Title
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Publication Date
1984

LBL-17300
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Physics Division

Submitted to Nature

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January 1984

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-17300

Evidence in Crater Ages for Periodic Impacts on the Earth

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Large impact craters on the earth show a 28.4 million year periodicity in their ages, in remarkable agreement with the frequency and phase of the periodic mass extinctions seen in the fossil record.

24 January 1984

submitted to NATURE

When it was discovered that the mass extinction at the end of the Cretaceous was coincident with the impact of an asteroid or comet on the earth[1], it was generally assumed that such events would be random in time. When evidence of another impact was found at a second paleontological boundary, the Eocene-Oligocene[2], it appeared possible that such impacts would be found responsible for many of the other extinctions. It was difficult, however, to reconcile the impact picture with a periodicity found in the geological record, first seen qualitatively in various aspects of pelagic sediments by A. G. Fischer and M. A. Arthur[3], and then analyzed quantitatively in the fossil record of family extinctions by D. M. Raup and J. J. Sepkoski[4]. There was no obvious reason why asteroid impacts should occur periodically, and it is particularly difficult to find astronomical mechanisms with the long (26 million year) period that had been detected. A possible solution to this conundrum was suggested by M. Davis, P. Hut, and R. A. Muller[5] who proposed that an unrecognized companion star, orbiting the sun with a 26 million year period, triggers a shower of 10^9 comets as it passes through the Oort comet cloud at perihelion. A few of these comets should strike the earth within the following million years. In this model it is plausible for most large impacts on the earth to occur during these relatively brief showers rather than during the long periods in between.

To test a prediction implicit in this model we looked for evidence of periodicity in the record of impact craters on the earth. A recent compilation by R. Grieve[6] lists 88 dated craters for which signs of shock metamorphism suggest probable impact origin. The known craters are located primarily in stable, well-studied regions in North America, Europe, Australia, and the U.S.S.R. There are no known impact craters on the sea floor. The list shows a strong bias toward recent craters, most of which will probably be removed by erosion in the near future; 12 of the 88 dated craters have ages within the last 5 million years. We estimate that the craters in Grieve's compilation represent about 10% to 25% of the impact craters still existing on the earth.

We restricted ourselves to impact craters in roughly the range of ages in which Raup and Sepkoski saw the periodicity, i.e. 5 to 250 million years before present. The lower limit of 5 million years was chosen to reduce the bias from the large number of craters surviving from the recent past. In order to be able to see periods as short as 26 million years, we included only craters whose uncertainty in age is ±20 Myr or less. The 13 craters in the list that meet these criteria are listed in Table 1. Since Grieve's compilation was made, there have been some improved measurements, and some older ages need to be revised on the basis of new standardized decay constants. After a search of the literature we developed our own revised values for the crater ages and their uncertainties, and these are listed in the table under the column "revised ages". To avoid any possibility of bias, however, we confined the bulk of our analysis in this paper to the values given by Grieve rather than our own. Near the end of this paper we will discuss the effect on our analysis of using the revised numbers in place of Grieve's values.

In Figure 1(a) a rectangle of unit area has been used to represent each crater with diameter greater than 10 km. (We will discuss the sensitivity of our analysis to the choice of diameter cutoff later.) The width of the rectangle is twice the standard deviation error in the age, and overlapping rectangles have been stacked. In Figure 1(b) the rectangles have been replaced by Gaussian distributions, with the RMS for each crater set by the uncertainty in the age. This plot represents our best statistical representation of the history of impacts on the earth during the last 250 million years. A periodicity of roughly the right frequency and phase to agree with the Raup and Sepkoski analysis is evident, as indicated by the arrows which are spaced by about 28 million years.

The Fourier power spectrum of Figure 1(b) is shown in Figure (2). (We found no essential difference between the Fourier transforms of Figures 1(a) and 1(b).) In this plot the peak near the frequency 0.035 Myr^{-1} corresponds to a period of 28.4 Myr, with the first maximum at 13 Myr. The arrows shown in Figure (1) actually correspond to the frequency and phase found in this Fourier transform.

In order to understand the statistical significance of the peak in the Fourier power spectrum, we generated Monte-Carlo simulations of craters with random ages. 1000 sets were generated, each containing 11 craters with random ages between 5 and 250 million years, but with age errors (i.e. Gaussian widths) identical with and in the same order as those from the real craters. The Fourier transform was calculated for each of the simulated sets; the average of the 1000 power spectra are shown with the dotted line in Figure (2). In each of the 1000 Fourier power spectra we searched for peaks as high as the one seen at 0.035 Myr^{-1} in the real data. In Figure (3) we have plotted the fraction of the 1000 data sets which showed any such peak above a given frequency as a function of that frequency. As can be seen in this plot, for frequencies of 0.035 or greater (periods of 28.4 million years or less) a peak as high as the one in the real data appears as a statistical fluctuation in only 8 of the 1000 randomly generated sets. From this analysis we conclude that our confidence level in the existence of the periodicity is about 99%. Other analyses (e.g. finding the number of large peaks in the 1000 Monte-Carlo sets with periods within 2 Myr of the 26 Myr period of Raup and Sepkoski; analysis of the statistics of the peaks; chisquare calculations; simulations with craters weighted according to diameter) gave confidence levels ranging from 97% to 99.5%.

Another way of displaying the periodicity, suggested to us by S. Perlmutter, is shown in Figure (4). For every pair of craters in our list of 11 large craters, the difference in their ages was plotted as a Gaussian with the two errors combined in quadrature; these Gaussians were then superimposed. Peaks show in this plot for differences of 28.4 Myr and all multiples thereof.

To estimate the accuracy of our frequency and phase determination, we performed a Monte-Carlo generation of 20 sets of craters in each of which the 11 craters were initially forced to occur at precisely 28 Myr intervals, and then randomly jittered (using Gaussian statistics) according to the uncertainties in the real crater data. The Fourier transform was then taken, and a best fit frequency and phase determined. From these simulations we estimate the uncertainty in our period to be approximately ± 1 Myr, and the uncertainty in the time of the first maximum to be ± 2 Myr.

The periodicity agrees with that of Raup and Sepkoski not only in frequency but also in phase. The age of the first crater maximum, 13 ± 2 million years, is identical with the age of their first "extinction event". One might worry that our frequency is different from that of Raup and Sepkoski (28.4 ± 1 Myr period vs. 26 Myr) and that this would cause their cycles to be out of phase with ours after 100 Myr. However there are uncertainties in the age determination of the paleontological boundaries that increase significantly for ages of 100 Myr and greater. In Figure (5) we have plotted a band representing our 28.4 ± 1 Myr period along with the best estimates for the paleontological ages and errors, as evaluated by Harland et al.[7] With the possible exception of the Tithonian event, a 28.4 Myr periodicity is a good fit to the extinction events of Raup and Sepkoski. Note that there is a slippage of one cycle between the crater events and the extinction events, so that the Permian-Triassic event is cycle 10 in the extinction sequence and cycle 9 in the crater sequence. The cycle slippage occurs in the 150-200 Myr interval, when there are 3 minor extinction events (7 to 15% of the families dying out) but only 2 predicted. We conclude that the record is not well defined in the region of slippage. This is supported by the fact that when Raup and Sepkoski divided the extinction sequence into two halves, they found that 27 to 29 Myr periodicities were significant at better than 95% confidence in both halves. Fischer and Arthur's qualitative cyclicity record[3] shows one less cycle than ours, with the Permian-Triassic event at cycle 8. Again the cycle slippage occurs in the 150-200 Myr region, which is clearly the weakest part of the paleontological-stratigraphic record. The ages of the extinction events are best determined in the most recent four cycles; during this period the agreement in phase between the extinction events and the crater ages adds additional confidence to the fit. The a priori probability that random crater ages would show a periodicity and phase agreeing with that of the extinction events is less than 5 $\times 10^{-3}$.

To test the sensitivity to our chosen cutoffs in age and crater size, we have repeated much of the above analysis for different values of these parameters. We varied the crater diameter cutoff continuously from 0 km to 20 km; the 28.4 Myr peak was significant at all these values, and reached its maximum intensity for a 5 km cutoff (20% higher than the peak in Fig. 2). Inclusion of the data below 5 Myr or above 250 Myr did not significantly affect the peak height, but it did increase the background level. We also tried removing craters from our list to test the sensitivity of our analysis to the presence or absence of particular craters. The only crater in our nominal list of 11 which does not contribute to the 28.4 Myr periodicity is Lappajarvi with age 77 ± 4 Myr. When we lowered the diameter threshold, adding craters, we found a second peak in the power spectrum at .047 Myr^{-1} (period of 21 Myr). A peak at this frequency is also present in Figure 2, but with lesser apparent significance. Since our noise estimates had been made for random distributions of craters, to investigate the meaning of this peak we generated Monte-Carlo data sets which had a sequence of craters with a real 21 Myr or 28 Myr periodicity, jittered by the age errors, in addition to a few craters with random ages. We found that in the presence of a real 28 Myr period, a second spurious peak often appeared at 21 Myr, but that in the presence of a real 21 Myr period there was no false 28 Myr peak. Based on these simulations, we believe that there is no significant evidence for a real 21 Myr periodicity. The 21 Myr peak was strongly suppressed when we either increased the crater diameter threshold above 2 km, or weighted the contribution of the craters to the Fourier transform by a factor proportional to their diameters.

As mentioned earlier, to avoid any possibility of bias in crater selection we deliberately chose not to reevaluate any of the data in doing our initial analysis, but accepted the compilation of Grieve at face value. We now turn our attention to the revised ages from Table 1, which are based on our own search of the literature. Paleontological dates on lake beds within craters have allowed us to add three new craters to the list, Grieve #43 (10 km diameter, age 7 ± 4 Myr), #35 (20 km diameter, age 13 ± 11 Myr), and #65 (15 km diameter, age 185 ± 10 Myr). The second two fit reasonably into our periodicity, which includes 13 Myr and 183 Myr among its cycles. We also list four craters for which there are minor adjustments in the age values or their uncertainties, Grieve #'s 50, 56, 33, and 54. These adjustments make no significant difference in our analysis, with the exception of Grieve #50. This is the 14 km crater at

Lappajarvi which, as we mentioned previously, does not contribute to the spectrum at 28.4 Myr. With the age estimate tightened from 77 ± 4 to 78 ± 2 Myr, we can definitely exclude it from any cyclic process that has a narrow phase of activity, such as that proposed in the solar companion model[5]. It is vital to continue to obtain smaller errors for the craters ages.

The agreement between the period and phase of the crater data and that of the fossil extinctions is strong supporting evidence for the hypothesis that the extinctions were caused by periodic impact showers. The fact that we find typically one or more craters to associate with each cycle, despite the fact that Grieve's compilation covers less than 10% of the earth's surface, implies that many impacts occur during each shower. This is corroborated by the discovery of at least three different levels of microtektites near the Eocene-Oligocene boundary[14]. However given the relatively large crater-age uncertainties, we as yet have no indication that the showers have a short duration. The fact that the periodicity is found primarily among the larger craters suggests that there may be a random background of low energy impacts in addition to the showers. This is plausible if the shower craters come from comets and the background craters from asteroids. Such background impacts, including an occasional very large one, are inevitable in view of the statistics of modern Apollo asteroids[15]. Comet velocities are higher than those of the asteroids, and half of the comets (but none of the asteroids) enter the solar system with retrograde motion leading to head-on impacts. These two factors can increase the impact energy of comets over that of asteroids (assuming equal masses) by an order of magnitude. A modest improvement in the ages measured for a few craters will do much to clarify the nature of the showers.

Acknowledgments: We are very grateful to Saul Perlmutter, both for his help in producing the Fourier transforms, and his help in interpreting them. We have benefited greatly from the critical analysis and suggestions of many of our colleagues, particularly L. W. Alvarez, F. Crawford, and T. Mast.

This research was done while one of us (W.A.) was supported by a fellowship from the John Simon Guggenheim Memorial Foundation, the other (R.A.M.) by a fellowship from the John D. and Catherine T. MacArthur Foundation. It was partially funded by the National Science Foundation Alan T. Waterman Award, by National Science Foundation grant EAR-81-15858, and by the Department of Energy under Contract DE-AC03-76SF00098.

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Table 1

Impact craters with diameters of 5 km or more, ages between 5 and 250 million years, and one standard deviation age uncertainties of 20 Myr or less. The first age given is taken from the compilation by Grieve[4], and it is the primary one used in the analysis done in this paper. No age value was included unless there was an error estimate available. The "Revised Ages" are our own estimates based on current values for decay constants, and on radiometric and paleontological data in the references cited. Only the craters in this list with diameter of 10 km or greater are used in Figs. 1 through 4.

Crater #	Diameter (km)	Age[4] (Myr)	Revised age	ref.	Location
43	10		7 ±4	13	Karla, U.S.S.R.
35	20		13 ±11	8	Haughton, Canada
73 (88*)	24	14.8 ±0.7			Ries, Germany
60	28	38 ±4			Mistastin, Labrador
99	8.5	37 ±2			Wanapitei, Ontario
69	100	39 ±9			Popigai, Siberia
50	14	77 ±4	78 ±2	9	Lappajarvi, Finland
87	25	95 ±7			Steen River, Alberta
18	25	100 ±5			Boltysh, Ukraine
52	17	100 ±20			Logoisk, U.S.S.R.
56	5	118 ±2	119 ±2	12	Mien Lake, Sweden
33	22	130 ±6	133 ±6		Gosses Bluff, Australia
74	23	160 ±5			Rochechouart, France
65	15		185 ±10	10	Obolon, Ukraine
70	80	183 ±3			Puchezh-Katunki, USSR
54	70	210 ±4	214 ±3	11	Manicouagan, Quebec

*Since these two craters are probably from the same event, we included only the larger one.

FIGURE CAPTIONS

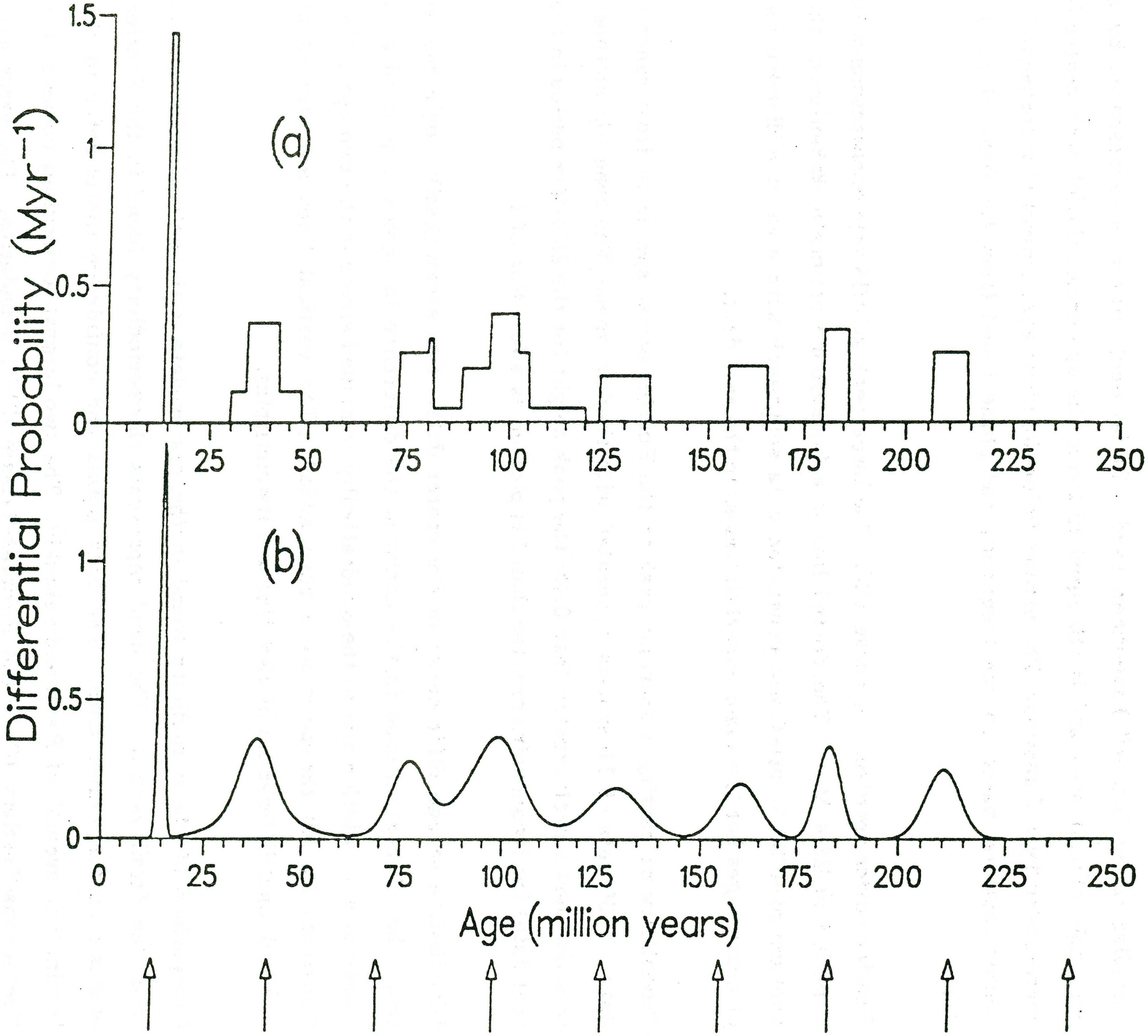
1. Impact craters on the earth with diameter greater than 10 km and age between 5 and 250 Myr. Only craters with listed age uncertainties of 20 Myr or less in the compilation by Grieve[6] have been used. In (a) each crater is represented by a rectangle of unit area and width equal to twice the age error. In (b) each crater is represented by a Gaussian. The arrows below (b) show ages expected from periodic comet showers, based on the frequency and phase found from the best fit to the data.

2. Fourier power spectrum of curve 1(b). The large peak at 0.35 Myr^{-1} corresponds to a period of 28.4 Myr. The dotted line is a background estimate, taken from the average of 1000 Monte-Carlo generated data sets, each with a random distribution of crater ages but the same uncertainties as in the real data.

3. Probability of getting a spurious peak in the Fourier power spectrum from random data. 1000 sets of 11 craters generated with random ages. The fraction of these sets that had a peak greater than 0.46 (the peak height for the 28.4 Myr period in the real data) for frequencies greater than f is plotted as a function of f.

4. Distribution of age differences in the crater data. For every possible pair chosen from the 11 craters used in the analysis, the difference in ages was plotted as a Gaussian with width equal to the quadratically combined errors in the two ages. The Gaussians for all the pairs were then added. The vertical lines are plotted at nominal ages differences of 28.4 Myr and its multiples.

5. Comparison of the periodicity found in the crater data with the extinction events from the fossil record. The band represents the periodicity found in the Fourier analysis of the crater data. The data points and confidence limits refer to the "extinction events" of Raup and Sekoski[3]. The two largest extinctions occur at the Cretaceous-Tertiary (C-T) and Permian-Triassic (P-T) boundaries. The error bars assigned to these events are derived from the review of the time scale by Harland et al[7]. Cycle numbers for extinction events are given in parentheses; slippage of one cycle between the two data sets is discussed in the text. Because of the constraint that paleontological stages must occur in the proper sequence, model ages[7] sometimes fall outside the range of relevant radiometric data, as in the case of the Tithonian.



(a)
(b)
Differential Probability (Myr^{-1})
1.5
1
0.5
0
0
25
50
75
100
125
150
175
200
225
250
Age (million years)

Fig. 1

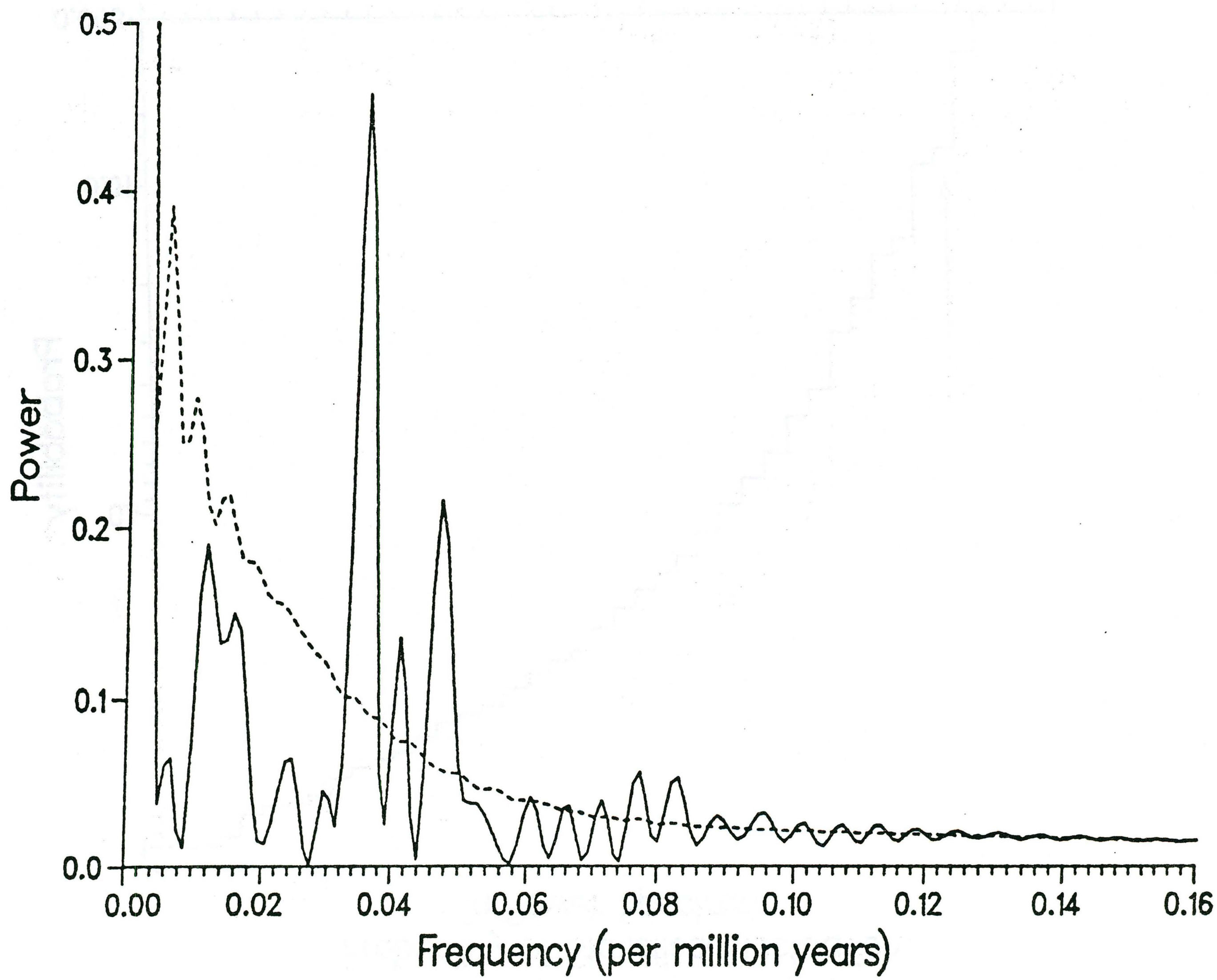

Power
0.5
0.4
0.3
0.2
0.1
0.0
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
Frequency (per million years)

Fig. 2

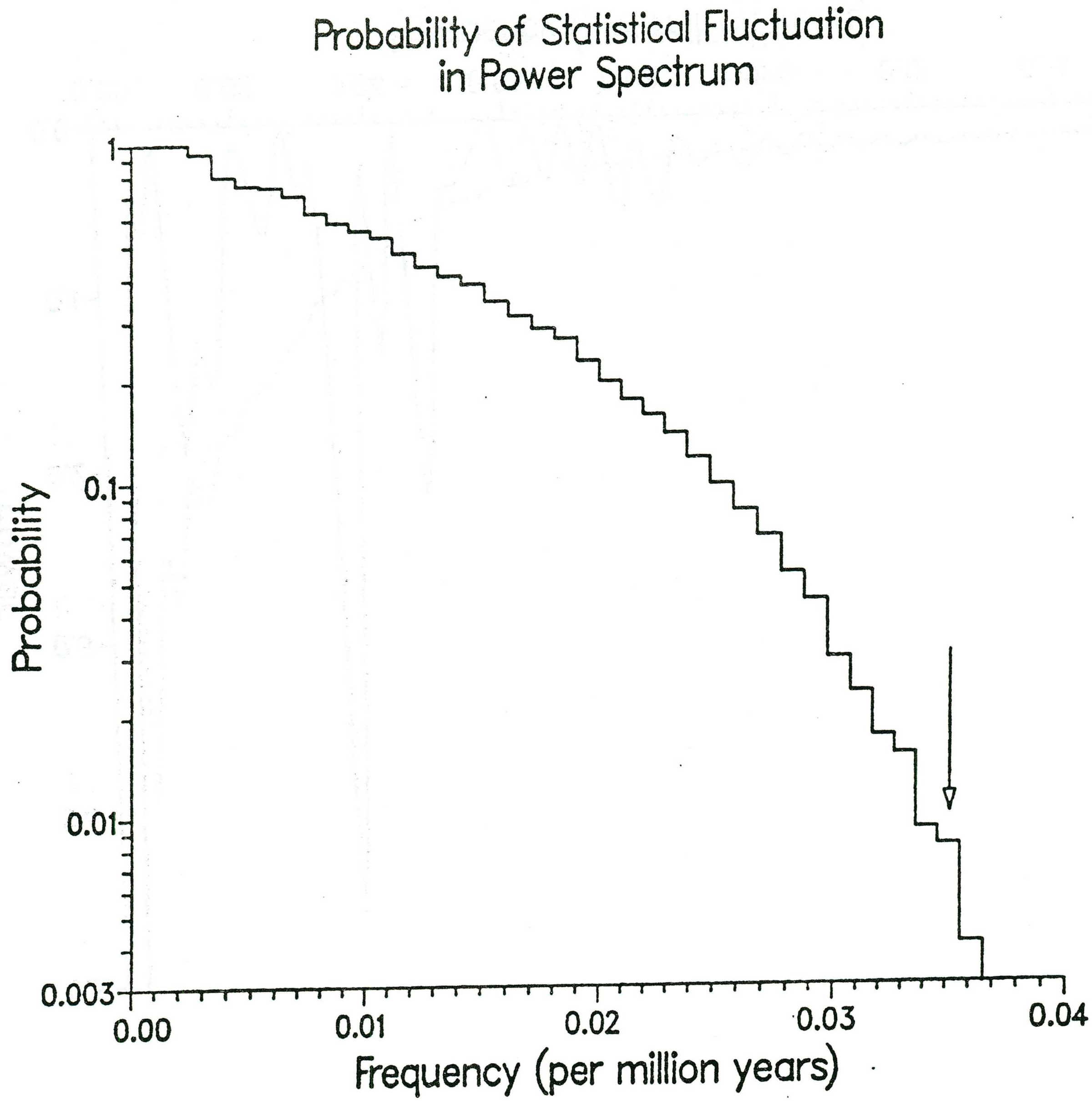
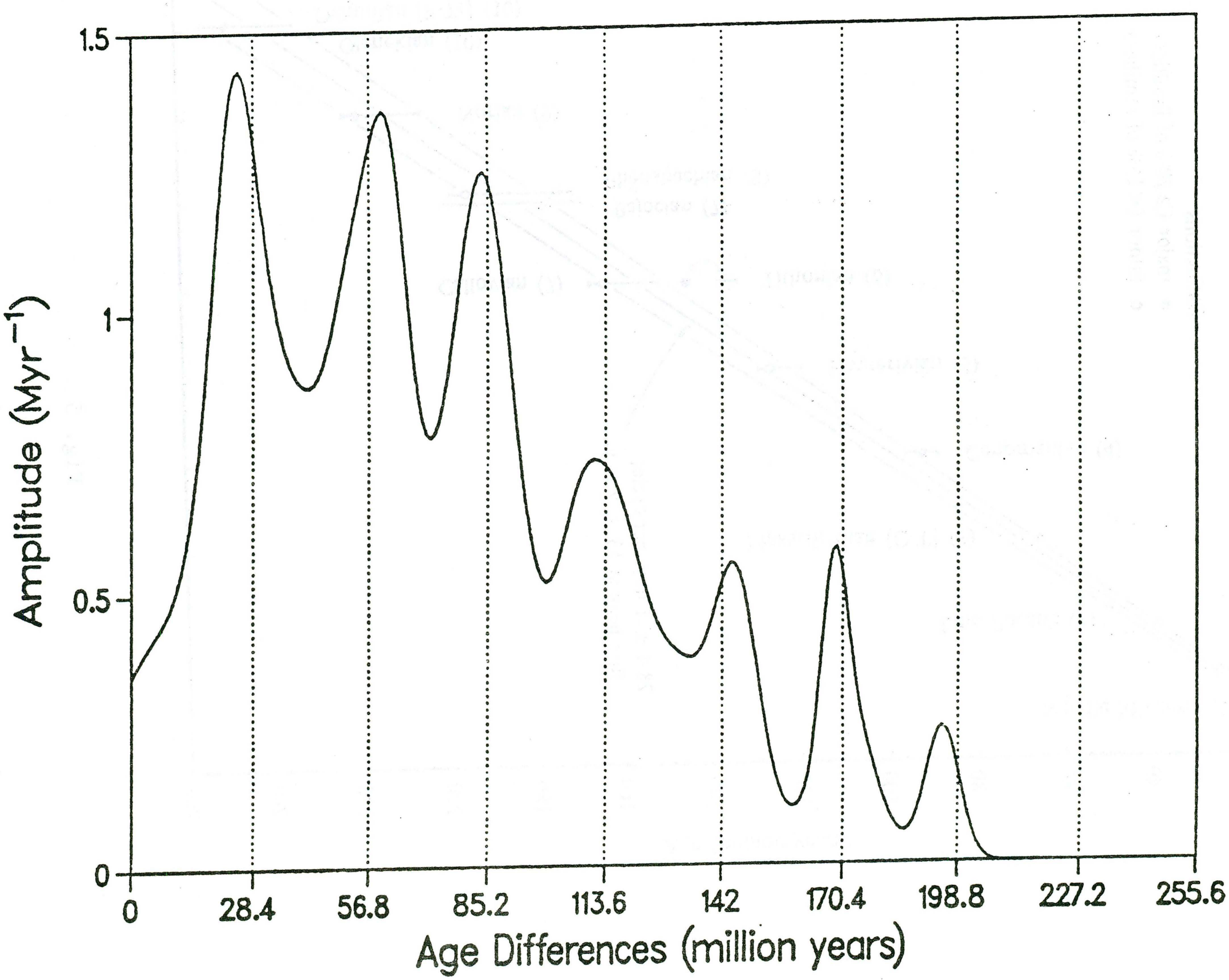

Probability of Statistical Fluctuation
in Power Spectrum
Probability
1
0.1
0.01
0.003
0.00
0.01
0.02
0.03
0.04
Frequency (per million years)

Fig. 3



1.5
1
0.5
0
Amplitude (Myr⁻¹)
0
28.4
56.8
85.2
113.6
142
170.4
198.8
227.2
255.6
Age Differences (million years)

Fig. 4

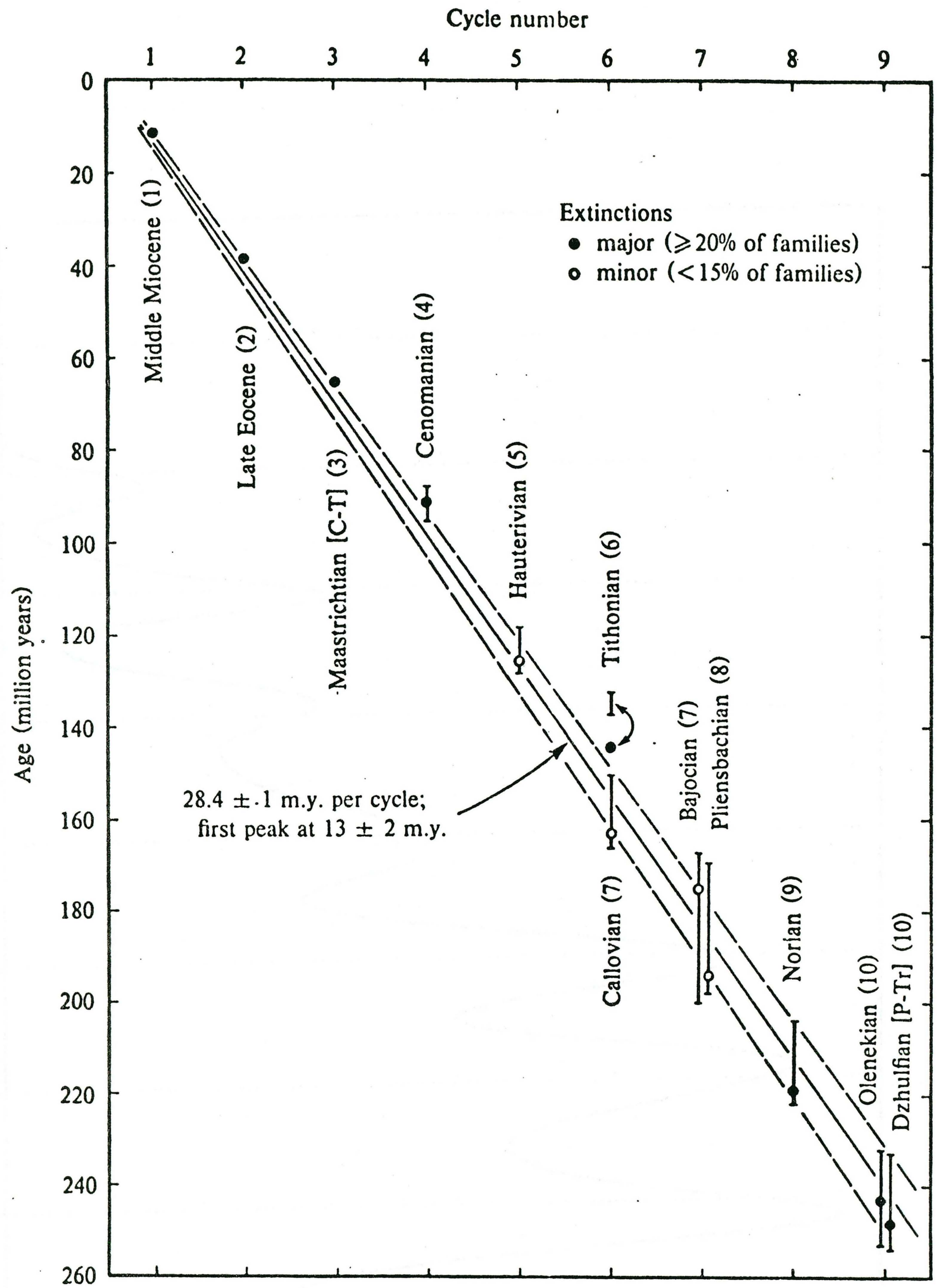

Cycle number
1
2
3
4
5
6
7
8
9
Age (million years)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
Extinctions
● major (≥20% of families)
o minor (<15% of families)
Middle Miocene (1)
Late Eocene (2)
Maastrichtian [C-T] (3)
Cenomanian (4)
Hauterivian (5)
Tithonian (6)
Callovian (7)
Bajocian (7)
Pliensbachian (8)
Norian (9)
Olenekian (10)
Dzhulfian [P-Tr] (10)
28.4 ±.1 m.y. per cycle;
first peak at 13 ± 2 m.y.

Fig. 5