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3	1	RAPID COMMUNICATION
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6	2	MASS EXTINCTIONS OVER THE LAST 500 MYR: AN ASTRONOMICAL CAUSE?
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8	3	by ANATOLY D. ERLYKIN ⁺ , DAVID A.T. HARPER ^{*,3} , TERRY SLOAN ⁺ and ARNOLD W. WOLFENDALE ³
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15	10	Abstract: A Fourier analysis of the magnitudes and timing of the Phanerozoic mass extinctions (MEs)
16 17	10	demonstrates that many of the periodicities claimed in other analyses are not statistically significant
18	11	Mercover we show that the periodicities associated with assillations of the Solar System about the
19	12	Coloction plane are too imagular to give person pools in the Sourier period egreene. This loads us to
20	13	Galactic plane are too irregular to give narrow peaks in the Fourier periodograms. This leads us to
21	14	conclude that, apart from possibly a small number of major events, astronomical causes for MEs can
22	15	largely be ruled out.
23 24	16	Key words: mass extinctions, periodicity, astronomical processes. Phanerozoic
25	10	key words. mass extinctions, periodicity, astronomical processes, r hancrozoie
26	17	INTRODUCTION
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28	18	The cause (or causes) of mass extinctions (MEs) of marine and terrestrial biological genera
29 30	19	has been debated for many decades (see Hallam 2004) and there is, not surprisingly, an extensive
31	20	and impressive portfolio of research in this area (see for example, McLeod 2014, together with Bond
32	21	and Grasby 2017 for more recent reviews). Insofar as the problem is germane to understanding the
33	22	evolution of life on Earth, its solution is important.
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36	23	The cause can either be firstly, astrophysical, such as the impact of asteroids, or secondly,
37	24	terrestrial, due to changes in habitat together with drama induced by climate change and plate
38	25	tectonic movements, or both. Our aim here is, specifically, to determine or not the astrophysical
39	26	influence on MEs and the Earth's ecosystems through deep time.
40 41	27	Periodicity in fossil range data in a loose sense, has been recognised for some time (Newell
42	27	1952) The initial guantification, however, of periodicity in marine mass extinctions (Paun and
43	20	Sonkocki 1092) prompted a range of actronomical evaluations. The Sun's escillation about a Solar
44	29	septosti 1982) prohibited a range of astronomical explanations. The suff s oscillation about a solar
45	50	plane (Schwartz and James 1984), Oschlation of the Solar System vertically about a galactic plane
46 47	31	(Rampino and Strother 1984), the presence of a distant Solar companion, Nemesis (Davis <i>et al.</i> 1984;
48	32	Whitmire and Jackson 1984), the existence of a tenth planet (Whitmire and Matese 1985), i.e.
49	33	beyond the orbit of Pluto, and periodic comet showers (Alvarez and Muller 1984). To these can be
50	34	added some earlier explanations, prior to the Raup and Sepkoski analysis, including periodic doses
51	35	of cosmic rays (CR) controlled by reversals in the Earth's magnetic field (Hatfield and Camp 1970)
52 53	36	and climate change based on fluctuating Solar energy and rhythms in mantle convection and
53 54	37	associated processes (Fischer 1977). The concept of periodicity, however, has not received universal
55	38	acceptance. In a critique of the flurry of astronomical papers, Hallam (1984) noted the many
56	39	terrestrial causes of mass extinction including climate and sea-level changes together with
57	40	volcanicity while emphasising the shortcomings of the Fossil Record at that time in providing an
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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 muchupdated range distribution of families and genera initiated and established by the late Jack Sepkoski

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3	85	(http://strata.geology.wisc.edu/jack/), and the occurrence database that forms the basis for the
4	86	Paleobiology Database (https://paleobiodb.org/#/). We have chosen to analyse the former, firstly
5	87	since both databases appeared to perform similarly in time-series analysis (Melott and Bambach
6	88	2014) and secondly through the kindness of Dr Richard Bambach that database, updated where
7 8	89	relevant particularly taking account of new absolute age constraints was made available to us. In
9	90	all there were 163 genus extinction events, with 147 if the large extinction neaks around 250 Ma
10	01	and \$470 Ma are excluded (see below). The distribution of <i>B</i> values is examined and forms the basis
11	91	for discussion. This is followed by a search for periodicities in the D record and also in 27 metaorite
12	92	for discussion. This is followed by a search for periodicities in the P-record and also in 57 meteorite
13 14	93	craters by Fourier analysis. The significances of the peaks in the Fourier periodograms are examined
14	94	in some detail and conclusions drawn.
16	05	Additional complementary and confirmatory analyses of more historic data sets provided by
17	95	Change Deters together with Debde and Miller, online supplementary material (see
18	90	Shahan Peters together with Rohue and Miller, Online supplementary material (see
19	97	http://www.annuaireviews.org/doi/suppi/10.1146/annurev.eartn.33.092203.122654) are noted
20	98	below and the details provided in Supplementary Material.
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22	99	ANALISIS OF THE GENUS EXTINCTION PROPORTIONS THROUGH TIME (P)
24	100	As is well known, the mean <i>P</i> -value increases with age in an approximately linear fashion (see Figure
25	101	1, solid (dashed) line excludes (includes) the large extinctions around 250 Ma and >470 Ma). Linear
26	102	fits give a reasonable representation of the data and these are adopted rather than more
27	103	complicated ones. There are, however, large deviations from the median line. Figures 2(a) and 2(b)
29	104	show the frequency distribution of ΔP , the displacement of the P-value from the two linear fits
30	105	shown in Figure 1. The solid smooth curves in Figures 2 show a maximum likelihood fit to the data of
31	106	a Gaussian distribution plus an exponential tail: a Gaussian being a natural curve to fit, not least
32	107	because it fits so well for negative delta-P values. Good fits were obtained with the value of the
33 34	108	Pearson test statistic $y^2 = 10.9$ for 13 degrees of freedom in Figure 2(a) and $y^2 = 18.4$ for 13
35	100	degrees of freedom in Figure 2(b). The data at ages beyond 470 Ma have very large positive and
36	109	degrees of freedom in Figure 2(b). The data at ages beyond 470 wa have very large positive and
37	110	negative fluctuations from the linear fit and therefore seem somewhat anomalous, perhaps
38	111	reflecting the instability and lack of resilience of the Cambrian ecosystem, its different composition
39	112	and structure (Bambach 1983, 1985; Bush and Bambach 2011). However, Figure 2(b) shows that if
40 41	113	the whole age range is fitted, similar results are obtained to those up to age 470 Ma in Figure 2(a)
42	114	with the exponential tail approximately doubled in amplitude mainly because of the addition of the
43	115	large ME values beyond 470 Ma. Hence we conclude that the data are well represented by a
44	116	Gaussian distribution and an exponential tail.
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46	117	The implication of such a Gaussian form at small values of ΔP is that each P-value is the resultant of

117 The implication of such a Gaussian form at small values of ΔP is that each *P*-value is the resultant of 118 smaller scale, i.e. less catastrophic events. For $\Delta P > 0.1$ the Gaussian component is negligible and 119 the exponential tail dominates; this strongly suggests contributions from mechanisms which caused 120 more catastrophic damage.

122 THE SEARCH FOR PERIODICITIES

123 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.

136 The Fourier integrals for a particular angular frequency ω are deduced by simply averaging the 137 readings. Thus:

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

139 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 140 number of events considered and ΔT is the total time range over which the sample of data is taken. 141 The absolute amplitude of the Fourier component with frequency ω is then given by

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

142 In order to judge the significance of any observed peak, random values of the P_i and t_i were 143 generated and passed through the analysis programme. The process was repeated many times and 144 the significance of a peak in the data is judged by the number of occurrences of peaks from the 145 random distribution with greater amplitude and therefore significance than the one observed in the 146 data.

148 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

- 163 dates were passed through the analysis chain. The random events were generated with a
- 164 distribution of genus proportion of a similar shape to the data (Figure 2) about the trend line. The

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3	165	process was repeated 1000 times. It was observed that 10% of the random extinction data had
4	166	peaks which were larger, i.e. more significant than those seen in the vicinity of 27 myr in Figures 3(a-
5	167	c) and 60% of those in Figures 4(a-c). These fractions show that the observed peaks in the data have
7	168	limited statistical significance. It is therefore plausible that the peaks are the results of statistical
8	169	fluctuations rather than a repetitive physical process for either the genus proportion (Figure 3) or
9	170	single events (Figure 4). Other factors which show that the 27 myr peak is unlikely to be related to an
10	171	astrophysical mechanism of any known kind are as follows:
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13	172	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
14	173	different character in time range 270-470 Ma in Figure 3(c). (Note that the time for the Solar System
15	174	(SS) to orbit the Galaxy is of order 250 myr). If the signal were real, the peak value should be similar
16 17	175	in each time range;
18	176	2. The wide range of other peaks at periods with no astrophysical significance means that the cluster
19 20	177	around 27 myr could be accidental and not related to a repetitive astrophysical source;
21	178	3. As shown elsewhere (e.g. Wolfendale and Wilkinson 1988), there is no evidence, nor theoretical
22	179	justification, for precise 'bursts' of asteroids or comets when the SS crosses the Galactic Plane;
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25	180	4. Similarly, Cosmic Ray (CR) effects are negligible insofar as changes in the CR intensity variation
26	181	over the 500 myr interval should be too small to produce MEs (Bailey et al. 1987; Shaviv, 2002a,b;
27 28	182	Sloan and Wolfendale 2008, 2013 and references therein).
29	183	As noted above two additional, albeit historical, data sets were also analysed (see Supplementary
30 31	184	Material for details). Fourier analyses of the Bambach dataset generated in detail herein and those
32	185	for the Rohde and Muller together with Peters data show large peaks at the following frequencies:
33	186	[24, 27, 38, 47 and 60 myr], [24.5, 27, 38, 48, 61 myr] and [25, 27, 38, 47 and 62 myr], respectively.
34	187	All three datasets display their major peaks with probabilities >10% that they occurred by chance,
35	188	and thus are not significant. Understandably, the heights of the peaks differ across the analyses,
36	189	but the shapes of the distributions (N> P vs P) are the same.
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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 (apartfrom the Chicxulub asteroid noted below).

234 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

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2	246	long term weathering. The latter effect probably causes the very large differences in frequency of
4	247	detected craters from place to place over the land
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6 7	248	A search was made for a correlation between the P value for an extinction and the diameter, D, of
8	249	the nearest crater in time. No correlation could be found. Hence there seems to be no general
9	250	connection between craters and MEs (apart from Chicxulub 65 Ma). Neither is there a connection
10	251	between the distribution of the integral <i>P</i> -values $N(> P)$ vs <i>P</i> and that of bolide energies
11	252	(represented by $E = RD^4$) and the integral energy distribution ($N(> E)$ versus E). One would have
12	253	expected that P and E would be related if MEs and asteroid impacts were strongly correlated. Other
14	254	candidates such as the giant Wilkes Land Crater have been associated with the end Permian
15	255	extinction; but neither the age of that crater or its association with the Permian-Triassic events are
16	256	proven. Its location under the Antarctic ice (Weihaupt 2010) is a formidable barrier to any further
1/ 18	257	investigation at present.
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20	258	From this we conclude that there is little evidence from craters that there is a connection between
21	259	MEs and astronomical events.
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25	261	CONCLUSIONS
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27	262	There is strong evidence that the frequency distribution of the probability of genus extinctions has
28	263	two components – a near-Gaussian distribution and a small exponential tail. The mean probability
30	264	has fallen with time. This is a consequence of the planet's increasing biodiversity, possibly populated
31	265	too by evolutionary-more-stable, longer-ranging species.
32	266	Based on the one event and the operatics of actoroid impacts (in the order of 10^{23} loules for a
33	200	major impact: see http://impact.oso.jc.ac.uk/impactEffects: Shulto at al. 2010) a case can be made
34 35	207	for the few events in the exponential tail being due to such impacts, although high energy torrestrial
36	200	For the few events in the exponential tail being due to such impacts, although high-energy terrestrial causes, such as those associated with velcanisity (in the order of 2 x 10^{21} loules for a major eruntion)
37	209	Plang 1084) or intense climate change (e.g. Ponton and Twitchett 2002; Harper et al. 2014; Einnegan
38	270	of a (2016) are equally as likely in the absence of any geological evidence of impact. The evidence
39 40	271	in the main Coursian region are likely to be due to many different sources for example thermal
41	272	In the main Gaussian region are likely to be due to many different causes, for example thermal
42	273	effects of terrestrial origin [e.g. those associated with climate fluctuations (e.g. Maynew <i>et al.</i> 2008,
43	274	2012) and plate tectonic processes, particularly the effects of Large Igneous Provinces (e.g. Bond and
44 45	275	Grasby 2017)].
45 46	276	We show that the evidence for periodicities in the extinction record, from Fourier analysis, is
47	277	statistically weak. Furthermore, we show that periodicity of the oscillation of the Solar System about
48	278	the Galactic plane is too variable to produce a parrow peak in such a Fourier analysis. Hence the
49	270	claim of such regular astronomical phenomena contributing to mass extinctions is not well founded
50 51	280	Instead terrestrial causes are favoured for the vast majority of MEs (see also McLeod 1998, 2005 and 2014)
52	281	Bond and Grasby 2017).
53	282	
54	202	
55	283	Acknowledgements. We thank Dr Alistair McGowan and an anonymous reviewer for their careful
50 57	284	and detailed comments that improved the manuscript. The latter suggested we should analyse a
58	285	couple of the more historic datasets, which we did. Dr Richard Bambach generously permitted use of
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286 his updated database and engaged in robust discussions of our findings. Sloan, Erlykin and 287 Wolfendale are grateful to the Kohn Foundation for financial support. Harper acknowledges the 288 receipt of a research fellowship from the Leverhulme Trust and support from the Wenner-Gren 289 Foundation (Sweden). 290 291 REFERENCES 292 DATA ARCHIVING STATEMENT 293 Data for this study are available in the Dryad Digital Repository: 294 http://dx.doi.org/10.5061/dryad.xxxx 295 ALVAREZ, L. W., ALVAREZ, W., ASARO, F. and MICHEL, H. V. 1980. Extraterrestrial cause for the 296 Cretaceous-Tertiary extinction. Science, 208, 1095-1108. 297 ALVAREZ, W. and MULLER, R.A. 1984. Evidence for crater ages for periodic impacts on the Earth. 298 Nature, 308, 718-720. 299 BAHCALL, J.N. and BAHCALL, S. 1985. The Sun's motion perpendicular to the galactic plane. 300 Nature, 316, 706-708. 301 BAILEY, M.E., WILKINSON, D.A. and WOLFENDALE, A.W. 1987. Can episodic comet showers 302 explain the 30-myr cyclicity in the terrestrial record? Monthly Notices of the Royal 303 Astronomical Society, 227, 863-885. 304 BAMBACH, R.K. 1983. Ecospace utilization and guilds in marine communities through the 305 Phanerozoic. 719-746. In TEVESZ, M. and MCCALL, P. (eds.), Biotic Interactions in Recent 306 and Fossil Benthic Communities. Topics in Geobiology 3, Springer. 307 BAMBACH, R.K. 1985. Classes and adaptive variety: The ecology of diversification in marine 308 faunas through the Phanerozoic. 191-253. In VALENTINE, J.W. (ed.), Phanerozoic Diversity 309 Patterns: Profiles in Macroevolution. Princeton University Press. 310 BAMBACH, R.K. 2006. Phanerozoic biodiversity mass extinctions. Annual Review Earth Planetary 311 Science, 34, 127-155. 312 BAMBACH, R.K., KNOLL, A.H. and WANG, S.C. 2004. Origination, extinction and mass depletions 313 of marine diversity. Paleobiology, 30, 522-542. 314 BENTON, M.J. 1993 (ed.). The fossil record 2. Palaeontological Association and Chapman and Hall, 315 London. 845 pp. 316 BENTON, M.J. 1995. Diversity and extinction in the history of life. *Science*, 268, 52-58. 317 BENTON, M.J. and HARPER, D.A.T. 2009. Introduction to paleobiology and the fossil record. John 318 Wiley and Sons. 342 pp. 319 BENTON, M.J. and TWITCHETT, R. 2003. How to kill (almost) all life: the end-Permian extinction 320 event. Trends in Ecology and Evolution, 18, 358-365. 321 BLONG, R.J. 1984. Volcanic hazards: A sourcebook on the effects of eruptions. Academic Press. 322 424 pp. 323 BOND, D.P.G. and GRASBY, S.E. 2017. On the causes of mass extinctions. Palaeogeography, 324 Palaeoclimatology, Palaeoecology xxx, xxx-xxx (in press). 325 BRENCHLEY, P.J. and HARPER, D.A.T. 1998. Palaeoecology: Ecosystems, environments and 326 evolution. CRC Press, Taylor and Francis. 402 pp. 327 BUSH, A.M. and BAMBACH, R.K. 2011. Paleoecologic megatrends in marine Metazoa. Annual 328 Review of Earth and Planetary Science, 39, 241-269.

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 <i>Figure 3</i> <i>Figure 3</i> <i>Fourier amplitude of the genus extinction proportion as a function of period for the extinction and</i> <i>crater data; (a) including all 163 extinctions (detrended by the linear fit to all data in figure 1), (b) for</i> <i>extinctions younger than 250 Ma, (c) for those between ages 270-470 Ma, (d) for the 37 craters each</i> <i>with unit weight. Note the large groups of extinctions at around 260 Ma and more than 470 Ma</i> <i>have been excluded from (b) and (c). The data in (b) and (c) were detrended using the linear fit from</i> <i>1-460 Ma in Figure 1.</i> <i>449</i> 	44		
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 447 have been excluded from (b) and (c). The data in (b) and (c) were detrended using the linear fit from 448 1-460 Ma in Figure 1. 55 449 56 	51	446	with unit weight. Note the large groups of extinctions at around 260 Ma and more than 470 Ma
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55 449 56	54	448	1-460 Ma in Figure 1.
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450 *Figure 4* Fourier analysis of the extinctions with each extinction given unit weight, for comparison451 with the crater data in Figure 3(d), rather than weighted by the genus proportion as in Figure 3.

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453	Figure 5 Typical Fourier analyses of samples of 147 events generated as a pure sine wave distributed
454	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
455	myr. The lower 3 panels come from analyses of samples of 147 events generated in the same way
456	except that the periods were varied between events by a random amount with Gaussian

457 distributions of standard deviation 0.02, 0.04 and 0.06 times 27 myr, as indicated.







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Palaeontology

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 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).











