phenomenon is predicated first on correct identification of events and only then by statistical analysis, established validity of the latter (*1*) becomes extraneous if the former is uncertain.

In 1983, the results of anomalon studies in which track-etching techniques were used in CR-39 plastic became available. The track method has excellent Z resolution and is sensitive to relativistic heavy ions with $Z > 8$ to 10 and to interactions with $\Delta Z \geq 1$. My convoy explanation is not clearly able to account for those observations by Heinrich *et al.* (*5*) and Tincknell *et al.* (*6*) in plastic which qualitatively appear to support those in emulsion. However, in 1984, both Stevenson *et al.* (*15*) and Symons *et al.* (*16*) reported the probable absence of anomalous mean free paths in plastic as the result of excellent statistics in conjunction with Cherenkov counting techniques. Moreover, in 1984, Heinrich *et al.* (*17*) improved their track-etching experiment and did not observe statistically significant anomalous mean free paths in plastic.

In conclusion, recent Cherenkov and track measurements have refuted the evidence for the anomalon effect in plastics. The authors of those studies rightly state that their results do not eliminate the possible production of anomalons on the heavier silver and bromine nuclei of emulsions. However, I have called attention to serious problems with the emulsion results vis-à-vis fragment Z-distributions at odds with counter and radiochemical measurements. I also have shown that the increased reaction probability evident in emulsion tracks of relativistic projectile fragments during their first few centimeters can be explained by a conventional model which includes two different final-state descriptions: (i) the possibility that multiple components of the forward-peaked projectile fragmentation process share a common track, and (ii) the likelihood that some fragments are produced in transient, low-excitation particle-unbound states that decay in flight into collinear products. In each separate situation, only a fraction (≤ 20 percent) of the observed events needs to be of the more complex but conventional nature summarized above. Both would reasonably be expected to contribute to explaining the seemingly anomalous values consistently obtained for experimental interaction mean free paths in emulsion via the prescribed but suspect procedure.

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References and Notes

1. E. M. Friedlander *et al.*, *Phys. Rev. Lett.* **45**, 1084 (1980); E. M. Friedlander *et al.*, *Phys. Rev. C* **27**, 1489 (1983).
2. A. L. Robinson, *Science* **210**, 174 (1980); D. E. Thomsen, *Sci. News* **123**, 284 (1982); *ibid.* **124**, 20 (1983); *ibid.* **125**, 118 (1984).
3. H. B. Barber, P. S. Freier, C. J. Waddington, *Phys. Rev. Lett.* **48**, 856 (1982); M. M. Aggarwal, K. B. Bhalla, G. Das, P. L. Jain, *Phys. Lett. B* **112**, 31 (1982).
4. P. L. Jain and G. Das, *Phys. Rev. Lett.* **48**, 305 (1982).
5. W. Heinrich *et al.*, *Nucl. Phys. A* **400**, 315c (1983).
6. M. L. Tincknell, P. B. Price, S. Perlmutter, *Phys. Rev. Lett.* **51**, 1948 (1983).
7. P. J. Karol, *Phys. Rev. C* **11**, 1203 (1975); *Can. J. Chem.* **61**, 750 (1983).
8. A more appropriate scaling would be by mass number (A) (implying an isotope effect). Accordingly, for $\epsilon \sim 0.8$, I calculate $<\lambda(A> = \Lambda A^{-b} = 26.3A^{-0.41}$ in emulsion and $<\lambda(A)> = 37.5A^{-0.48}$ in CR-39 plastic.
9. J. R. Grover and A. A. Caretto, *Annu. Rev. Nucl. Sci.* **14**, 51 (1964); J. B. Cummings, R. W. Stoenner, P. E. Haustein, *Phys. Rev. C* **14**, 1554 (1976); H. H. Heckman, D. E. Greiner, P. J. Lindstrom, H. Shwe, *ibid.* **17**, 1735 (1978); D. L. Olson *et al.*, *ibid.* **24**, 1529 (1981).
10. Further discussion in (*1*) concerns analysis of two-link chain events for $\Delta Z = 0$, 1 vis-à-vis those for $\Delta Z = 2$ to 5 and might seem to exclude neutron consorts. The anomalous mean-free-path behavior is equally evident in each set, $\Delta Z = 0$ being indicative of a neutron-induced interaction. However, in a two-link chain topology, the second event is associated with the main PF more than 95 percent of the time. According to the data of Friedlander *et al.*, 30 to 40 percent of the "normal" PF's in this group have $\Delta Z = 0$, 1. As a result, segregation of events by ΔZ is not very discriminating for or against neutron-induced processes.
11. R. L. Clarke *et al.*, *Phys. Rev. D* **27**, 2773 (1983).
12. P. L. Jain, M. M. Aggarwal, K. L. Gomber, *Phys. Rev. Lett.* **52**, 2213 (1984).
13. G. D. Westfall *et al. Phys. Rev. C* **19**, 1309 (1979).
14. W. R. Webber and D. A. Brautigam, *Astrophys. J.* **260**, 894 (1982).
15. J. D. Stevenson, J. A. Musser, S. W. Barwick, *Phys. Rev. Lett.* **52**, 515 (1984).
16. T. J. M. Symons *et al.*, *ibid.*, p. 982.
17. W. Heinrich *et al.*, *ibid.*, p. 1401.
18. G. M. Chernov *et al.*, *Nucl. Phys. A* **412**, 534 (1984).
19. E. M. Friedlander, H. H. Heckman, Y. J. Karant, *Phys. Rev. C* **27**, 2436 (1983).
20. Supported by the U.S. Department of Energy Office of High Energy and Nuclear Physics.

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Geological Rhythms and Cometary Impacts

Abstract. *Time-series analysis reveals two dominant, stable long-term periodicities approximately equal to 33 ± 3 and 260 ± 25 million years in the known series of geological and biological upheavals during the Phanerozoic Eon. Because the cycles of these episodes agree in period and phase with the cycles of impact cratering on Earth, these results suggest that periodic comet impacts strongly influence global tectonism and biological evolution. These two periodicities could arise from interactions of the solar system with interstellar clouds as the solar system moves cyclically through the Galaxy.*

The geological record has long been suspected of being periodic (*1–3*). Several collections of geological data possess enough homogeneity, precision, and completeness to permit statistically meaningful searches for long-term periodicities. One such data set is the list of geological ranges of marine organisms compiled by Sepkoski (*4*). Statistical analysis of the small subset covering Cenozoic and Mesozoic times [the past 250 million years (m.y.)] has revealed an approximate periodicity of either ~26 m.y. (*5*) or ~30 m.y. (*6*) in marine mass extinctions. We present here statistical evidence that this periodicity and another long-term periodicity (at ~260 m.y.) dominate the geological record of global tectonism over Phanerozoic time (the past 600 m.y.).

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 m.y., 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, nonparametric 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. 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 conducted by Stothers (7) and here show that significant periodicities are (usually) remarkably stable in the presence of even large amounts of random scatter, although their residuals indices can mildly fluctuate. 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 m.y. (Cenozoic and Mesozoic), ~30 m.y. (Mesozoic), and 36 ± 11 m.y. (Phanerozoic) were 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 eight episodes have been dated according to the time scale of Palmer (11) and are listed in Table 1]. The spectrum of the residuals index, shown in Fig. 1a, contains two high peaks, one at ~33 m.y. and the other at ~21 m.y.

Table 1. Dates (millions of years ago) 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

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 seven dates, which cover the last 180 m.y., shows peaks at ~34, ~23, and ~18 m.y. (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 to 50 m.y. 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 which have been redated by Roubault *et al.* (15) and are listed in Table 1]. Figure 2 reveals a cluster of three high spectral peaks located at ~31, ~33, and ~36 m.y. and a fourth high peak at 20 m.y. When the data are separated into two consecutive time intervals, the high peaks show up at periods of 32 and 20 m.y. (t = 0 to 250 m.y.) and at 35 and 22 m.y. (t = 251 to 570 m.y.).

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 researchers find that, over Phanerozoic time, the dominant intermediate-term periodicity is 34 m.y. If the time series is divided into two subseries (t = 0 to 285 m.y. and t = 286 to 570 m.y.), the dominant period becomes 32 m.y.

When longer trial periods are considered, Negi and Tiwari obtained the largest spectral peak in geomagnetic reversal frequencies at 285 m.y. Different analytical techniques and other geomagnetic data sets have given for this long periodicity 300 ± 40 m.y. [Crain *et al.* (17)], ~350 m.y. [McElhinny (18)], 250 ± 50 m.y. [Ulrych (19)], and 297 ± 34 m.y. [Irving and Pullaiah (20–22)]. 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 m.y. during the Phanerozoic. Eight orogenic episodes that have been listed for the

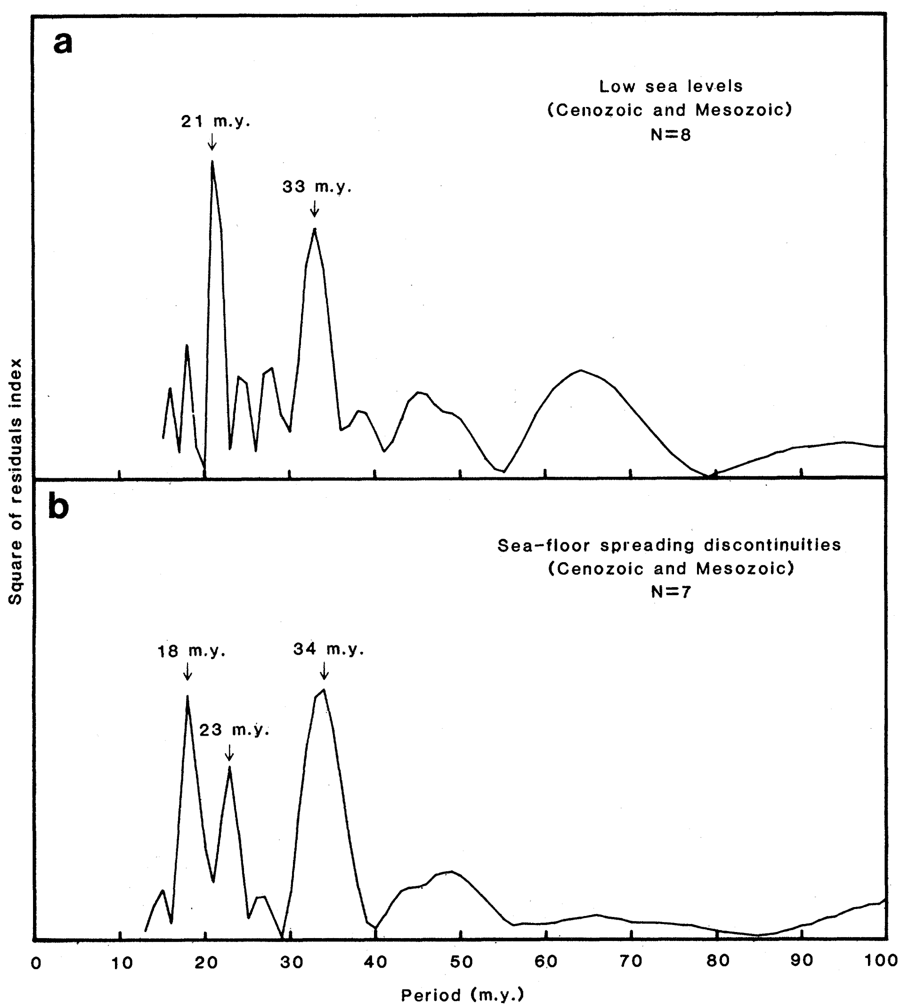

Fig. 1. Marine phenomena: the square of the residuals index as a measure of goodness of fit for various trial periods. (a) Low sea levels. (b) Sea-floor spreading discontinuities.

Precambrian (t = 1200 to 3600 m.y.) by Seyfert and Sirkin (*23*) yield a similar, but sharper, periodicity of about 220 m.y. There are other forms of tectonism, for example, alkaline intrusions, which episodically affect continental interiors. Using Macintyre's (*24*) set of 49 dated Canadian and non-Canadian carbonatite intrusions during Phanerozoic and Proterozoic time (t = 0 to 1840 m.y.) and adopting for any date that he lists as a range just the midpoint, we find a very high spectral peak at ~235 m.y. This period is (at least formally) well determined from nearly eight cycles and agrees with Macintyre's estimated average interval of 233 m.y. between emplacement episodes. Similarly, we have performed a spectral analysis of 38 dated Phanerozoic kimberlite intrusions (t = 0 to 420 m.y.), taken from the following sources: Davis (*25*) for the U.S.S.R., Brazil, and the Solomon Islands; Crough *et al.* (*26*) for West Africa and Zaire; and England and Houseman (*27*) for North America and Southern Africa. The largest spectral peak occurs at ~280 m.y.

The foregoing results suggest that 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 geological record, our statistical search for long cycles has consistently turned up two dominant periodicities at 30 to 36 m.y. and 235 to 285 m.y. during the Phanerozoic Eon (*28*).

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 Earth by large bodies such as comets and asteroids are capable, in theory, of imparting enough energy and momentum to trigger the observed geophysical and climatic disturbances (*3, 23, 29*). We have recently shown that episodes of terrestrial impact cratering apparently took place with a mean period of 31 ± 1 m.y. during the Cenozoic and Mesozoic eras (*6*). In our analysis, we used Grieve's (*30*) lists of impact-crater ages, omitting ages that were less than 1 m.y. (to avoid a bias toward the recent) or listed only as upper limits; 41 ages were used (*31*). The results of a similar analysis of the ages of 65 known Phanerozoic impact craters (but including ages less than 1 m.y.) are shown in Fig. 3a. For comparison, 32 craters with diameters $D \geq 10$ km, which have a higher survival rate and therefore are more nearly uniformly sampled in time (*30*), have been used for Fig. 3b; their ages go back to 365 m.y. (omitting one outlier at 485 m.y.). In view of the fact that 71, 57, and 29 percent of the full set of 65 crater ages are divisible by 5, 10, and 50, respectively, the dominant periodicity is quite clearly 32 ± 1 m.y. If only the 22 Paleozoic impact craters (of all sizes) are used, the dominant period is 33 ± 1 m.y. (*32*).

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 Fig. 3, a and b, together with an additional high peak at ~400 m.y., are listed by their periods in column 1 of Table 2. Our preferred interpretation of these ten 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

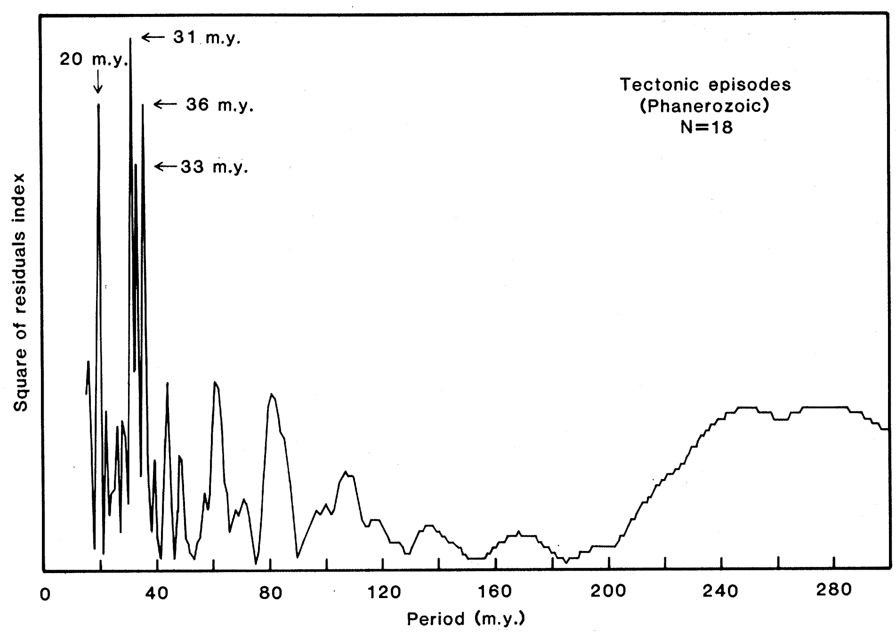

Fig. 2. Tectonic episodes: the square of the residuals index as a measure of goodness of fit for various trial periods.

Table 2. Periods (in millions of years) 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	50 ± 3	56	47	$\frac{3}{2}P_1$ (48)
61	61		68	63	$2P_1$ (64)
70	81	74			$\frac{5}{2}P_1$ (80)‡
96		90	(138)	114	$3P_1$ (96)‡
260	270	235§	280	285	P_2 (260)
~400		560§		~700‖	$2P_2$ (520)

*From Negi and Tiwari (*16*). †P ~ 15 m.y. according to Mazaud *et al.* (*21*) for t = 0 to 100 m.y. ‡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. §Derived by including 21 Proterozoic dates (t = 600 to 1840 m.y.) (making a total of N = 49). ‖Also obtained by Ulrych (*19*).

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

Episodes	N	Time range	P_1	P_2*	$(t_0)_1$	$(t_0)_2$
Low sea levels	8	0–250	33 ± 1		−3 ± 5	
Sea-floor spreading discontinuities	7	0–180	34 ± 2		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
	21	600–1840		280		
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

*Approximate. †From Negi and Tiwari (*16*), using Walsh spectrum analysis. ‡From Rampino and Stothers (*6*), using least-squares analysis.

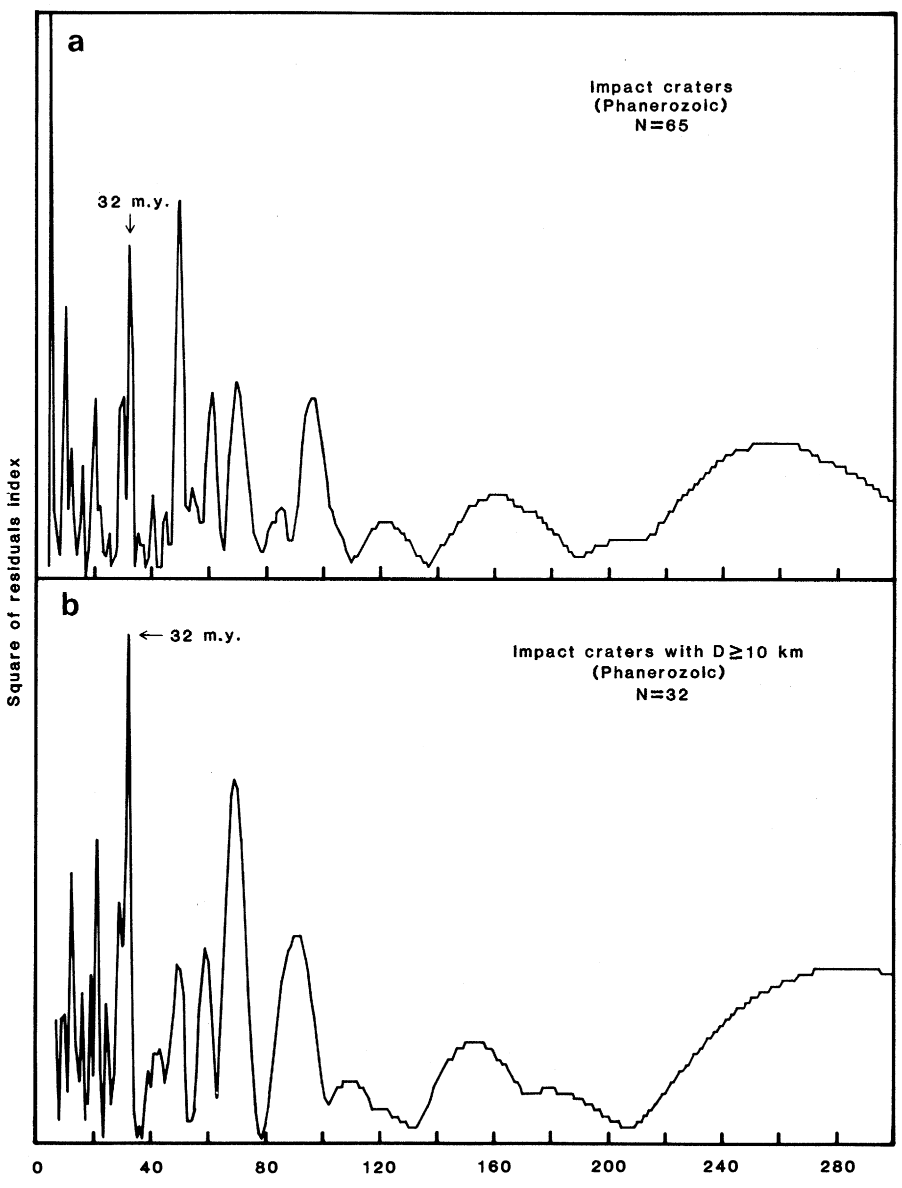

Fig. 3. Terrestrial impact craters: the square of the residuals index as a measure of goodness of fit for various trial periods. The unmarked high spectral peaks at periods of 5, 10, and 50 m.y. are artifacts due to rounding of the ages of many of the older craters. (a) Impact craters. (b) Impact craters with $D \geq 10$ km.

and magnify or diminish the amplitudes of the peaks, we are able to identify two basic periods in terrestrial impact cratering: ~32 and ~260 m.y., 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 geological 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 geological data) has a length of 20 to 23 m.y. 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 geological crises are most likely related.

Cyclicity in impact cratering could arise from the following mechanism (*6*). If the solar system's family of comets is by some means gravitationally disturbed by an outside body, then, as Hills (*33*) showed, a shower of comets will be directed to relatively small perihelion distances, where some of the comets will hit Earth. We have shown 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 m.y. (*6*). Since massive interstellar clouds show a moderately 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, 30 to 36 m.y., and (ii) that the expected astronomical period is 33 ± 3 m.y. For each of the observed time series, we have accordingly generated and analyzed by the method of Stothers (*7*) a set of 1000 random time series covering the same interval of time with the same number of sample times as in the observed time series. If at a fixed 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 $(m/1000) \times 100$ percent. These levels turn out to be 5, 10, 4, and 0.1 percent for $P = 33$ m.y. 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 m.y.), the basic impact-cratering period (32 ± 1 m.y.), and the only known regular galactic period (33 ± 3 m.y.). This probability is less than 10^{-4}.

The long-term stability of the galactic period throughout the Phanerozoic Eon was probably high, although minor short-term fluctuations undoubtedly occurred (*34*). Our work suggests that the geological and impact-cratering periods could not have drifted by more than ± 10 percent (*32*).

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 (for example, 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 the geological and astronomical evidence that we have analyzed.

At present, we have no explanation for the very long period $P_2 \approx 260$ m.y. 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 m.y. (*34*).

Our quantitative results suggest that 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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References and Notes

1. A. G. Fischer and M. A. Arthur, *Soc. Econ. Paleontol. Mineral. Spec. Publ.* **25**, 19 (1977).
2. G. E. Williams, Ed., *Megacycles* (Hutchinson Ross, Stroudsburg, Pa., 1981).
3. W. H. McCrea, *Proc. R. Soc. London Ser. A* **375**, 1 (1981).
4. J. J. Sepkoski, Jr., *Milwaukee Contrib. Biol. Geol.* **51**, 1 (1982).
5. D. M. Raup and J. J. Sepkoski, Jr., *Proc. Natl. Acad. Sci. U.S.A.* **81**, 801 (1984). In earlier related work on marine environments and ocean temperatures, Fischer and Arthur (*1*) and F. H. Dorman [*J. Geol.* **76**, 297 (1968)] proposed cycles of 32 and 30 m.y., respectively. Reanalyzing Raup and Sepkoski's data, J. A. Kitchell and D. Pena [*Science* **226**, 689 (1984)] have recently found a pseudoperiod of 31 m.y., but they as well as A. Hoffmann and J. Ghiold [*Geol. Mag.*, in press] have emphasized that mass extinctions are difficult to identify, date, and demonstrate to be other than stochastic processes. For these reasons, we have turned to other kinds of geological data that possess reliable radiometric, rather than purely stratigraphic, dates.
6. M. R. Rampino and R. B. Stothers, *Nature (London)* **308**, 709 (1984).
7. R. Stothers, *Astron. Astrophys.* **77**, 121 (1979). Virtually the same method has been independently developed and tested by Raup and Sepkoski (*5*).
8. D. V. Ager, *J. Geol. Soc. London* **138**, 159 (1981).
9. P. E. Damon, in *The Late Cenozoic Glacial Ages*, K. K. Turekian, Ed. (Yale Univ. Press, New Haven, Conn., 1971), p. 15.
10. P. R. Vail *et al.*, *Am. Ass. Pet. Geol. Mem.* **26**, 83 (1977). Fischer and Arthur's (*1*) eight marine crises, dated according to the Palmer (*11*) time scale and analyzed by the method of Stothers (*7*), show two high spectral peaks at ~35 and ~20 m.y.
11. A. R. Palmer, *Geology* **11**, 503 (1983).
12. P. R. Vogt, O. E. Avery, E. D. Schneider, C. N. Anderson, D. R. Bracey, *Tectonophysics* **8**, 285 (1969); R. L. Larson and W. C. Pitman III, *Geol. Soc. Am. Bull.* **83**, 3645 (1972).
13. W. Schwan, *Bull. Am. Ass. Pet. Geol.* **64**, 359 (1980). The dates are given on p. 363.
14. H. Stille, *ibid.* **20**, 849 (1936). Regional orogenies during the Cenozoic and Mesozoic eras have already been shown to recur at intervals of ~30 m.y. [for example, R. L. Grasty, *Nature (London)* **216**, 779 (1967); R. W. Kistler *et al.*, *Geol. Soc. Am. Bull.* **82**, 853 (1971)].
15. M. Roubault *et al.*, *Nor. Geol. Tidsskr.* **47**, 375 (1967). Use of the Palmer (*11*) time scale gives virtually the same results.
16. J. G. Negi and R. K. Tiwari, *Geophys. Res. Lett.* **10**, 713 (1983). D. M. Raup (personal communication) has essentially confirmed the results of Negi and Tiwari by using the method of Stothers (*7*); he finds the dominant period at ~30 m.y.
17. I. K. Crain, P. L. Crain, M. G. Plaut, *Nature (London)* **223**, 283 (1969).
18. M. W. McElhinny, *Science* **172**, 157 (1971).
19. T. Ulrych, *Nature (London)* **235**, 218 (1972).
20. E. Irving and G. Pullaiah, *Earth-Sci. Rev.* **12**, 35 (1976).
21. A. Mazaud, C. Laj, L. de Sèze, K. L. Verosub, *Nature (London)* **304**, 328 (1983).
22. Paleomagnetic polar-path cycles ($t = 0$ to 2500 m.y.) also seem to have a period of ~250 m.y. [W. A. Morris, P. W. Schmidt, J. L. Roy, *Phys. Earth Planet. Inter.* **19**, 85 (1979)].
23. C. K. Seyfert and L. A. Sirkin, *Earth History and Plate Tectonics* (Harper & Row, New York, 1979), p. 238. The dates of the orogenies are 1.2, 1.45, 1.7, 1.85, 2.53, 2.73, 3.0, and 3.6 billion years.
24. R. M. Macintyre, *Nature (London)* **230**, 79 (1971). A later compilation of just the Cenozoic and Mesozoic carbonatites was also published by Macintyre [*J. Geol. Soc. London* **133**, 375 (1977)] but has not been used separately here. Dates of initiation of several Cenozoic and Mesozoic flood basalts are also known [P. R. Vogt, *Nature (London)* **240**, 338 (1972); Basaltic Volcanism Study Project, *Basaltic Volcanism on the Terrestrial Planets* (Pergamon, New York, 1981)] but are too few and too imprecise for our purpose.
25. G. L. Davis, *Carnegie Inst. Washington Yearb.* **77**, 895 (1977–8).
26. S. T. Crough, W. J. Morgan, R. B. Hargraves, *Earth Planet. Sci. Lett.* **50**, 260 (1980).
27. P. England and G. Houseman, *ibid.* **67**, 109 (1984).
28. Sepkoski's (*4*) time curve of geologic ranges of marine organisms during the Phanerozoic also shows some evidence of a very long period of 200 to 300 m.y. [see C. B. Hatfield and M. J. Camp, *Geol. Soc. Am. Bull.* **81**, 911 (1970); A. G. Fischer, *Geol. Soc. London Newslett.* **8** (No. 6), 2 (1979); L. M. Van Valen, *Nature (London)* **307**, 50 (1984)]. The evidence from widespread glaciations is less clear but suggests a mean time interval of 150 to 300 m.y. during the past 1000 m.y. [N. Christie-Blick, *Icarus* **150**, 423 (1982)].
29. E. J. Öpik, *Ir. Astron. J.* **5**, 34 (1958); D. J. McLaren, *J. Paleontol.* **44**, 801 (1970); H. C. Urey, *Nature (London)* **242**, 32 (1973); D. J. Mullan, *Science* **181**, 553 (1973); S. V. M. Clube, *Vistas Astron.* **22**, 77 (1978); W. M. Napier and S. V. M. Clube, *Nature (London)* **282**, 455 (1979); L. W. Alvarez, W. Alvarez, F. Asaro, H. V. Michel, *Science* **208**, 1095 (1980); S. V. M. Clube and W. M. Napier, *Earth Planet. Sci. Lett.* **57**, 251 (1982); L. T. Silver and P. H. Schultz, Eds. *Geol. Soc. Am. Spec. Pap. 190* (1982), p. 1; N. Winkless and I. Browning, *Climate and the Affairs of Men* (Harper, New York, 1975), chap. 2.
30. R. A. F. Grieve, *Geol. Soc. Am. Spec. Pap. 190* (1982), p. 25. See both table 2 and the text.
31. W. Alvarez and R. A. Muller [*Nature (London)* **308**, 718 (1984)] used Fourier analysis to search for periodicities in a more restricted sample of impact craters: 11 well-dated craters with $D \geq 10$ km in the age range 5 to 250 m.y. (*30*). They located one significant cycle with $P = 28.4 \pm 1$ m.y. and $t_0 = 13 \pm 2$ m.y. The method of Stothers (*7*), used on their data, closely reproduces their result, since it gives $P = 28.5 \pm 1$ m.y. and $t_0 = 13 \pm 3$ m.y. However, Alvarez and Muller omitted three well-dated craters with $D \geq 10$ km and ages less than 5 m.y. (*30*). By including in the analysis these three craters (which have ages of 1.3, 3.5, and 4.5 m.y.), the method of Stothers (*7*) yields $P = 30 \pm 1$ m.y. and $t_0 = 8 \pm 3$ m.y. This agrees with our previously derived result, $P = 31 \pm 1$ m.y. and $t_0 = 5 \pm 6$ m.y., for 41 craters of all sizes in the same age range (1 to 250 m.y.). It is clear that Alvarez and Muller obtained values of P and t_0 that are significantly different from ours (*6*) because they excluded the most recent large craters. Other arbitrary deletions or groupings of crater ages can also alter the results somewhat [see J. J. Sepkoski, Jr., and D. M. Raup, in *Dynamics of Extinction*, D. Elliott, Ed. (Wiley, New York, in press)]. Alvarez and Muller's work was done 2 months after ours [*Sci. Am.* **250**, 68 (April 1984); *Discover* **5**, 28 (May 1984)].
32. The slight decrease in the dominant period from Paleozoic to Cenozoic-Mesozoic times that is shown by the impact-crater data and the tectonism data probably has no significance, since it does not show up in the carbonatite data.
33. J. G. Hills, *Astron. J.* **86**, 1730 (1981).
34. K. A. Innanen, A. T. Patrick, W. W. Duley, *Astrophys. Space Sci.* **57**, 511 (1978); G. E. Williams, *Earth Planet. Sci. Lett.* **26**, 361 (1975).
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