disc, the latter providing a topical connection between the evolution of life, extinctions and events in space (Randall 2015). These studies suggest that both biological and geological evolution on Earth may be controlled by a periodicity in Galactic dynamics.

In order to investigate further the reality of periodicity and its relevance for the history of life on Earth, we start by examining the time series of MEs from the work of Bambach (2006), Melott and Bambach, (2011, 2013 and 2014) which gives the proportion, P, and age of each genus extinction as shown in Figure 1. There are two widely used databases (see McLeod 2014). The much-updated range distribution of families and genera initiated and established by the late Jack Sepkoski (http://strata.geology.wisc.edu/jack/), and the occurrence database that forms the basis for the Paleobiology Database (https://paleobiodb.org/#/). We have chosen to analyse the former, firstly since both databases appeared to perform similarly in time-series analysis (Melott and Bambach 2014) and secondly through the kindness of Dr Richard Bambach that database, updated where relevant particularly taking account of new absolute age constraints, was made available to us. In all there were 163 genus extinction events, with 147, if the large extinction peaks around 250 Ma and >470 Ma are excluded (see below). The distribution of *P*-values is examined and forms the basis for discussion. This is followed by a search for periodicities in the *P*-record and also in 37 meteorite craters by Fourier analysis. The significances of the peaks in the Fourier periodograms are examined in some detail and conclusions drawn.

Additional, complementary and confirmatory analyses of more historic data sets provided by Shanan Peters together with Rohde and Miller, online supplementary material (see http://www.annualreviews.org/doi/suppl/10.1146/annurev.earth.33.092203.122654) are noted below and the details provided in Supplementary Material.

ANALYSIS OF THE GENUS EXTINCTION PROPORTIONS THROUGH TIME (P)

As is well known, the mean *P*-value increases with age in an approximately linear fashion (see Figure 1, solid (dashed) line excludes (includes) the large extinctions around 250 Ma and >470 Ma). Linear fits give a reasonable representation of the data and these are adopted rather than more complicated ones. There are, however, large deviations from the median line. Figures 2(a) and 2(b) show the frequency distribution of ΔP, the displacement of the *P*-value from the two linear fits shown in Figure 1. The solid smooth curves in Figures 2 show a maximum likelihood fit to the data of a Gaussian distribution plus an exponential tail; a Gaussian being a natural curve to fit, not least because it fits so well for negative delta-*P* values. Good fits were obtained with the value of the Pearson test statistic $\chi^2 = 10.9$ for 13 degrees of freedom in Figure 2(a) and $\chi^2 = 18.4$ for 13 degrees of freedom in Figure 2(b). The data at ages beyond 470 Ma have very large positive and negative fluctuations from the linear fit and therefore seem somewhat anomalous, perhaps reflecting the instability and lack of resilience of the Cambrian ecosystem, its different composition and structure (Bambach 1983, 1985; Bush and Bambach 2011). However, Figure 2(b) shows that if the whole age range is fitted, similar results are obtained to those up to age 470 Ma in Figure 2(a) with the exponential tail approximately doubled in amplitude mainly because of the addition of the large ME values beyond 470 Ma. Hence we conclude that the data are well represented by a Gaussian distribution and an exponential tail.

The implication of such a Gaussian form at small values of ΔP is that each *P*-value is the resultant of smaller scale, i.e. less catastrophic events. For $\Delta P > 0.1$ the Gaussian component is negligible and the exponential tail dominates; this strongly suggests contributions from mechanisms which caused more catastrophic damage.

THE SEARCH FOR PERIODICITIES

Fourier analysis

Much has been written about Fourier analysis and the statistical methods used to judge the significance of any result. Omersbashich (2006) showed that, if a Gauss-Vanicek spectral analysis of the same data used by Melott (2010) to deduce the presence of their 62 myr peak, the peak disappears. This shows that manipulation of data can introduce biases. In this paper we adopt a simple approach which does not need binning, manipulation of the data to fill in gaps or interpolation to fixed time intervals. The avoidance of such data manipulation should lead to fewer biases in the analysis. However, to avoid generating spurious peaks in the Fourier analysis some detrending of the data is necessary. Here we adopt the simplest method of subtracting the appropriate trend line shown in Figure 1. Detrending by more complicated curves such as polynomials would only reduce the significance of any Fourier peaks and thereby may lead to valuable information being discarded.

The Fourier integrals for a particular angular frequency ω are deduced by simply averaging the readings. Thus:

$$R(\omega) = \frac{2\Delta T}{N}\sum_{i=1}^{N} \Delta P_i \cos \omega t_i \quad \text{and} \quad I(\omega) = \frac{2\Delta T}{N}\sum_{i=1}^{N} \Delta P_i \sin \omega t_i$$

where ΔP_i is the deviation of the *P* value from the trend line of the event at age t_i, *N* is the total number of events considered and ΔT is the total time range over which the sample of data is taken. The absolute amplitude of the Fourier component with frequency ω is then given by

$$A(\omega) = \sqrt{}(R(\omega)^2 + I(\omega)^2)$$

In order to judge the significance of any observed peak, random values of the P_i and t_i were generated and passed through the analysis programme. The process was repeated many times and the significance of a peak in the data is judged by the number of occurrences of peaks from the random distribution with greater amplitude and therefore significance than the one observed in the data.

Periodicity in the time series of the* P*-values

There is a wealth of literature on claims for periodicities in the extinction records (see above), with periodicities ranging from 13 to 64 myr (Bambach 2006). 27 myr is currently favoured, marginally, but this is largely because the perceived frequency of the Solar System oscillating around the Galactic Plane is of a similar magnitude (Bahcall and Bahcall 1985; Shaviv 2002a,b).

Figures 3(a-c) show periodograms from Fourier analyses of the genus extinction proportions with age from Bambach (2006) shown in Figure 1. Since the craters are only assigned unit weight, Figures 4(a-c) show for comparison similar periodograms of the extinctions with each given unit weight rather than weighted by the genus proportion*, ΔP*, as in Figure 3. The data are shown separately for the periods 1-250 myr and 270-470 myr which each correspond roughly to one orbit of the solar system around the Galaxy. Various peaks occur including peaks around a period near to 27 myr. To see if the large groups of extinctions around 260 Ma and 500 Ma affect the Fourier analyses they are excluded from Figures 3(b) and (c) and 4(b) and (c) but they are included in Figures 3(a) and 4(a). Comparison shows that the effects of these peaks on the Fourier analysis are insignificant.

To check the statistical significance of the peaks in Figures 3 and 4, random genus proportions and dates were passed through the analysis chain. The random events were generated with a distribution of genus proportion of a similar shape to the data (Figure 2) about the trend line. The process was repeated 1000 times. It was observed that 10% of the random extinction data had peaks which were larger, i.e. more significant than those seen in the vicinity of 27 myr in Figures 3(a-c) and 60% of those in Figures 4(a-c). These fractions show that the observed peaks in the data have limited statistical significance. It is therefore plausible that the peaks are the results of statistical fluctuations rather than a repetitive physical process for either the genus proportion (Figure 3) or single events (Figure 4). Other factors which show that the 27 myr peak is unlikely to be related to an astrophysical mechanism of any known kind are as follows:

1. The peak in the region of 27 myr is present only for the interval 1-250 Ma in Figure 3(b). It has a different character in time range 270-470 Ma in Figure 3(c). (Note that the time for the Solar System (SS) to orbit the Galaxy is of order 250 myr). If the signal were real, the peak value should be similar in each time range;

2. The wide range of other peaks at periods with no astrophysical significance means that the cluster around 27 myr could be accidental and not related to a repetitive astrophysical source;

3. As shown elsewhere (e.g. Wolfendale and Wilkinson 1988), there is no evidence, nor theoretical justification, for precise ‘bursts’ of asteroids or comets when the SS crosses the Galactic Plane;

4. Similarly, Cosmic Ray (CR) effects are negligible insofar as changes in the CR intensity variation over the 500 myr interval should be too small to produce MEs (Bailey *et al*. 1987; Shaviv, 2002a,b; Sloan and Wolfendale 2008, 2013 and references therein).

As noted above two additional, albeit historical, data sets were also analysed (see Supplementary Material for details). Fourier analyses of the Bambach dataset generated in detail herein and those for the Rohde and Muller together with Peters data show large peaks at the following frequencies: [24, 27, 38, 47 and 60 myr], [24.5, 27, 38, 48, 61 myr] and [25, 27, 38, 47 and 62 myr], respectively. All three datasets display their major peaks with probabilities >10% that they occurred by chance, and thus are not significant. Understandably, the heights of the peaks differ across the analyses, but the shapes of the distributions (N> P vs P) are the same.

The variability of the oscillation period of the Solar System

The Solar System (SS) in its orbital journey round the Galaxy oscillates above and below the Galactic plane. It encounters different concentrations of mass in this journey, e.g. it moves into and out of the spiral arms of the Galaxy. In consequence it is continually accelerating and decelerating. Hence its period and phase are rather variable. Phenomena which cause variations in period and phase from one oscillation to the next and, thereby 'jitter' in the periodicity, are listed as follows (the references in brackets refer to the source of data used to calculate the standard deviation in the period).

1. Stellar mass density varies from place to place by about 40% during the orbit of the SS leading to a 20% variation in period (Scheffer and Elasser 1992). (A simple model consisting of a uniform slab of matter shows that the oscillation period varies as the square root of the density in the Galactic plane);

2. Dark Matter. There are two effects. Firstly the effect on the total mass density and, secondly, the effect of discrete 'clumps' in deflecting the orbit. Insofar as the total mass of dark matter in clumps is probably about 10% of the total mass, the effect on the period is not negligible. Using data from Charbonnier *et al.* (2012) we estimate a 10% variation in the oscillation period of the SS about the Galactic plane from such clumps. In fact, the data referred to indicate a 'significant collision' every 50 myr. Furthermore, reference needs to be made to the thin disk of Dark Matter model of Randall and Reece (2014). Such a thin disk could cause further changes in the oscillation period of the SS about the Galactic plane as well as leading to several problems such as the effect on stellar dynamics.

Taking these factors together it is estimated that the period of successive oscillations varies by at least$\pm 20\%$. Such variability in the period will influence any Fourier amplitude peak which is caused by a repetitive process such as repetitive crossings of the Galactic plane.

The sensitivity of the Fourier analysis to the variability of the sinusoidal period was investigated by passing through the analysis programme samples of events generated at random times with a pure sine wave distribution of genus proportions. The starting period of the sine wave was chosen to be 27 myr which was then varied by a fraction generated randomly between events. Figure 5 shows the results for a pure sine wave (upper panel) and as the period is varied (lower panels). The variations in period were chosen to be Gaussian distributed with standard deviations of 2%, 4% and 6% of 27 myr. It can be seen that the peak broadens and disappears to be less than the noise level if the variation of the period was generated with more than 5% of 27 myr. As explained above, any astronomical cause would be expected to have a larger variation in period and phase than this. The observed Fourier peak at 27 myr is therefore too distinct to be caused by repetitive crossings of the Galactic plane because of the variation in phase and period expected in the Galaxy. Figure 5 shows that astronomical processes with the expected variable periodicity cannot leave a discernible spectral peak; in which case the significance of peaks in extinctions is irrelevant to the search for astronomical causes.

From this we conclude that there is little evidence that MEs have an extra-terrestrial origin (apart from the Chicxulub asteroid noted below).

ANALYSIS OF THE CRATER AGES

The 37 (‘meteroritic-‘) craters from Rampino (2015) and Rampino and Caldeira (2015) were Fourier analysed. These craters have relatively well-defined ages. The analysis shows that a peak in the Fourier amplitudes occurs at a period near 27 myr (see Figure 3d). Again to test the statistical significance of the peaks, 1000 groups of 37 random crater ages were passed through the Fourier analysis program. These showed that 39% of the random spectra had larger peaks, i.e. more significant peaks, than the one observed in the data. This shows that the peak has a high probability to be a statistical fluctuation and hence is not statistically significant. This indicates that the evidence that the peak has a repetitive astrophysical cause is statistically weak.

The quality of the data is degraded by many effects such as the rather strange groupings over very short (few myr) intervals, the loss of craters which have disappeared under the oceans, those prior to the Jurassic largely lost due to subduction processes, and the degradation of the craters due to long term weathering. The latter effect probably causes the very large differences in frequency of detected craters from place to place over the land.

A search was made for a correlation between the *P* value for an extinction and the diameter, *D*, of the nearest crater in time. No correlation could be found. Hence there seems to be no general connection between craters and MEs (apart from Chicxulub 65 Ma). Neither is there a connection between the distribution of the integral *P*-values $N(> P)$ vs *P* and that of bolide energies (represented by $E = RD^4$) and the integral energy distribution ($N(> E)$ versus *E*). One would have expected that *P* and *E* would be related if MEs and asteroid impacts were strongly correlated. Other candidates such as the giant Wilkes Land Crater have been associated with the end Permian extinction; but neither the age of that crater or its association with the Permian-Triassic events are proven. Its location under the Antarctic ice (Weihaupt 2010) is a formidable barrier to any further investigation at present.

From this we conclude that there is little evidence from craters that there is a connection between MEs and astronomical events.

CONCLUSIONS

There is strong evidence that the frequency distribution of the probability of genus extinctions has two components – a near-Gaussian distribution and a small exponential tail. The mean probability has fallen with time. This is a consequence of the planet's increasing biodiversity, possibly populated too by evolutionary-more-stable, longer-ranging species.

Based on the one event and the energetics of asteroid impacts (in the order of 10^{23} Joules for a major impact; see http://impact.ese.ic.ac.uk/ImpactEffects; Shulte *et al.* 2010), a case can be made for the few events in the exponential tail being due to such impacts, although high-energy terrestrial causes, such as those associated with volcanicity (in the order of 2×10^{21} Joules for a major eruption; Blong 1984) or intense climate change (e.g. Benton and Twitchett 2003; Harper *et al*. 2014; Finnegan *et al*. 2016) are equally as likely in the absence of any geological evidence of impact. The extinctions in the main Gaussian region are likely to be due to many different causes, for example thermal effects of terrestrial origin [e.g. those associated with climate fluctuations (e.g. Mayhew *et al*. 2008, 2012) and plate tectonic processes, particularly the effects of Large Igneous Provinces (e.g. Bond and Grasby 2017)].

We show that the evidence for periodicities in the extinction record, from Fourier analysis, is statistically weak. Furthermore, we show that periodicity of the oscillation of the Solar System about the Galactic plane is too variable to produce a narrow peak in such a Fourier analysis. Hence the claim of such regular astronomical phenomena contributing to mass extinctions is not well founded. Instead terrestrial causes are favoured for the vast majority of MEs (see also McLeod 1998, 2005 and 2014; Bond and Grasby 2017).

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DATA ARCHIVING STATEMENT
Data for this study are available in the Dryad Digital Repository:
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Figure 1.

The depth of the extinction or extinction proportion, *P*, of the genus extinctions as a function of time for the extinction events. The solid line shows the linear fit up to age 460 Ma and the dashed line that for all the data referred to in the text.

Figure 2.

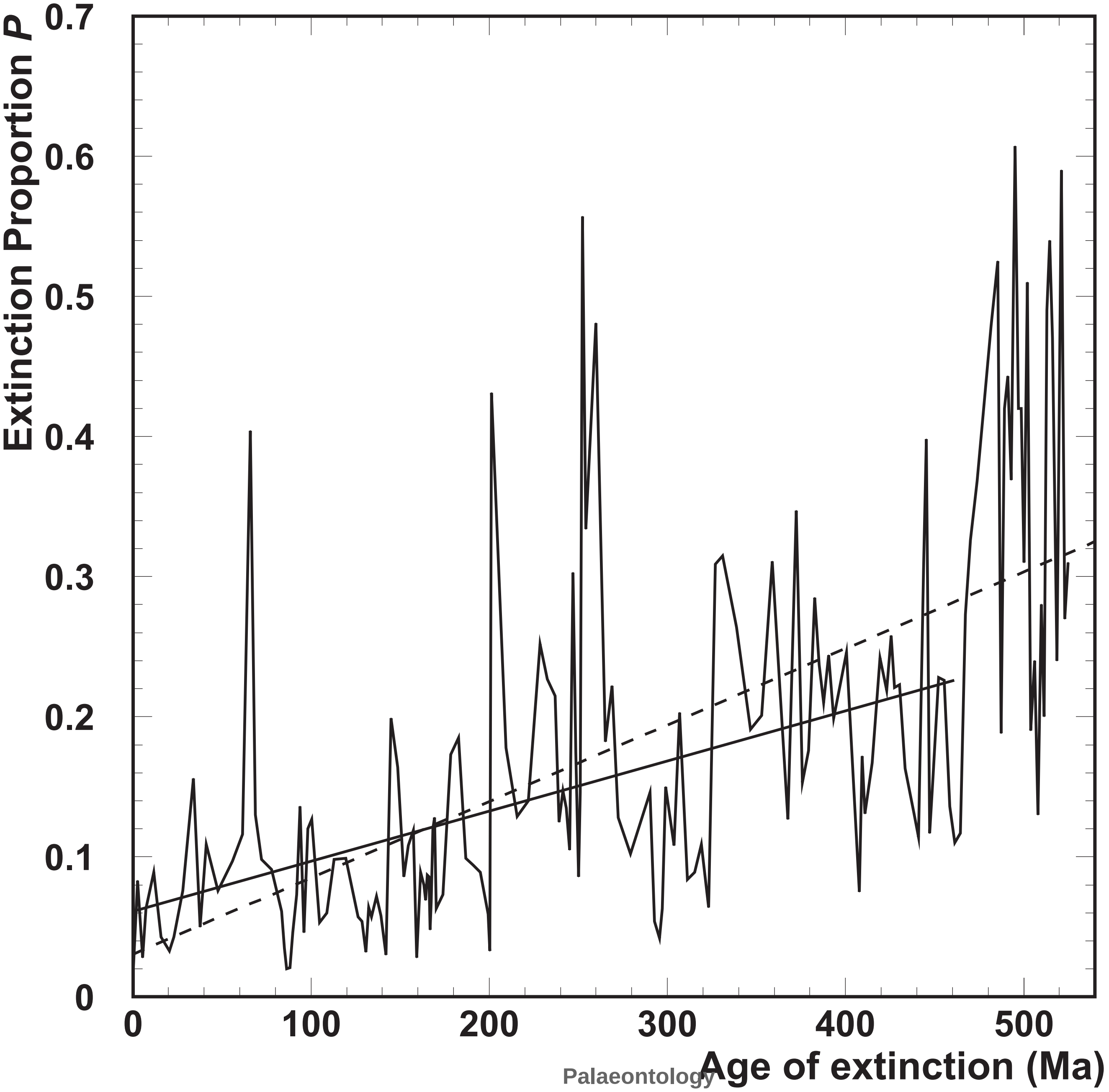
Frequency distribution of the ‘amplitude’ of the probability of genus extinctions, ΔP. By amplitude is meant the excursion from the linear fits in Figure 1. (a) for the data from ~~0-460~~ 0-470 Ma (b) for data from 0-530 Ma. The smooth solid curves shows the maximum likelihood fit of a Gaussian distribution plus an exponential tail described in the text. The dashed curves show the individual contributions of the Gaussian and the exponential tail.

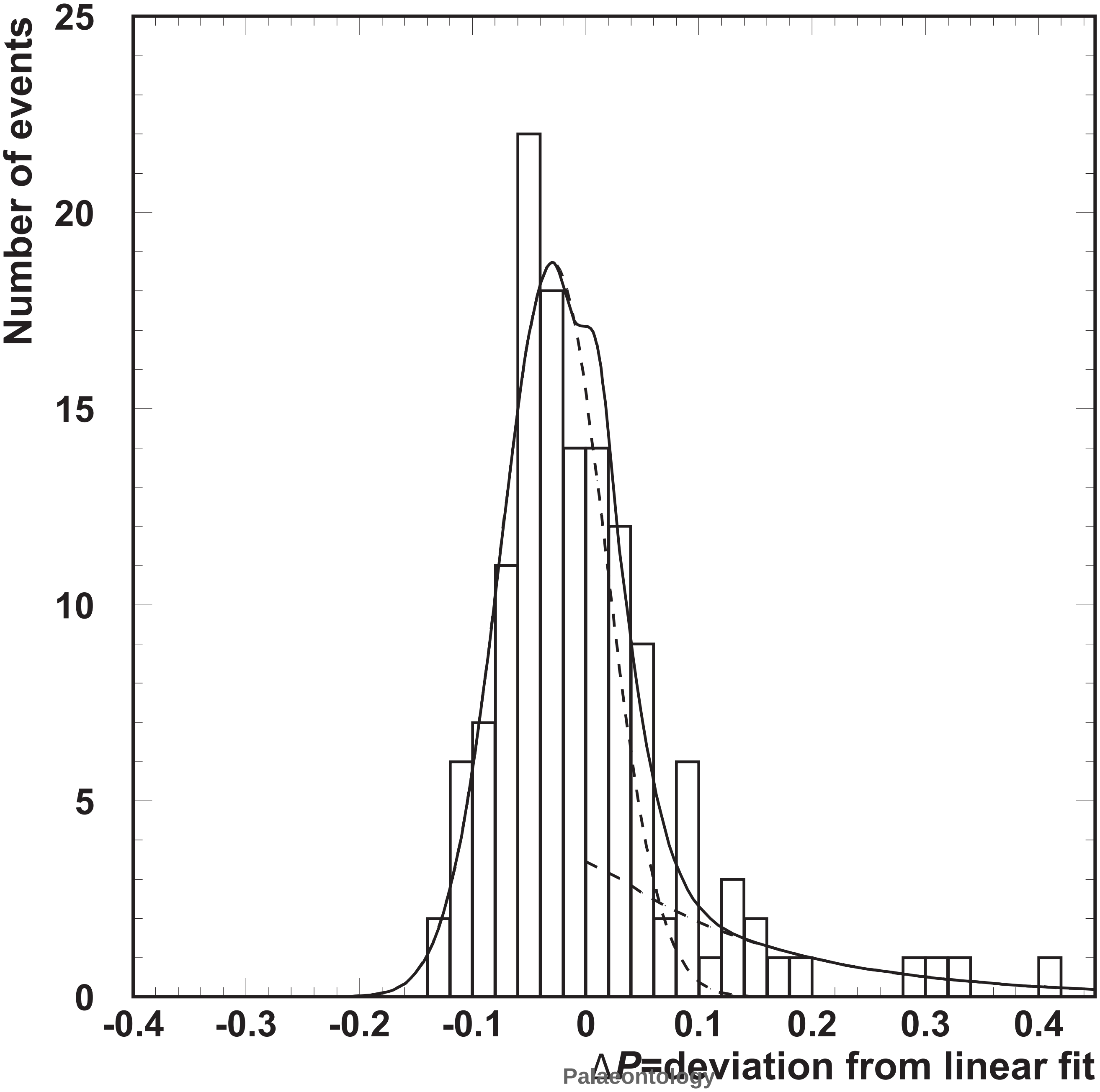
Figure 3

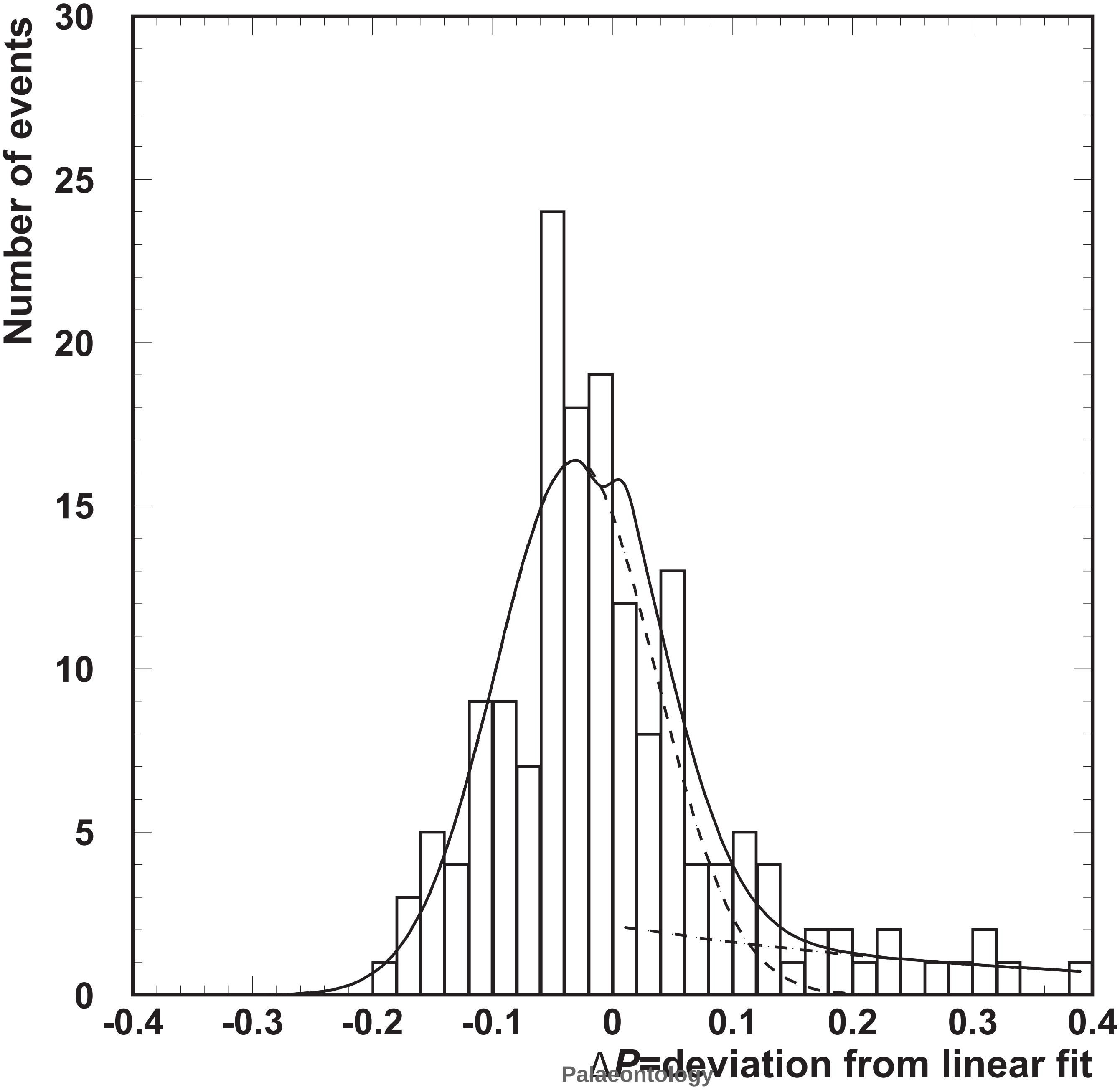
Fourier amplitude of the genus extinction proportion as a function of period for the extinction and crater data; (a) including all 163 extinctions (detrended by the linear fit to all data in figure 1), (b) for extinctions younger than 250 Ma, (c) for those between ages 270-470 Ma, (d) for the 37 craters each with unit weight. Note the large groups of extinctions at around 260 Ma and more than 470 Ma have been excluded from (b) and (c). The data in (b) and (c) were detrended using the linear fit from 1-460 Ma in Figure 1.

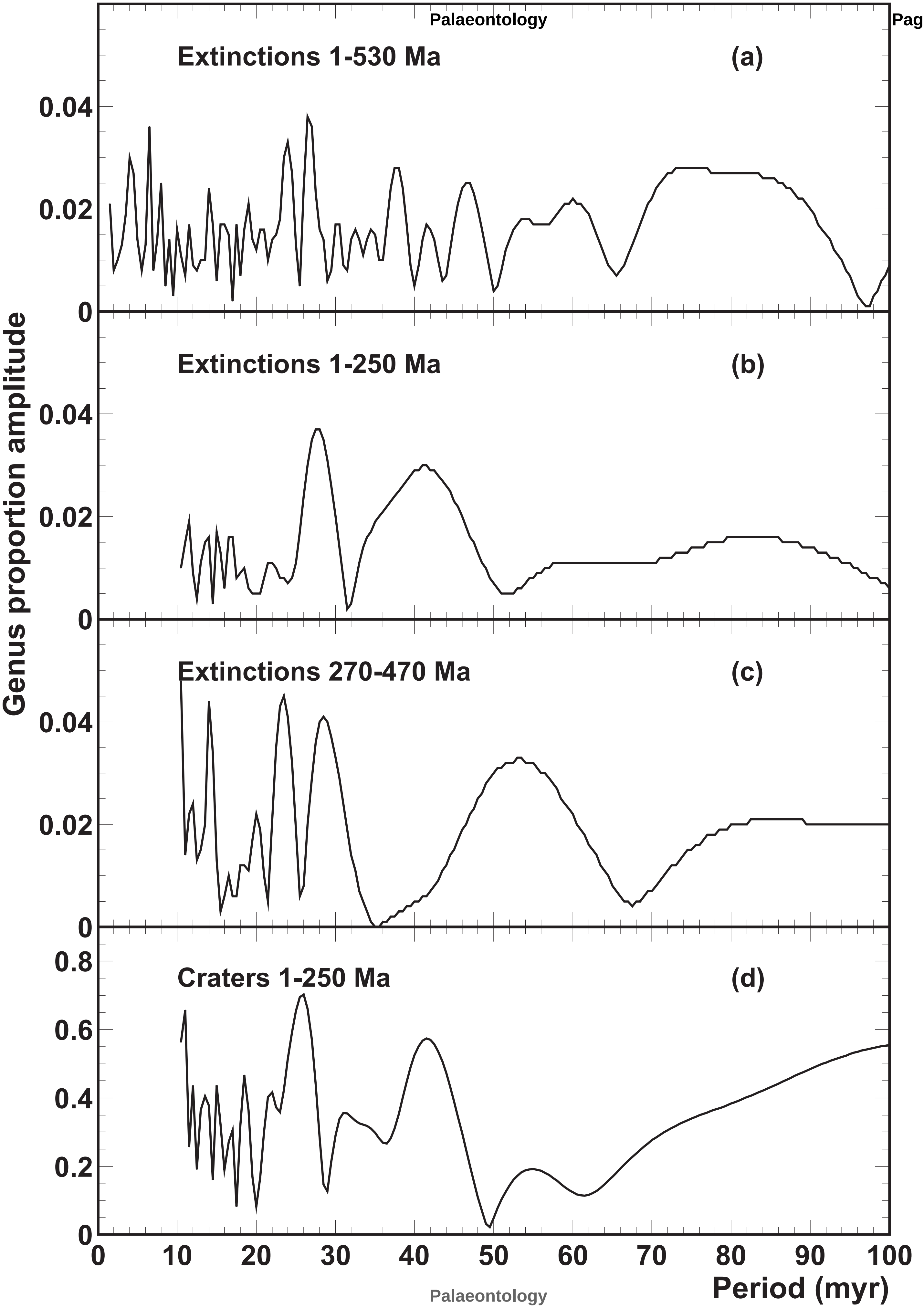
Figure 4 Fourier analysis of the extinctions with each extinction given unit weight, for comparison with the crater data in Figure 3(d), rather than weighted by the genus proportion as in Figure 3.

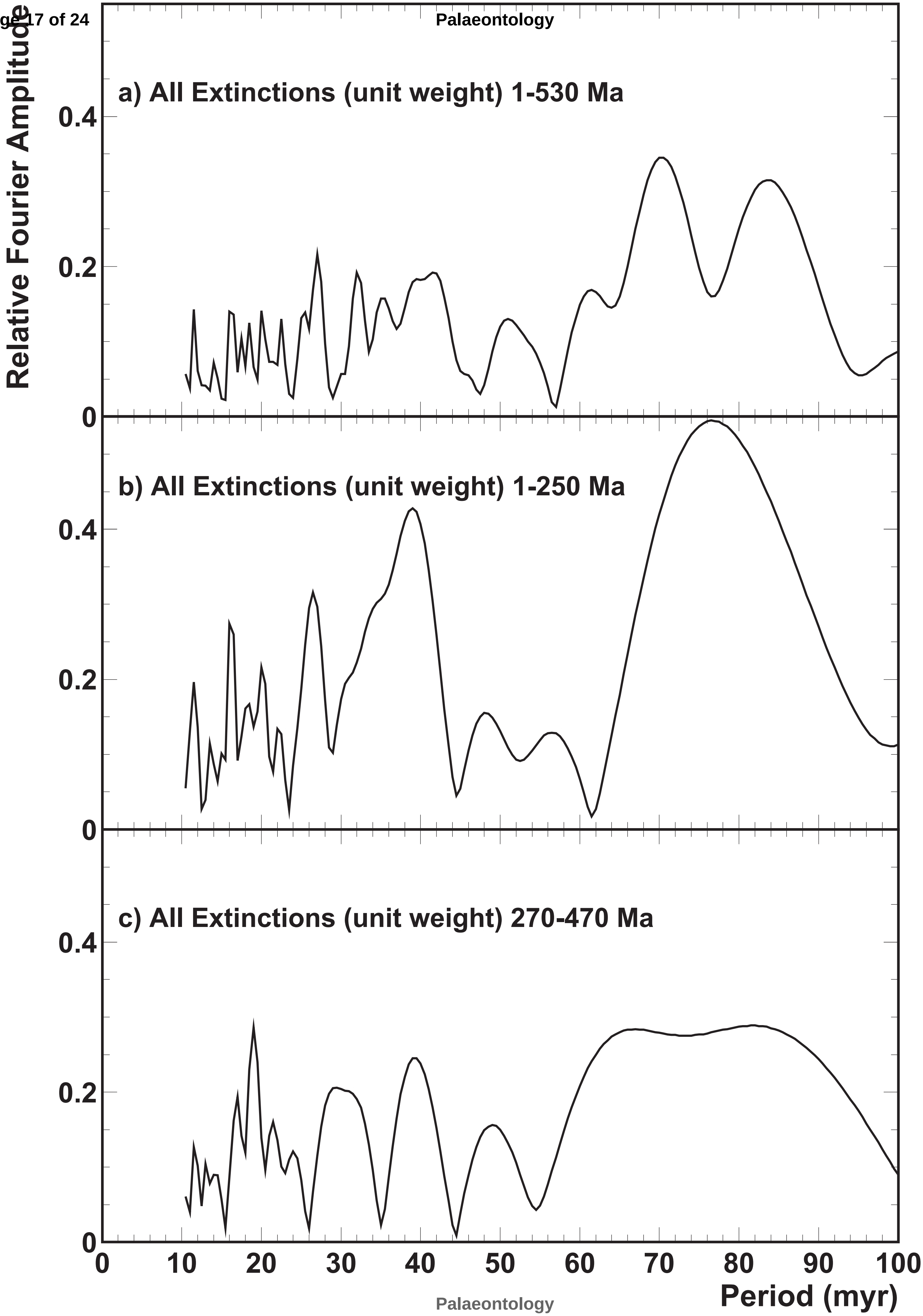
Figure 5 Typical Fourier analyses of samples of 147 events generated as a pure sine wave distributed as $P(t) = 0.04\ \sin \omega t$. In the upper panel the value of ω is fixed to correspond to a period of 27 myr. The lower 3 panels come from analyses of samples of 147 events generated in the same way except that the periods were varied between events by a random amount with Gaussian distributions of standard deviation 0.02, 0.04 and 0.06 times 27 myr, as indicated.

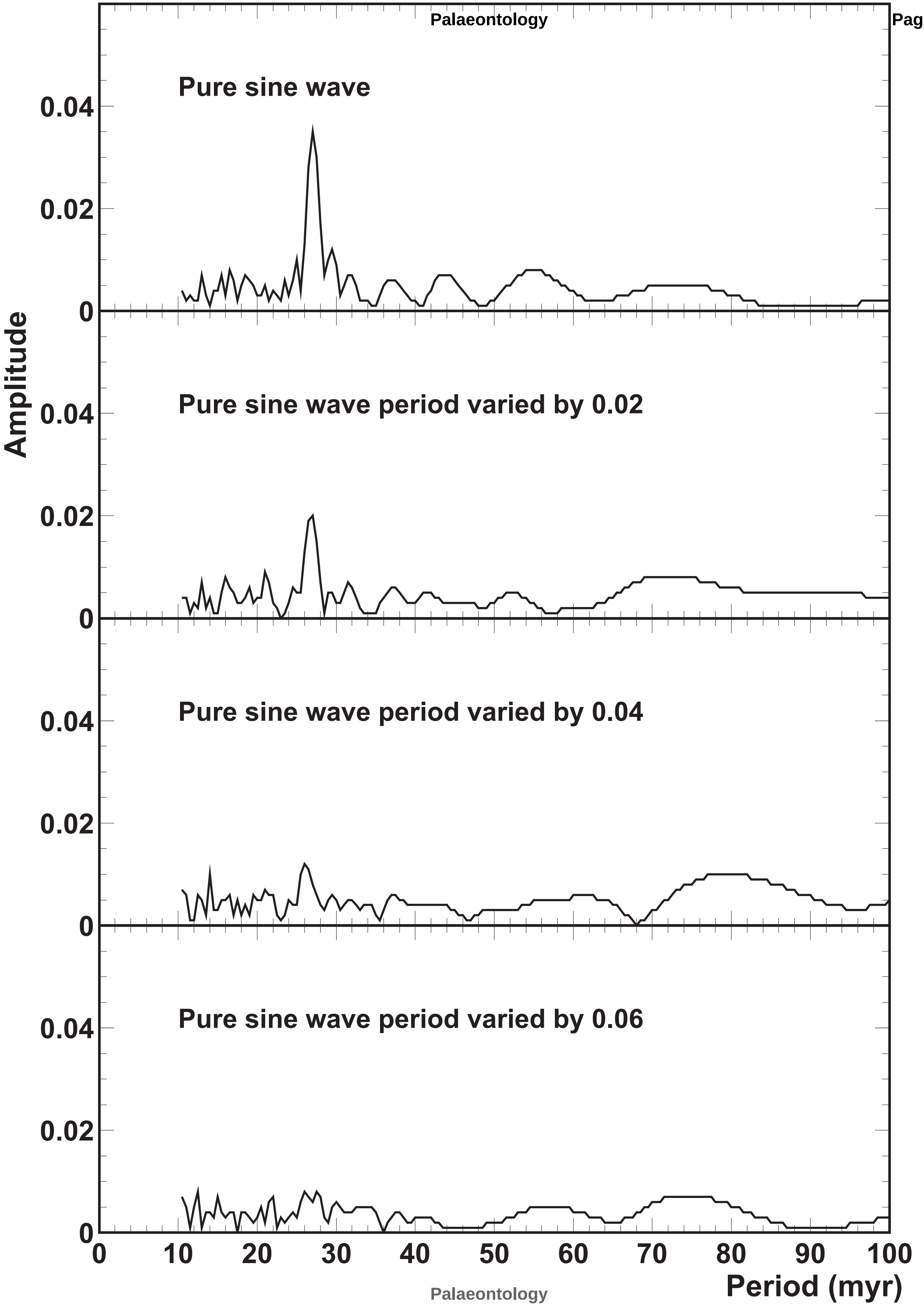

Extinction Proportion P
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
500
Age of extinction (Ma)


Number of events
25
20
15
10
5
0
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
ΔP=deviation from linear fit


Number of events
30
25
20
15
10
5
0
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
ΔP=deviation from linear fit


Extinctions 1-530 Ma
(a)
Extinctions 1-250 Ma
(b)
Extinctions 270-470 Ma
(c)
Craters 1-250 Ma
(d)
Genus proportion amplitude
0
0.02
0.04
0
0.2
0.4
0.6
0.8
0
10
20
30
40
50
60
70
80
90
100
Period (myr)


Relative Fourier Amplitude
a) All Extinctions (unit weight) 1-530 Ma
b) All Extinctions (unit weight) 1-250 Ma
c) All Extinctions (unit weight) 270-470 Ma
0.4
0.2
0
0.4
0.2
0
0.4
0.2
0
0
10
20
30
40
50
60
70
80
90
100
Period (myr)


Pure sine wave
Pure sine wave period varied by 0.02
Pure sine wave period varied by 0.04
Pure sine wave period varied by 0.06
Amplitude
0.04
0.02
0
0
10
20
30
40
50
60
70
80
90
100
Period (myr)

Supplementary Material

This supplementary material includes the analyses for two further time-series datasets from the Phanerozoic. Two older datasets (Peters together with Rohde and Muller, both abstracted from http://www.annualreviews.org/doi/suppl/10.1146/annurev.earth.33.092203.122654) were interrogated by Fourier analysis. The results are presented here. Figure 1 displays the proportion of extinctions through the Phanerozoic, minus background and with a best fit line, and secondly Figure 3 shows a Fourier analysis of the data for the Peters dataset. Similarly, Figure 4 displays the proportion of extinctions through the Phanerozoic, minus background and with a best fit line, and secondly Figure 5 shows a Fourier analysis of the data for, this time, the Rohde and Muller dataset. As noted in the main text: Fourier analyses of the Bambach dataset generated in detail, discussed in main text, and those for the Rohde and Muller together with Peters data show large peaks at the following frequencies: [24, 27, 38, 47 and 60 myr], [24.5, 27, 38, 48, 61 myr] and [25, 27, 38, 47 and 62 myr], respectively. All three datasets display their major peaks with probabilities >10% that they occurred by chance, and thus are not significant. Understandably, the heights of the peaks differ across the analyses, but the shapes of the distributions (N> P vs P) are the same.

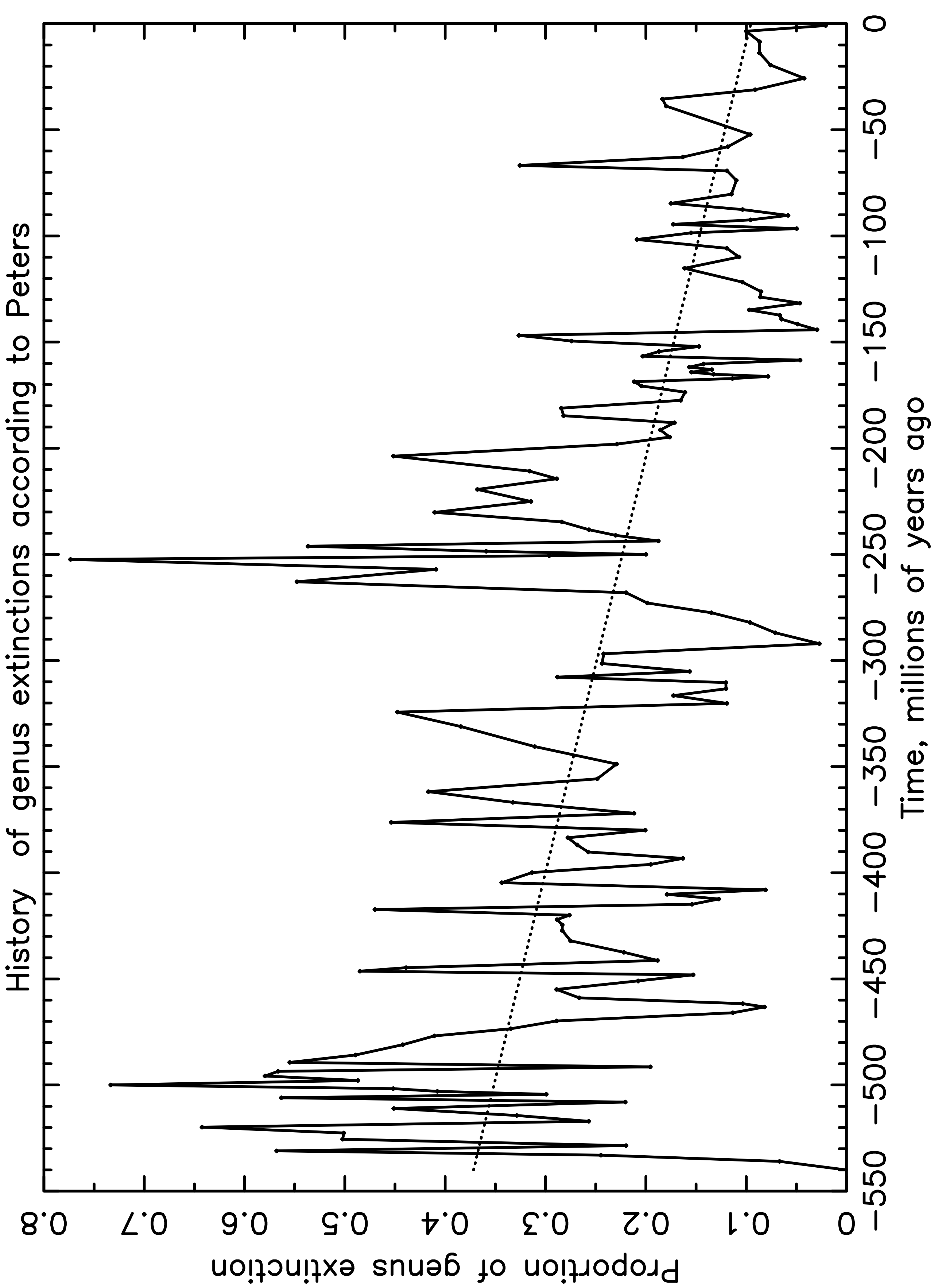
Figure 1. Proportion of extinctions through the Phanerozoic (based on plots of the Peters dataset).

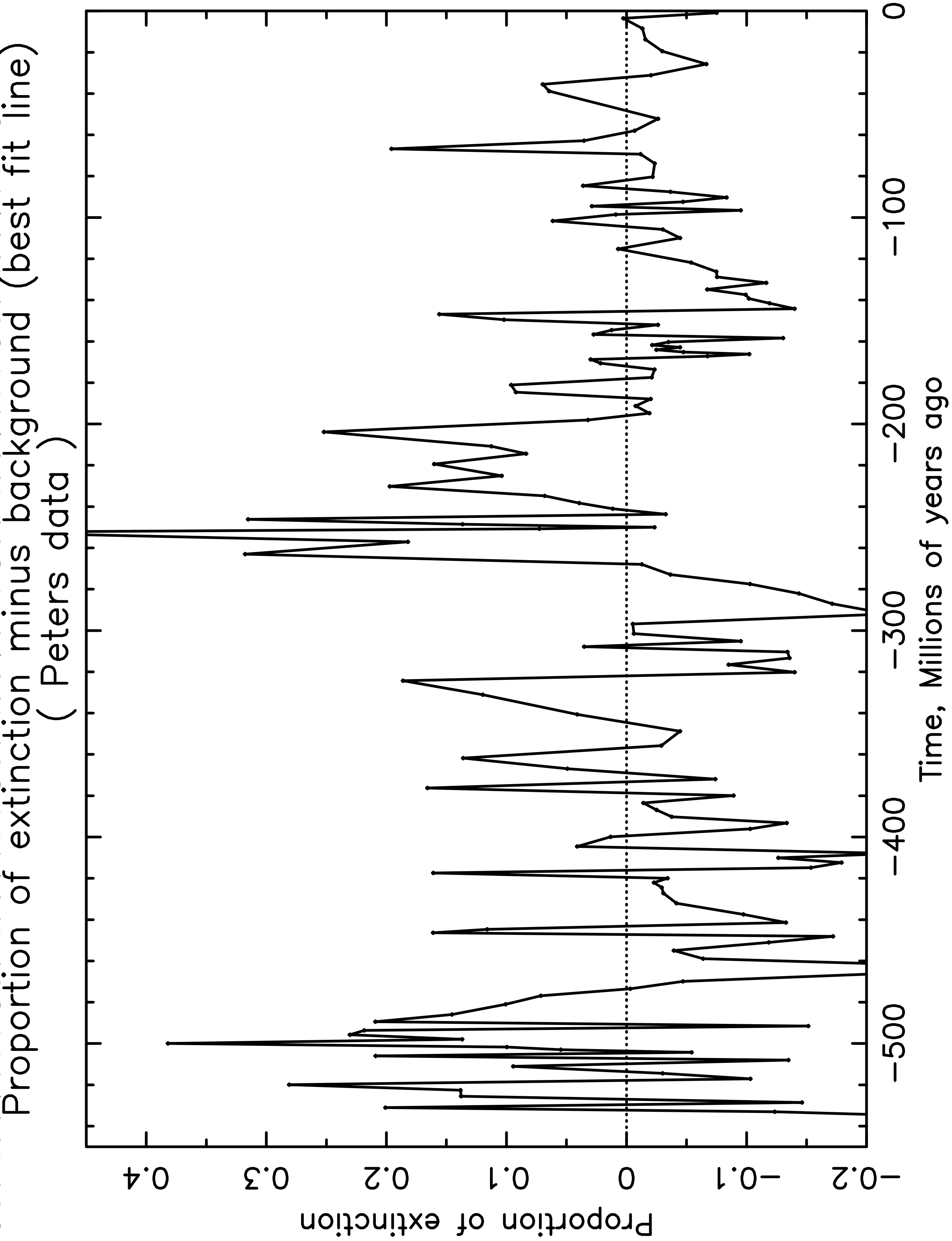
Figure 2. Proportion of extinctions through the Phanerozoic, minus background, with a best fit line (based on plots of the Peters dataset).

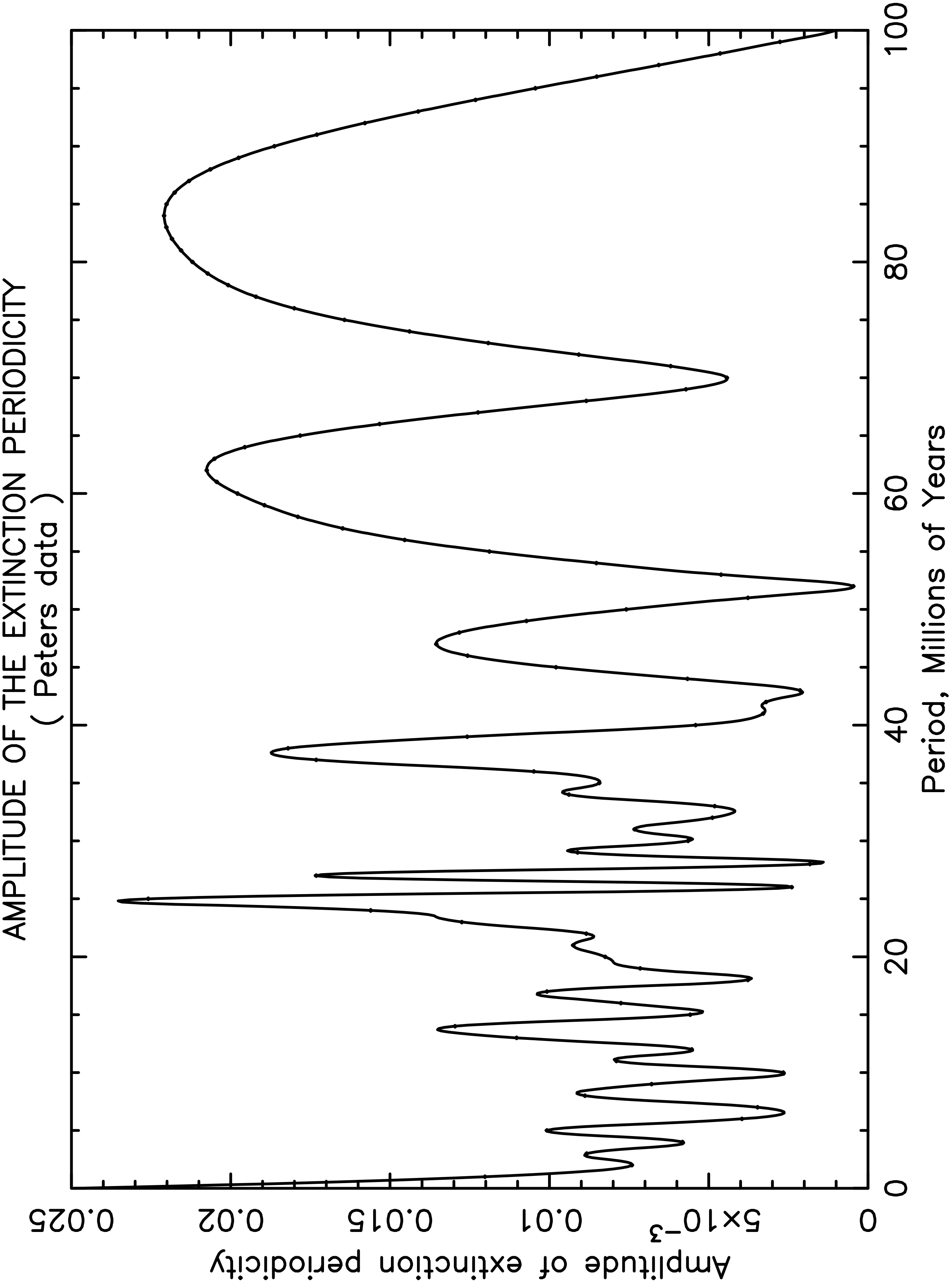
Figure 3. Fourier analysis of the Peters dataset (see text for explanation).

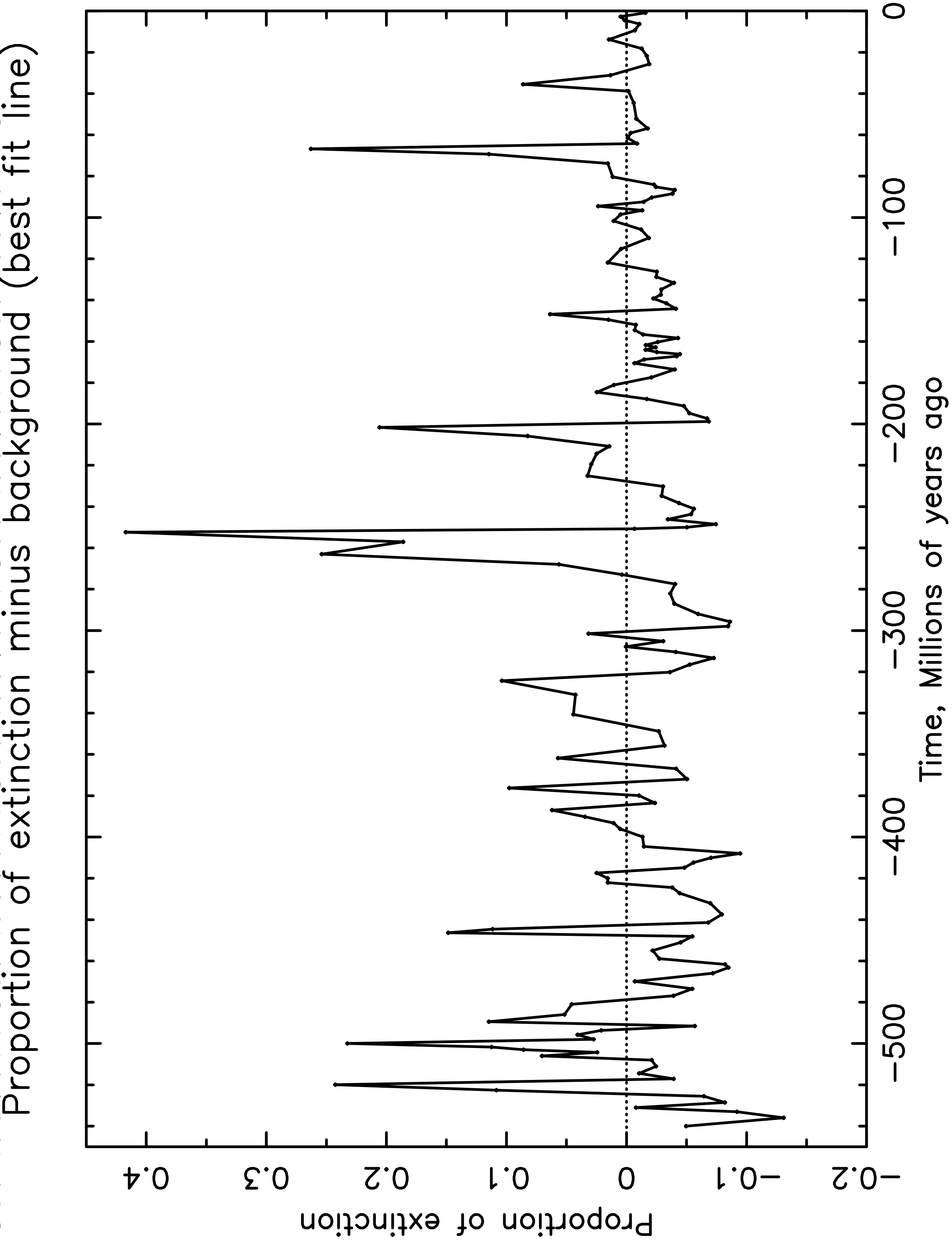
Figure 4. Proportion of extinctions through the Phanerozoic, minus background, with a best fit line (based on plots of the Rohde-Muller dataset).

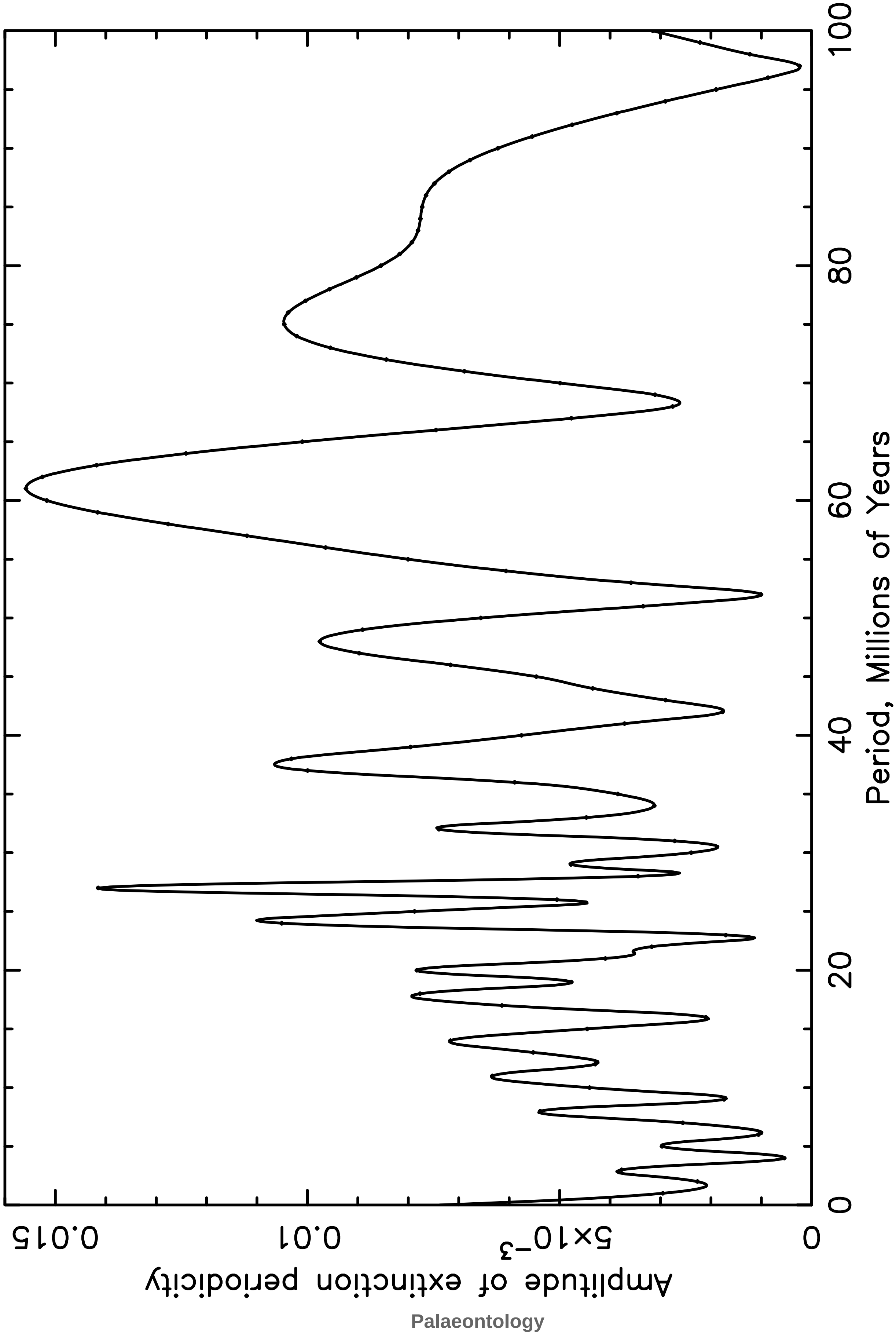
Figure 5. Fourier analysis of the Rohde-Muller dataset (see text for explanation).


History of genus extinctions according to Peters
Time, millions of years ago
0
−50
−100
−150
−200
−250
−300
−350
−400
−450
−500
−550
Proportion of genus extinction
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8


Proportion of extinction minus background (best fit line)
(Peters data)
Time, Millions of years ago
0
−100
−200
−300
−400
−500
Proportion of extinction
0.4
0.3
0.2
0.1
0
−0.1
−0.2


AMPLITUDE OF THE EXTINCTION PERIODICITY
(Peters data)
Period, Millions of Years
0
20
40
60
80
100
Amplitude of extinction periodicity
0
5×10⁻³
0.01
0.015
0.02
0.025


Proportion of extinction minus background (best fit line)
Time, Millions of years ago
0
−100
−200
−300
−400
−500
Proportion of extinction
0.4
0.3
0.2
0.1
0
−0.1
−0.2


Period, Millions of Years
0
20
40
60
80
100
Amplitude of extinction periodicity
0
5×10⁻³
0.01
0.015