ARE PERIODICITIES IN CRATER FORMATIONS AND MASS EXTINCTIONS RELATED?

S. YABUSHITA
Department of Applied Mathematics & Physics, Kyoto University, Kyoto 606, Japan

(Received 13 October, 1994)

Abstract. Periodicities in crater formation rate and mass-extinctions are reviewed. The former exhibits a period of 30 million yr, while the latter appear to have a periodicity at 26 myr. Results obtained earlier that small craters better satisfy the adopted criterion for statistical testing is shown due to the fact that there is a strong clustering of small craters in a recent past (<10 myr). On the basis of the dataset of craters compiled by Grieve, it is shown that there are several craters for which no mass extinctions correspond. The difference in the periods of the craters and of mass extinctions and the lack of mass extinctions that correspond to large craters appear to suggest that the two periodicities are not interrelated, and large impacts merely act as triggers for the mass-extinctions; the only exception being the K/T boundary.

1. Introduction

In 1984 Raup and Sepkoski (1984) published a controversial paper where they claimed to have detected a periodicity in the extinction rate of marine fauna. Since such a periodicity is unlikely to be controlled by terrestrial processes, they proposed that the periodicity might be caused by extra-terrestrial processes. Accepting this suggestion, Alvarez and Muller (1984) investigated if a periodicity could be detected in the ages of large craters then known and claimed to have detected a period at 26 million yr.

A number of investigations have since been undertaken to substantiate or refute the hypotheses (Stothers, 1988; Rampino and Stothers, 1986; Grieve *et al.*, 1985; Shoemaker and Wolfe, 1986; and papers cited therein; Yabushita, 1991). Although it seems difficult to argue definitely, it appears likely that the mass extinctions and crater formation rate exhibit periodicities. The periods derived are close to each other and the closeness has led some authors (Alvarez and Muller, 1984; Rampino, 1993; Rampino and Stothers, 1986) to argue that the periodicity in the crater formation rate controls the mass-extinction periodicity.

There are, however, two aspects to the problem which do not appear to be consistent. One is the fact that small craters (diameter, $D < 10$ Km) exhibit a periodicity while the large ones appear to be less periodic (Yabushita 1991, 1992). The second is the difference between the period in the crater formation ($P \simeq 30$ myr) and the period ($P \simeq 27$ myr) in the mass extinctions (Rampino 1992). Although the two periods may appear to be consistent with each other, as one goes back in time, the epochs of crater formation peaks begin to differ from those of mass extinctions (there are 11 extinction peaks within the past 260 myr). One is thus led to enquire whether or not the hypothesis of periodic crater

Earth, Moon and Planets **64:** 207–216, 1994.

forming impacts controlling the mass extinctions is acceptable. In the present paper, this problem is addressed. It will be argued that the periodicity in the mass extinction may have nothing to do with the one in the crater formation.

2. Dataset

Various datasets have been used to investigate whether mass extinctions and crater ages exhibit periodicity or otherwise. These include the original datasets of Raup and Sepkoski (1984) and of Alvarez and Muller (1984). In any discussion of statistical nature, it is important to define the datasets to be used in the discussion. Here we use the datasets of Rampino and Caldeira (1992) for geological activities including mass extinctions and the one of Grieve (1993) for craters.

Rampino and Caldeira's result is based on 17,500 generea in the dataset of Sepkoski (1989) and contains 11 extinction peaks. These are listed in Table I. On the other hand, Grieve's dataset contains 139 craters. Although diameter value is ascribed for each of them, 35 craters in the dataset are given only lower on upper limits for the ages. Thus, the remaining 104 craters ages are associated with probable errors. The problem associated with problem errors will not be dealt with in the following. Of the 104 craters, those with ages <600 myr are 99 in number. The craters with ages ≥600 myr are scarce and we restrict ourselves to those with ages <600 myr. Then, those with D (diameter) <10 km are 59 in number while those with $D \geq$ 10 km are 40 in number.

3. Decay Rate of Craters

It is apparent that craters are continuously lost owing to weathering and tectonic activities. A glance at the distribution in ages of known craters shows that old craters are lost with time. This problem appears of importance in relation to discuss if the present epoch is in a comet shower.

As done in an earlier work (Yabushita, 1992), we divide the crater ages into 25 myr bins and estimate the decay rate by assuming an exponential law. To be more specific, we assume that the number of craters in the bin is given by

$$N(i) = N \exp(-ai), \quad i = 1, 2, \ldots, 23$$

where a is the decay constant to be obtained and N the normalization constant respectively. Since we have 25 myr bins, the total number of bins equals 24, with the first bin corresponding to the most recent epoch (age <25 myr). The decay constant is determined so that the mean square deviation may be minimized. In so doing, we omit the first bin, because as may be seen from Table II, there is an overwhelming excess of craters.

The values of the decay rate, a so determined are as follows;

Regardless of D $a = 0.102/25$ myr, $\mathrm{N} = 7.8$,

TABLE I

Mass extinctions and ages of craters that correspond to the extinctions within probable error. Mass extinction data from Rampino and Caldeira (1992), crater data from Grieve (1993)

Mass extinctions (myrBP)	Crater (myrBP)	D (km)
1.6		
11.2		
36.6	35 ± 5	100.2
	38 ± 4	28
66	65 ± 2	25
	64.98 ± 0.05	180
	65.7 ± 1	35
91	88 ± 3	24
	95 ± 7	25
113	115 ± 10	39
144	142 ± 0.5	22
176		
193	186 ± 8	23
216	214 ± 1	100
	219 ± 32	40
	220	80
245	249 ± 19	40

$$D < 10\,\mathrm{km} = 0.016/25\,\mathrm{myr}, \quad 1.5,$$

$$D \geq 10\,\mathrm{km} = 0.164/25\,\mathrm{myr}, \quad 6.8.$$

It is immediately seen that the decay constant is greater for craters with $D \geq 10$ km than for smaller ones. This is somewhat surprising; one would have supposed that large craters would be better conserved. The difference between the normalization constant N and the number of craters in the first bin yields an excess or a defficiency of the craters in the nearest past. The number of excess is 29 for $D < 10$ km and there is a defficiency of one crater for $D \geq 10$ km. One may therefore conclude that if there should be any comet shower, that shower is largely due to small craters. It seems more reasonable, however, to suppose that very small craters are lost at a rate much greater than for large ones. The average diameters of the craters in the adopted dataset are given below;

$$\overline{D}(\text{average } D) = 1.29\,\mathrm{km}; \quad \text{age} < 25\,\mathrm{myr}$$

$$D < 10\,\mathrm{km}$$

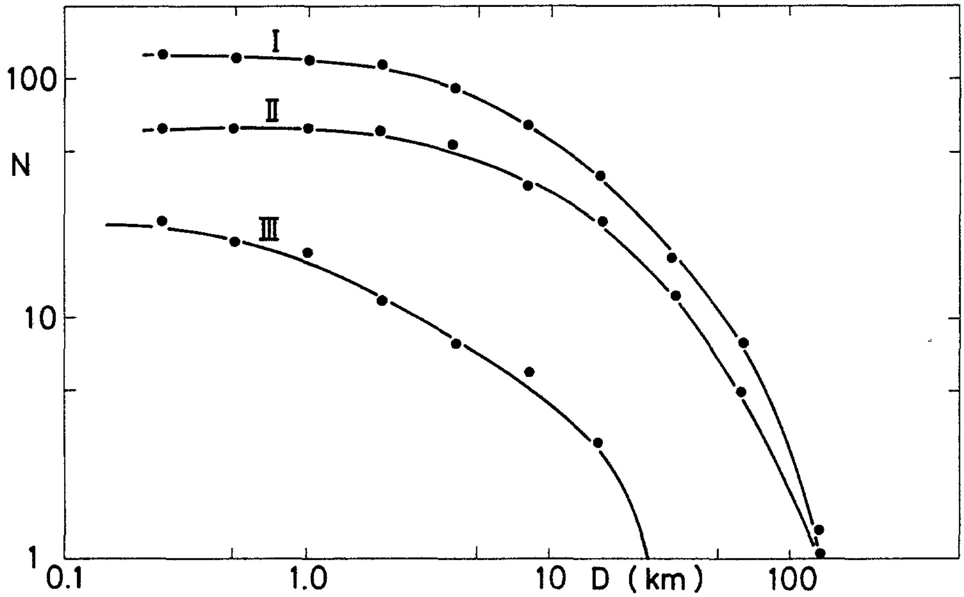

Fig. 1. Cumulative number of craters with diameters greater than D (Km). I for entire population, II for those with ages ≥ 25 myr and III for those with ages less than 25 myr, respectively. Note that for curves I and II, the cumulative numbers to increase for D less than 0.5 Km. This shows that there is an excess of small craters.

$\overline{D} = 5.35$ km; age > 25 myr

$D < 10$ km.

It is immediately clear that it is very small young craters which give rise to an enhanced excess of craters with ages <25 myr. It seems important therefore in testing the periodicity hypothesis of the crater formation rate to take into account the excess of very small craters in the first bin. The excess is also seen in Figure 1 which plot the cumulative number versus the crater diameter. It also follows that since the decay constants are not very large, it will be appropriate to test the periodicity hypothesis on the null-hypothesis that crater ages are uniformly randomly distributed, provided that we pay due attention to the clustering of small craters in the first bin.

4. Periodicity in the Crater Ages

Earlier, the present author (Yabushita, 1992) investigated whether or not the periodicity hypothesis can be substantiated by adopting a criterion proposed by Broadbent (1954, 1955) and by making use of earlier datasets on crater ages. Although a definite conclusion could not be obtained, a period at 30 myr seemed

TABLE II

Distribution of crater ages

Bin number	No. of craters	$D < 10$ km	$D \geq 10$ km
1 ($0 \leq t_i < 25$ myr)	37	31	6
2	6	2	4
3	9	2	7
4	4	0	4
5	7	4	3
6	3	1	2
7	2	2	0
8	1	0	1
9	6	1	5
10	1	0	1
11	1	1	0
12	3	0	3
13	2	2	0
14	0	0	0
15	3	1	2
16	3	2	1
17	1	1	0
18	2	2	0
19	3	2	1
20	0	0	0
21	1	1	0
22	1	1	0
23	3	3	0
24	0	0	0
Total	99	59	40

reasonably supported by the data. Again, a less conspicous period at 16.5 myr has been detected. It has also become apparent that small craters (D <10 km) are the ones that appear to be periodic, while large ones did not exhibit a periodicity which satisfies the adopted criterion.

In the present section, we carry out a similar statistical test for the new dataset. In so doing, it is important to include or exclude very small craters in the test for the reason derived in the preceeding section. Because there is an overwhelming excess of very small craters in the age interval (0.25 myr), it is quite likely that they may somehow give rise to spurious periodicity. In the following, we investigate whether the dataset adopted here yields periodicity which can be regarded significant from statistical point of view. In Figure 2 is plotted s/P, where s/P is given by

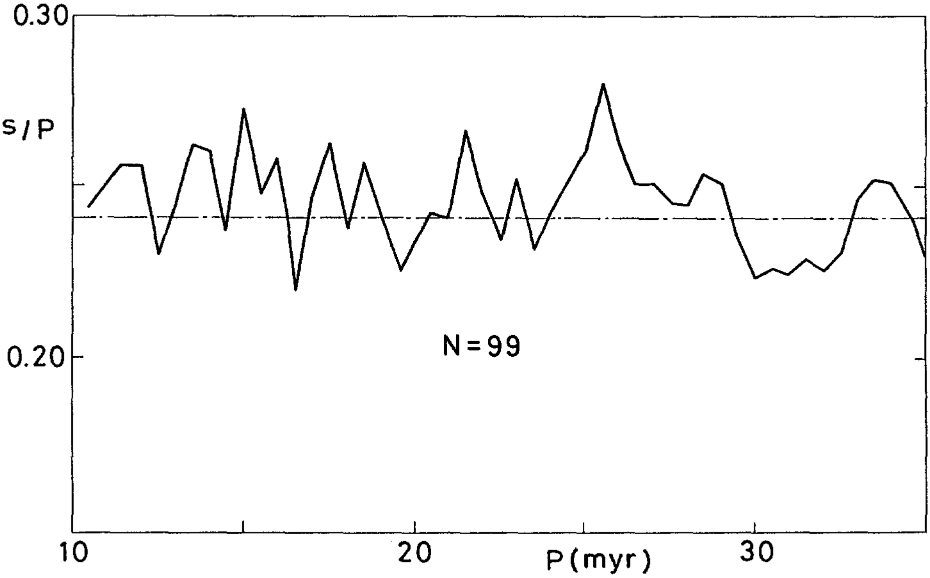

Fig. 2. The quantity s/P is plotted against P. The epoch α lies between 1 and 3 myr. The craters are such that the ages <260 myr. There are 99 such crateres in the Grieve dataset. The horizontal line is the level below which the adopted criterion by Broadbent is statisfied.

$$\frac{s^2}{p^2} = \frac{1}{N} \sum N_i = 1[t_i - (n_i P + \alpha)]^2 / P^2,$$

where $t_1, t_2, \ldots, t_N$ are crater ages, α and P are assumed epoch of the nearest impact and assumed period, respectively, n_i an integer so chosen that

$$| t_i - (n_i P + \alpha) | < P/2.$$

Clearly, s/P is a measure of deviation from an exact periodicity. The Broadbent criterion asserts that the inequality

$$\sqrt{N} \left(\frac{1}{3} - \frac{s^2}{\alpha^2} \right) > 1$$

be satisfied for the periodicity with period P to be statistically significant. The probability of the left hand side being greater than unity for the null-hypothesis of random distribution is less than 0.1%.

The s/P plotted in Figure 2 is for the entire dataset, namely, all of the craters are taken into account. That small craters are heavily populated among young ones is seen in Figure 1 where the cumulative number N of craters is plotted against the diameter. The curve I is for the entire population of 139 craters, and curve II for those with age between 25 and 600 myr (total number 99) while

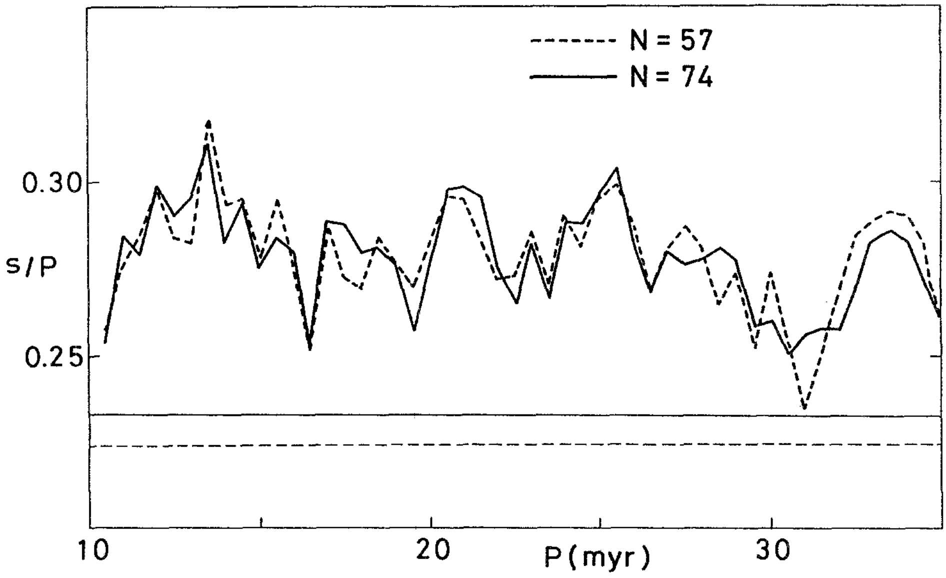

Fig. 3. The same as Figure 2 except that subsets of Grieve are used in calculating the quantity s/P. See Table III.

curve III is for those with ages less than 25 myr. It is immediately seen that the abundance of small craters (with diameters less than 2 km) relative to large ones is seen for the curve III. In other words, small craters are far better preserved for those with ages $\geq$25 myr. It is therefore impotant to investigate how the detected periodicity may be affected by removing the small craters.

In order to see how the result obtained and the detected period may by affected, we plot in Figure 3 s/P for a subset such that craters with D <2 km are removed; there are 74 samples. It is seen that a local mimimum at P = 30.5 myr is detected but it is above the Broadbent criterion. The mimimum value is $s/P = 0.251$ so that $\sqrt{N}(1/3 - S^2/d^2) = 0.70$. This is 0.9% point of the null-hypothesis. In the same figure is plotted s/P for another subset (those with $D \leq 5$ km are removed).; the subset then consists of 57 samples. A local mimimum at P = 31 myr is also detected. The value of s/P is 0.235 so that $\sqrt{N}(1/3 - s^2/d^2) = 0.85$. This is 0.2% point of the distribution.

Testing of other subsets of the database has been done and the result is summarized in Table III. One may reasonably conclude that although a period which satisfies the Broadbent criterion cannot be obtained when very small craters are removed from the dataset, a unique period at $P \simeq 30$ myr exhibits itself for a number of subsets of the data. If the dataset were a mere aggregate of random numbers, such a unique period would not be found. We therefore conclude that

TABLE III

Detected periods in the crater ages

Dataset (or subsets)	No. of samples	Periods	Broadbent criterion
All	99	30 myr	Satisfied
		19.5	Satisfied
		16.5	Satisfied
$D \geq 2$ Km	74	31	No (0.9%)
		16.5	No (0.6%)
$D \geq 5$ Km	57	31	No (0.2%)
		16.5	No (2%)
$D \geq 10$ Km	40	31	No (0.4%)
		16.5	No (7%)

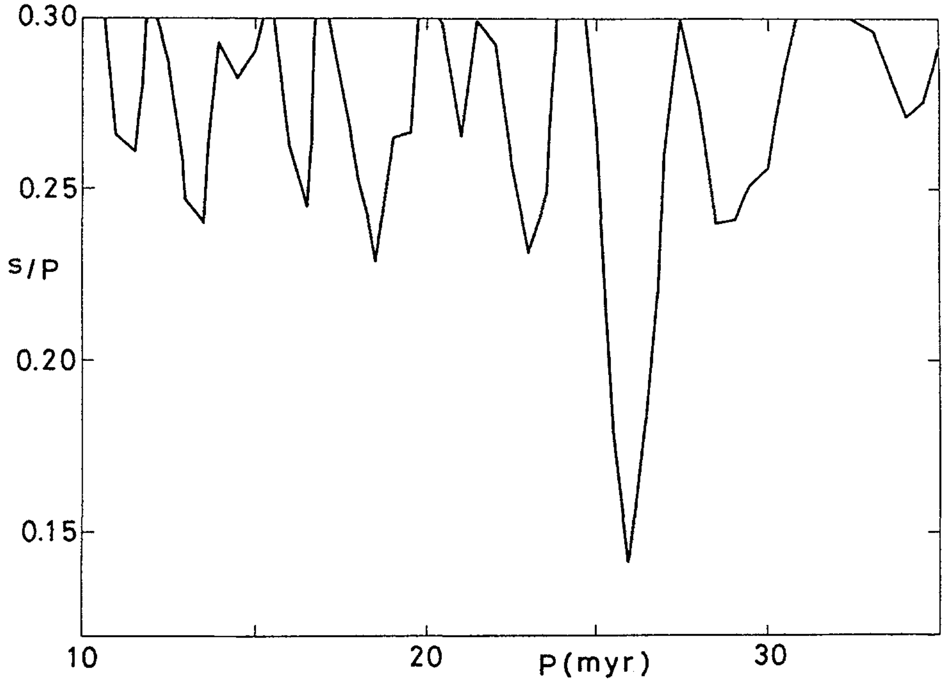

Fig. 4. s/P is plotted for the 11 peaks in the mass-extinction of Rampino and Caldeira (1992). An absolute mimimum is found at $P = 26$ myr.

the crater data yields a period of 30 myr, although the periodicity is not very apparent at a glance.

For subsets such that the detected period does not satisfy the Broadbent criterion, the level of confidence is given in the parenthesis.

5. Are the Periodicities of Crater Formation and Mass Extinctions Consistent?

We have shown in the preceding section that small craters are clustered in the recent past (<25 myr) and that when very small craters are removed, one can barely recognize periodicity in the crater ages at 30 and 16.5 myr. These periods have earlier been found by several authors (Shoemaker and Wolfe, 1986; Stothers 1989; Napier, 1989). The last mentioned author, in particular, drew attention to the period of 16.5 myr which is found in the frequency of the terrestrial magnetic reversals.

The aim of the present section, however, is to discuss if the detected periods are consistent with a similar periodicity in the rate of mass extinctions. Rampino and Caldeira (1992) has found 11 peaks in the rate of mass-extinctions over the past 260 myr and derived a period of 26.9 myr. The peaks in the rate are reproduced in Table 1. Rampino (1993) remarked that each peak is associated with a large crater within the error bar in the age determination. Following this remark, a crater with an age which appears related to an extinction peak is also given in Table I. We note that no crater can be associated with the extinction peaks at 1.6, 11.2 and 176 myr BP.

Accepting the causality between the craters and the extinction peaks in the Table I, one is led naturally to enquire if there are large craters which do not have any counterpart in the extinctions. It is seen from the Table I that craters as small as 22–23 km in diameters are associated with extinction peaks. Placing the dividing line at 20 km somewhat arbitrarily, the following craters do not have associated peaks in the extinction rate; 73 myr BP(65 km), 77.3 (23 km), 25 (20 km), 58 (22 km), 38 (28 km), 50 (45 km), 15.1 (24 km), 95 (25 km), 128 (55 km), 73 (25 km). Of these, craters at 73, 50, and 128 myr BP are sufficiently large to have probably caused a mass-extinction and yet no such peak has been found.

We also like to draw attention to the Ir concentration in the core of the Pacific Ocean (Kyte and Wasson, 1986). Although a peak is seen that corresponds to the K/T boundary, there is no peak which corresponds to the extinction at 36 myr BP although two large craters (one of them diameter, 100 km) are asssociated with the extinction peak; this also shows that the K/T boundary is a specific event. These considerations taken together appear to suggest that impacts represented by large craters merely act as triggers to mass-extinctions.

References

Alvarez, W. and Muller, R. A.: 1984, *Nature* **308**, 718.

Broadbent, S. R.: 1955, *Biometrika* **42**, 45.

Broadbent, S. R.: 1956, *Biometrika* **43**, 32.

Grieve, R. A. F., Sharpton, V. L., Goodacre, A. K., and Garvin, J. B.: 1985, *Earth Planet. Sci. Lett.* **76**, 1.

Grieve, R. A. F.: 1993, 'Dataset of Crateres Compiled by Grieve', can be obtained on application.

Kyte, F. T. and Wasson, J. T.: 1986, *Science* **231**, 225.

Napier, W. M.: 1989, in S. V. M. Clube (ed.), *Catastrophes and Evolution* Oxford University Press.

Rampino, M. R. and Stothers, R. B.: 1986, in R. Smoluchouwski, J. N. Bahcall, and M. Mathews (eds.), *The Galaxy and the Solar System*, University of Arizona Press.

Rampino, M. R. and Caldeira, K: 1992, in S. V. M. Clube, S. Yabushita, and J. Henrard (eds.), *Dynamics and Evolution of Minor Bodies with Galactic and Geological Implications*, Kluwer.

Rampino, M. R.: 1993, *Talk at the Erice Conference on Planetary Emergency.*

Raup, D. M. and Sepkoski, J. J. Jr.: 1984, *Proc. Natl. Acad. Sci.* **81**, 801.

Shoemaker, E. M. and Wolfe, R. F.: 1986, in R. Smoluchouwski, J. N. Bahcall, and M. S. Mathews (eds.), *The Galaxy and the Solar System*, University of Arizona Press.

Stothers, R. B.: 1988, *Observatory* **108**, 1.

Yabushita, S.: 1991, *MNRAS*. **250**, 481.

Yabushita, S.: 1992, *Earth, Moon and Planets* **58**, 57.