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GEOLOGICAL RHYTHMS AND COMETARY IMPACTS

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Abstract. Time-series analysis reveals two dominant, long-term periodicities approximately equal to 32 and 260 Myr in the known series of geological and biological upheavals during the Phanerozoic Eon. The cycles of these episodes agree in period and phase with the cycles of impact cratering on earth, suggesting that periodic comet impacts strongly influence earth processes.

The geologic record has long been suspected of being periodic (1,2,3). Several collections of geological data possess enough homogeneity, precision, and completeness that statistically meaningful searches for long-term periodicities can be made. One such set of data is the list of geologic ranges of marine organisms compiled by Sepkoski (4). Statistical analysis of the small subset covering Cenozoic and Mesozoic times (the past 250 Myr) has revealed an approximate periodicity of either ~26 Myr (5) or ~30 Myr (6) in marine mass extinctions. We present statistical evidence that both this periodicity and another long-term periodicity dominate also the geologic record of global tectonism over Phanerozoic time (the past 600 Myr).

To avoid any possibility of subjective bias in selecting the data to be analyzed, we have accepted, deliberately without revision, the published lists of dates of the various tectonic phenomena to be studied. These lists are possibly incomplete and may accidently include a few local or minor episodes; furthermore, some dates have large estimated errors, including rounding to the nearest 5 or 10 Myr, especially for the Paleozoic Era. This means that we cannot expect to find a perfect correlation between the dates of related, or possibly related, tectonic phenomena in different data sets. Furthermore, phase lags may well exist and unrelated mechanisms may be at work, among the different kinds of tectonic phenomena. Thus, a fair amount of noise in the data is inescapable.

Simple inspection, often used in the past, is a poor method of analyzing data of this kind for periodicities, since it sometimes fails to reveal periods at all and, at best, cannot predict the statistical significance of any periods detected. We have therefore adopted an objective, non-parametric method of time-series analysis, specifically designed for records in which just the dates (and not the amplitudes) of the events are recorded and noise is a problem (7). In this method, the observed times t are fitted to a linear formula of the type $t = t_0 + nP$ (where P is a trial period, t_0 is a trial value for the most recent epoch, and n is an integer) and the resulting sums of the squares of the residuals are minimized at each trial period. By subtracting the resulting spectrum of residuals for the different trial periods from the continuous part of this spectrum, a spectrum of signal peaks ("residuals indices") is obtained. We specifically point out that the mean time interval for N observations, $(t_N - t_1)/N$, is not (except by accident) a significant period in the sense of having a large residuals index. We do not expect it to be significant, since even a random time series always formally has a mean time interval. Furthermore, numerical tests in ref. 7 and here show that significant periodicities are (usually) remarkably stable in the presence of even large amounts of random scatter, although their precise residuals indices can fluctuate up and down. This means that N is not in general a determining factor. In order to avoid, in our present applications, all the possible spurious signals arising from high-frequency noise and the low-frequency cutoff, we have searched only the period domain extending from one-half the mean time interval between observations in the record up to the record length itself.

The first set of geological data that we have examined consists of major episodes of low global sea level. Mean time intervals of ~32 Myr (Cenozoic and Mesozoic), ~30 Myr (Mesozoic), and 36 ± 11 Myr (Phanerozoic) were previously found in global sea-level data by Fischer and Arthur (1), Ager (8), and Damon (9), respectively. We have performed a time-series analysis (of the type described above) for all major Cenozoic and Mesozoic low sea levels as given in Table 1 of Vail et al. (10) (these 8 episodes have been dated according to ref.

11 and are listed in our Table 1). The spectrum of the residuals index, shown in Fig. 1a, contains two high peaks, one around 33 Myr and the other around 21 Myr.

It has been suggested that sea-floor spreading, which shows episodic discontinuities in both speed and direction, may affect global sea level (12,13). Schwan's (13) dates of major discontinuities that seem to be global in nature are listed in Table 1. Spectral analysis of these 7 dates, which cover the last 180 Myr, shows peaks around 34, 23, and 18 Myr (Fig. 1b).

Active tectonism on the continents also appears to be correlated with episodes of low sea level, according to Damon (9). Thus, Williams (2) proposed recurrences of tectonism at intervals of 30-50 Myr. We have formally analyzed the dates of the pulse maxima for the 18 principal Phanerozoic orogenic phases of Stille (14), which are still considered authoritative (2) (but have been redated by Roubault *et al.* (15) and are listed in our Table 1). Fig. 2 reveals a cluster of 3 high spectral peaks located around 31, 33, and 36 Myr and a fourth high peak at 20 Myr. When the data are separated into two consecutive time intervals, the high peaks show up at periods of 32 Myr and 20 Myr (t = 0-250 Myr) and at 35 Myr and 22 Myr (t = 251-570 Myr).

The frequencies of geomagnetic reversals, which may be related to global tectonism (2), have been independently studied by Negi and Tiwari (16), using Walsh spectrum analysis. These authors find that, over Phanerozoic time, the dominant intermediate-term periodicity is 34 Myr. If the time series is divided into two subseries (t = 0-285 Myr and t = 286-570 Myr), the dominant period becomes 32 Myr.

When longer trial periods are considered, Negi and Tiwari obtain the largest spectral peak in geomagnetic reversal frequencies at 285 Myr. Different analytical techniques and other geomagnetic data sets have given for this long periodicity 300 ± 40 Myr (Crain et al.), ~350 Myr (McElhinny), 250 ± 50 Myr (Ulrych), and 297 ± 34 Myr (Irving and Pullaiah) (17,18). The apparent discrepancies probably arise from the fact that the record length in all cases covers only two of these long cycles.

According to Fig. 2, orogenic tectonism also shows a broad, but weak, spectral peak centered around 270 Myr during the Phanerozoic. Eight orogenic episodes that have been listed for the Precambrian (t = 1200-3600 Myr) by Seyfert and Sirkin (19) yield a similar, but sharper, periodicity of about 220 Myr. There are other forms of tectonism, e.g. alkaline intrusions, which episodically affect continental interiors. Using Macintyre's (20) set of 49 dated Canadian and non-Canadian carbonatite intrusions during Phanerozoic and Proterozoic time (t = 0-1840 Myr) and adopting for any date that he lists as a range just the midpoint, we find a very high spectral peak around 235 Myr. This period is (at least formally) well-determined from nearly 8 cycles and agrees with Macintyre's estimated average interval of 233 Myr between emplacement episodes. Similarly, we have performed a spectral analysis of 38 dated Phanerozoic kimberlite intrusions (t = 0-420 Myr), taken from the following sources: Davis for the U.S.S.R., Brazil, and the Solomon Islands; Crough et al. for West Africa and Zaire; and England and Houseman for North America and Southern Africa (21). The largest spectral peak occurs around 280 Myr.

The foregoing results suggest that the earth's history has been punctuated by periodic events of global magnitude, which have affected the evolution of oceans, continents, the geomagnetic field, and life. Despite the inevitable uncertainties in the radiometric and stratigraphic dates and in the degree of completeness of the known geologic record, our statistical search for long cycles has consistently turned up two dominant periodicities at 31-36 and 220-290 Myr during the Phanerozoic Eon (22).

What could have produced these geological cycles? There are no known internal terrestrial mechanisms operating even approximately regularly with these frequencies (2, 3). However, various external forcing mechanisms do exist. Collisions with the earth by large bodies like comets and asteroids are capable, in theory, of imparting enough energy and momentum to trigger the observed geophysical and climatic disturbances (3, 19, 23). We have recently shown that episodes of terrestrial impact cratering apparently took place with a mean period of 31 ± 1 Myr during the Cenozoic and Mesozoic Eras (6). In our analysis, we used Grieve's (24) lists of impact-crater ages, omitting ages that were less than 1 Myr (to avoid a bias toward the recent) or listed only as upper limits; 41 ages were used (25). The results of a similar analysis of the ages of 65 known Phanerozoic impact craters (but including ages less than 1 Myr) are shown in Fig. 3a. For comparison, 32 craters with diameters $D > 10$ km, which have a higher survival rate and therefore are more nearly uniformly sampled in time (24), have been used for Fig. 3b; their ages go back to 365 Myr (omitting one outlier at 485 Myr). In view of the fact that 71%, 57%, and 29% of the full set of 65 crater ages are divisible by 5, 10, and 50, respectively, the dominant periodicity is quite clearly 32 ± 1 Myr. If only the 22 Paleozoic impact craters (of all sizes) are used, the dominant period is 33 ± 1 Myr (26).

Many of the smaller peaks in the period spectrum for the impact-crater ages are high enough to warrant further investigation. The highest of these peaks in Figs. 3a and 3b, together with an additional high peak at ~400 Myr, are listed by their periods in column 1 of Table 2. Our preferred interpretation of these 10 periods, based on a simple method of diagnosis to detect the expected harmonics and multiples (7) and a principle of economy, appears in column 6 of the table. With allowance for the distorting effect of noise in the time series, which can shift slightly the periods of the spectral peaks and magnify or diminish the amplitudes of the peaks, we are able to identify two basic periods in terrestrial impact cratering: ~32 Myr and ~260 Myr, together with their lowest harmonics, lowest integer multiples, and combinations thereof, some of which show up strongly as a result of gaps and bunching in the age data (7).

Similarly, the most significant spectral peaks appearing in the comparable time-series analyses of Phanerozoic geologic events are also listed by their periods in Table 2. Agreement between these geologic periodicities and the periodicities obtained for the impact craters is very good (except in two relatively insignificant cases: the largest detected multiple of P_1 and the poorly determined $2P_2$, which is nearly of the same size as the record length and, in fact, could be an independent period). Another possible independent period (which appears prominent in some of the geologic data) has a length of 20-23 Myr, but is more likely just the multiple period $2P_1/3$; in contrast, the multiples $3P_1/4$ and $4P_1/3$ are found to be rather weak periods in most of the data. Since the large array of detailed agreements exists in spite of the different numbers of dates occurring in the time-series analyses (N ranges from 18 to 65), we conclude that large-body impacts and global geologic crises are most likely related.

Cyclicity in impact cratering could possibly arise from an astronomical mechanism that we recently proposed (6). If the solar system's family of comets is by some means gravitationally disturbed by an outside body, then as Hills (27) showed, a shower of comets will be directed to relatively small perihelion distances, where some of the comets will hit the earth. We suggested that such gravitational disturbances could arise from periodic encounters of the solar system with massive dark interstellar clouds of gas and dust. The fundamental astronomical period expected according to our model is the half-period of the solar system's vertical oscillation about the plane of the Galaxy (time between one plane crossing and the next), which is approximately 33 ± 3 Myr (6). Since massive interstellar clouds show some, though not a strong, concentration to the galactic plane, our mechanism provides an underlying, regular mean periodicity, coupled with a sizable scatter of the (otherwise stochastically independent) time intervals between successive encounters of the solar system with interstellar clouds. This is the type of periodicity exhibited by the geological and cratering data.

The statistical significance of our present results can now be estimated by recognizing (i) that the basic cratering period and the basic geological period lie in a very narrow range, 31-36 Myr, and (ii) that the expected astronomical period is 33 ± 3 Myr. For each observed time series, we have accordingly generated and analyzed by the method of ref. 7 a set of 1000 random time series covering the same interval of time with the same number of sample times. If at a given trial period the residuals index in the Monte Carlo simulations exceeds the residuals index in the empirical spectrum a total of *m* times, we can reject the hypothesis of randomness at a significance level of approximately (m/1000) x 100%. These levels turn out to be 5%, 10%, 1%, and 0.1% at P = 33 ± 3 Myr, in the case of low sea levels, sea-floor spreading discontinuities, tectonic episodes, and impact cratering, respectively. A more general measure of the statistical significance of our results is the calculated probability of obtaining an accidental coincidence between the basic geological period (33 ± 3 Myr), the basic impact-cratering period (32 ± 1 Myr), and the only known regular galactic period (33 ± 3 Myr). This probability is less than 10^{-4}.

Within the uncertainties inherent in any time-series analysis of the present kind, the mean phases of the derived geological and astronomical cycles also agree. Although phase lags may be expected to occur for geophysical reasons, and may well exist (e.g., for the sea-floor spreading discontinuities), the lags are mostly lost in the statistical errors of t_0 (Table 3). Thus, the most recent epoch of crossing of the galactic plane is statistically indistinguishable from the present time, according to virtually all of the geological and astronomical evidence that we have analyzed.

At present, we have no explanation for the very long period $P_2 \approx 260$ Myr. The statistical significance of this period is difficult to evaluate because of the width of the spectral peak in all of our data. Within the framework of possible galactic models, there are a number of theoretically expected periodicities related to encounters between the solar system and dense interstellar-cloud complexes in the major spiral arms, as the solar system revolves around the galactic center; these predicted periodicities range between one-half and four times the "galactic year" of 250 ± 50 Myr (28).

Our quantitative results suggest that the earth's tectonic processes are periodically punctuated, or at least modulated, by episodes of cometary impacts, and that the slow rhythms of terrestrial geology may be driven by a combination of extraterrestrial forces that have been stable during at least the Phanerozoic Eon.

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reproduces their result, since it gives P = 28.5 ± 1 Myr and t_0 = 13 ± 3 Myr. However, Alvarez and Muller omitted 3 well-dated craters with D > 10 km and with ages less than 5 Myr (24). By including in the analysis these 3 craters (which have ages of 1.3, 3.5, and 4.5 Myr), the method of ref. 7 yields P = 30 ± 1 Myr and t_0 = 8 ± 3 Myr. This agrees with our previously derived result, P = 31 ± 1 Myr and t_0 = 5 ± 6 Myr, for 41 craters of all sizes in the same age range (1-250 Myr). It is now clear that Alvarez and Muller obtained values of P and t_0 that are significantly different from ours in ref. 6 because they excluded the most recent large craters.

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Table 1. Dates (Myr BP) of marine and terrestrial tectonic episodes during the Cenozoic, Mesozoic, and Paleozoic Eras. The columns are not expected to correlate exactly for reasons given in the text.

Low sea levels	Sea-floor spreading discontinuities	Tectonic episodes (Cenozoic and Mesozoic)	Tectonic episodes (Paleozoic)
2	10	2	260
5	17	7	295
27	40	37	320
52	58	65	325
63	77	80	345
94	112	100	395
131	148	140	435
198		195	500
		225	570

Table 2. Periods in Myr corresponding to the highest peaks in the spectral analyses of five Phanerozoic time series.

Impact craters (N = 65)	Tectonic episodes (N = 18)	Carbonatite intrusions (N = 28)	Kimberlite intrusions (N = 38)	Geomagnetic reversals[†] (N = 24)	Probable interpretations
12	12	13	12	12	$\frac{1}{3} P_1$ (11), $\frac{2}{5} P_1$(13)
16	16	16	16	16[‡]	$\frac{1}{2} P_1$ (16)
20	20	23 ± 4	23	21	$\frac{2}{3} P_1$(21)
32 ± 1	33 ± 3	34 ± 5	35 ± 1	33 ± 1	P_1(32)
49	44	47	56	47	$\frac{3}{2} P_1$(48)
61	61	53	68	63	$2P_1$ (64)
70	81	74	--	71	$\frac{5}{2} P_1$ (80)[¶]
96	--	90	138	114	$3P_1$ (96)[¶]
260	270	235[*]	280	285	P_2 (260)
~400	--	560[*]	--	~700[§]	$2P_2$ (520)

[*] Derived by including 21 Proterozoic dates (t = 600-1840 Myr) (making a total of N = 49).

[†] Negi and Tiwari (16).

[‡] P ~ 15 Myr according to Mazaud *et al*. (17) for t = 0-100 Myr.

[§] Also obtained by Ulrych (17).

[¶] Few of the spectral peaks for the large multiple periods are expected to be prominent in any given time series (7), and, at most, only two such periods happen to show up in each of the present time series.

Table 3. Summary of the mathematical solutions for geologic periodicities (all times in Myr).

Episodes	N	Time range	P_1	P_2	$(t_o)_1$	$(t_o)_2$
Low sea levels	8	0-250	33	-	-3±5	-
Sea-floor spreading discontinuities	7	0-180	34	-	13±4	-
Tectonic episodes	18	0-600	33±3	270	2±8	40±4
	8	1200-3600	-	220	-	-
Carbonatite intrusions	28	0-600	34±5	235	-5±10	120±10
	49	0-1840	-	235	-	120±20
Kimberlite intrusions	38	0-420	35±1	280	9±6	100±10
Geomagnetic-reversal frequencies*	24	0-570	33±1	285	-	-
Mass extinctions†	9	0-250	30±1	-	10±7	-
Impacts	65	0-600	32±1	260	5±4	40±10

*Negi and Tiwari (16), using Walsh spectrum analysis.

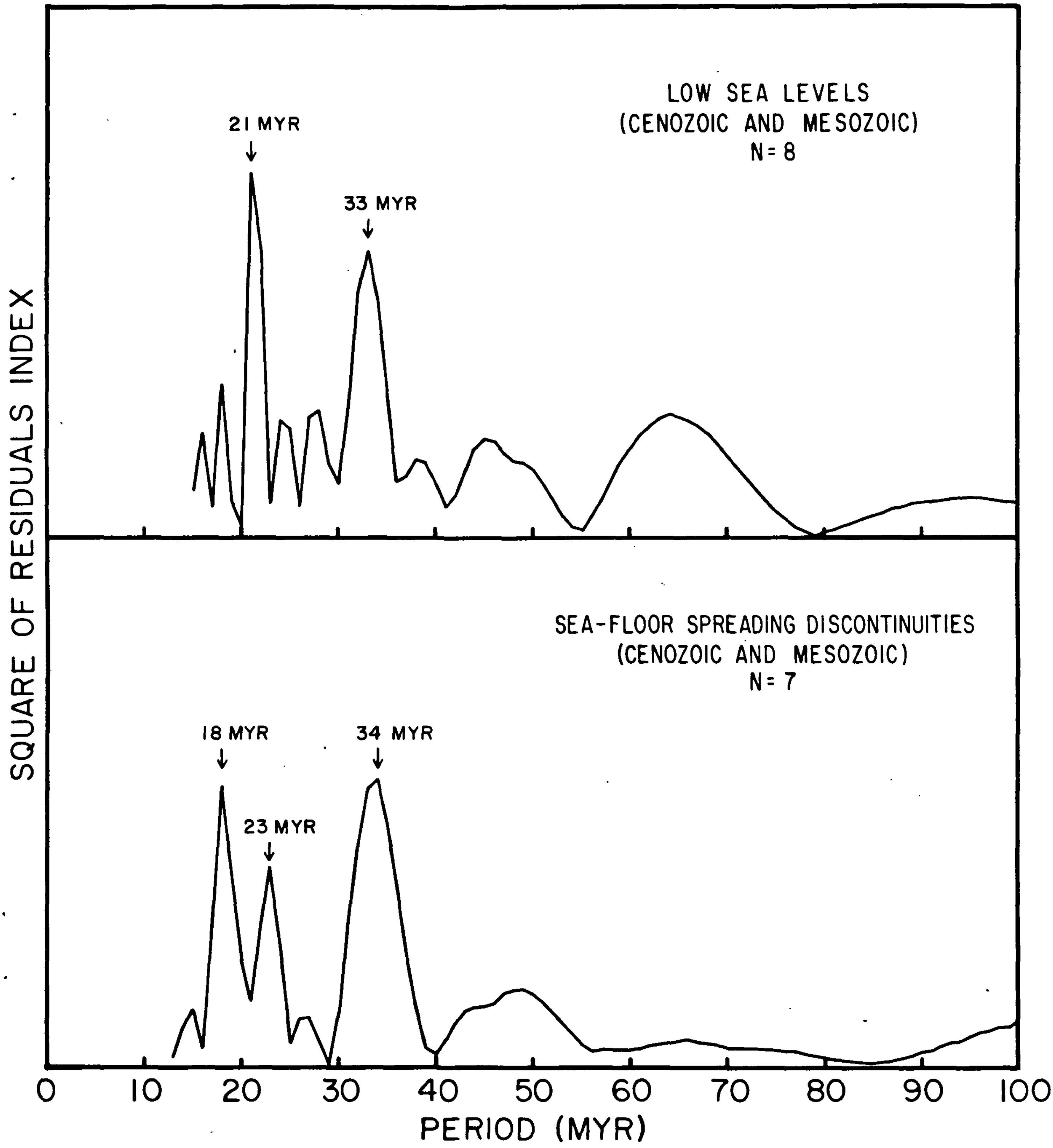
†Rampino and Stothers (6), using least-squares analysis.

FIGURE CAPTIONS

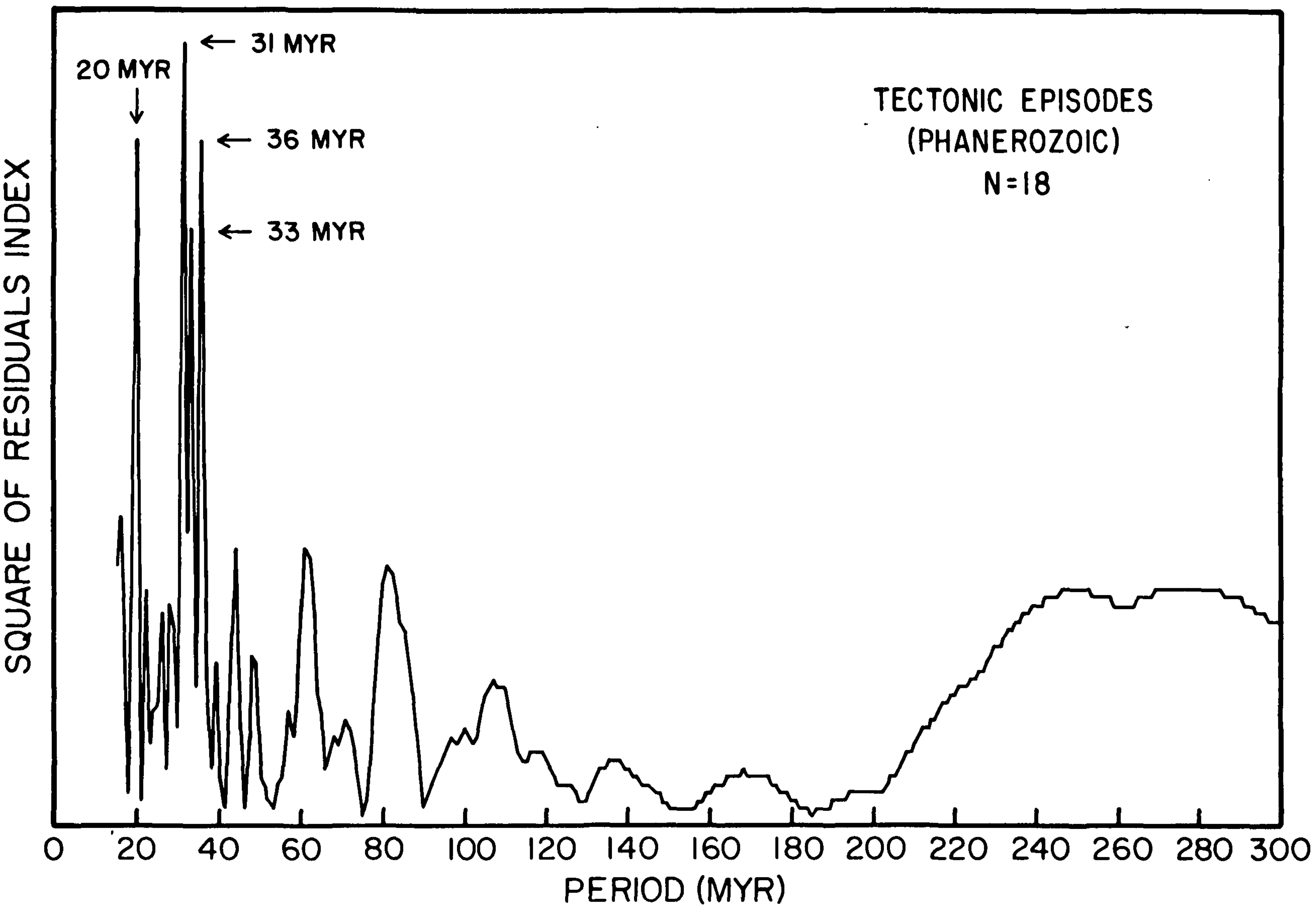
Fig. 1. Marine phenomena: the square of the residuals index as a measure of goodness of fit for various trial periods.

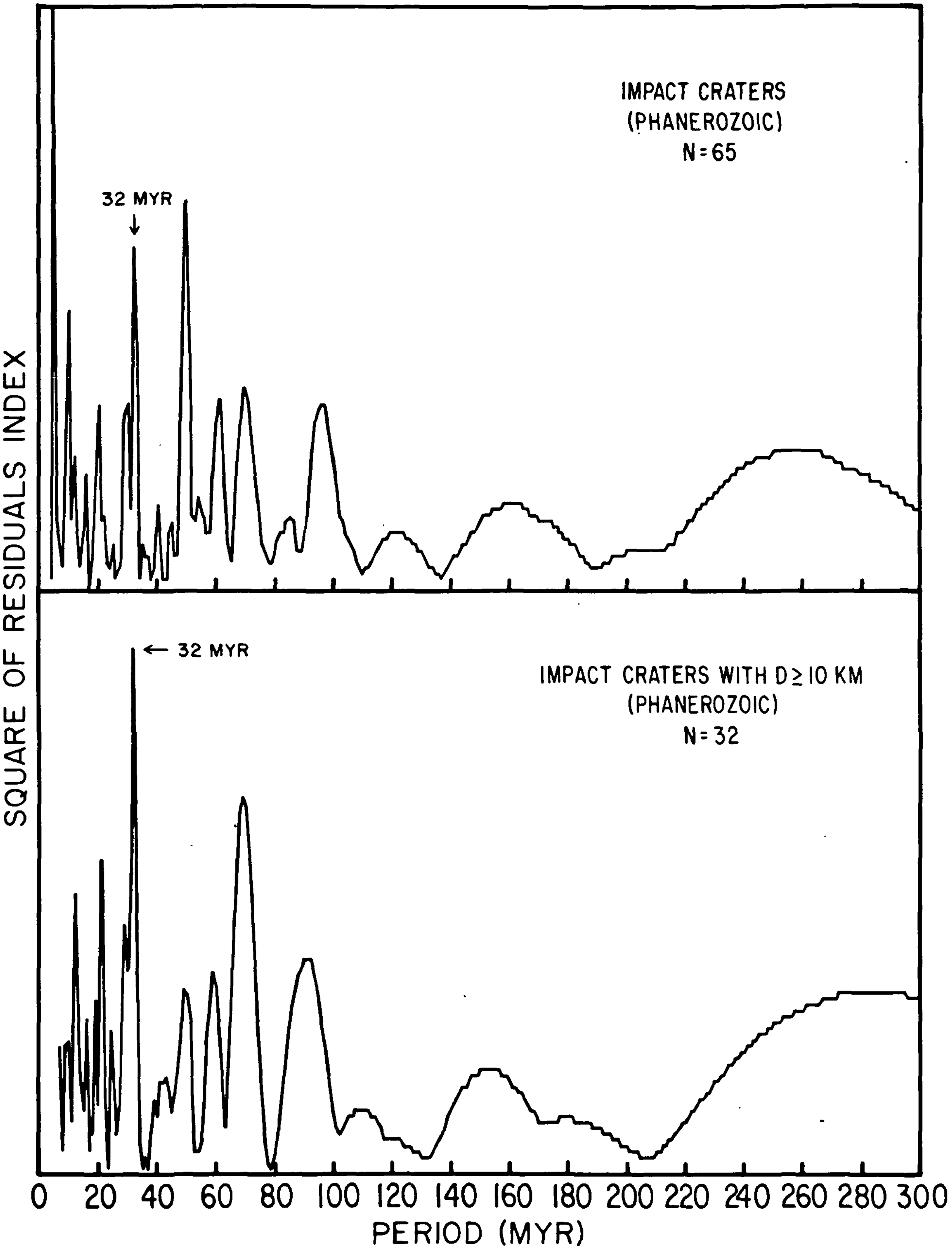
Fig. 2. Tectonic episodes: the square of the residuals index as a measure of goodness of fit for various trial periods.

Fig. 3. Terrestrial impact craters: the square of the residuals index as a measure of goodness of fit for various trial periods. The unmarked high spectral peaks at periods of 5, 10, and 50 Myr are artifacts due to rounding of many of the older crater ages.



LOW SEA LEVELS
(CENOZOIC AND MESOZOIC)
N= 8
21 MYR
33 MYR
SEA-FLOOR SPREADING DISCONTINUITIES
(CENOZOIC AND MESOZOIC)
N= 7
18 MYR
23 MYR
34 MYR
SQUARE OF RESIDUALS INDEX
0
10
20
30
40
50
60
70
80
90
100
PERIOD (MYR)


20 MYR
31 MYR
36 MYR
33 MYR
TECTONIC EPISODES
(PHANEROZOIC)
N=18
SQUARE OF RESIDUALS INDEX
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
PERIOD (MYR)


IMPACT CRATERS
(PHANEROZOIC)
N=65
32 MYR
32 MYR
IMPACT CRATERS WITH D≥10 KM
(PHANEROZOIC)
N=32
SQUARE OF RESIDUALS INDEX
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
PERIOD (MYR)