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FLOOD BASALTS AND EXTINCTION EVENTS

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Abstract. The largest known effusive eruptions during the Cenozoic and Mesozoic Eras, the voluminous flood basalts, have long been suspected as being associated with major extinctions of biotic species. Despite the possible errors attached to the dates in both time series of events, the significance level of the suspected correlation is found here, by an objective, direct method, to be 1% to 4%. Statistically, extinctions lag eruptions by a mean time interval that is indistinguishable from zero, being much less than the average residual derived from the correlation analysis. Oceanic flood basalts, however, must have had a different biological impact, which is still uncertain owing to the small number of known examples and differing physical factors. Although not all continental flood basalts can have produced major extinction events, the non-correlating eruptions (including most or all of the oceanic flood basalts) may have led to smaller marine extinciton events that terminated at least some of the less catastrophically ending geologic stages. Consequently, the 26 Myr quasiperiodicity seen in major marine extinctions may be only a sampling effect, rather than a manifestation of underlying periodicity.

Introduction

The still unproven hypothesis that continental flood basalt eruptions led to major extinctions of biotic species is usually based on two different kinds of evidence. First is the apparent agreement in time between the Deccan Traps eruption in India 66 My ago and the Cretaceous/Tertiary boundary extinctions, a coincidence that is supported by several other apparent coincidences of this type in the geologic record (Vogt, 1972; Rampino and Stothers, 1988). Second is a proposed physical connection, based on a probable chain of physical cause and effect (McLean, 1982; Devine et al., 1984; Officer et al., 1987; Courtillot et al., 1988) and also on theoretical calculations of the properties of the volcanic aerosol and dust cloud that must begin the chain (Stothers et al., 1986).

Since the linkage is still tentative, it is worth seeking further evidence, especially of a more quantitative nature. In particular, one would like to know whether the apparent coincidences of flood basalts and major extinction events in the geologic record are possibly only accidental flukes of timing or actually have a high statistical significance. This crucial question is the topic addressed in this paper.

Geological Data

Owing to the incompleteness of the record of known oceanic flood basalts, the present study makes use only of the 14 known continental flood basalts of Cenozoic and Mesozoic time (the past 250 Myr). This, however, is not a serious restriction, as will be demonstrated below. Moreover, these flood basalts probably constitute a nearly complete set for the continents. A listing is contained in Table 1, where the ages given are all based on the $^{40}Ar/^{39}Ar$ or U/Pb method, except for the Ethiopian, Madagascar, Namibian, South African, and Wrangellian flood basalts, for which only K/Ar and other less-accurate ages are available. Fortunately, an objective method of using a histogram of K/Ar dates to infer a reliable estimate of the true age has been devised, and has been calibrated, for the other continental flood basalts, by employing accurate $^{40}Ar/^{39}Ar$ dates (Rampino and Stothers, 1988). The estimated 1σ gaussian errors listed in Table 1 are therefore believed to be realistic. Another check on the estimated errors is provided by the probable simultaneity of the Namibian (135 ± 5 Myr) and Serra Geral (133 ± 1 Myr) eruptions, as well as of the West African (200 ± 3 Myr) and Eastern North American (201 ± 1 Myr) eruptions.

Major extinction events have been identified by Raup and Sepkoski (1984, 1986) on the basis of accelerated rates of marine species extinctions, at both family and genus levels, during the Cenozoic and Mesozoic (see also Sepkoski, 1989). The 10 events that are designated by them as "significant" (eight) or "possible" (two) events, within the category of "mass extinctions", are listed in Table 2 under the name of the geologic stage in which they occurred. Four "doubtful" events are omitted as being mere blips

TABLE 1. Ages of Continental Flood Basalt Eruptions

Flood basalt	Initiation age (Myr)	References*
Columbia River	17.0 ± 0.2	1, 2
Ethiopian	35 ± 2	1
Brito-Arctic	61 ± 1	3
Deccan	66 ± 1	4, 5, 6
Madagascar	90 ± 5	7, 8
Rajmahal	116 ± 2	9, 10
Serra Geral	133 ± 1	11
Namibian	135 ± 5	1
Antarctic	176 ± 2	12, 13
South African	190 ± 5	1
West African	200 ± 3	14
Eastern North American	201 ± 1	1, 15
Wrangellian	230 ± 5	16
Siberian	247 ± 2	17, 18, 19, 20

*(1) Rampino and Stothers, 1988. (2) Baksi and Farrar, 1990. (3) Mussett, 1986. (4) Duncan and Pyle, 1988. (5) Courtillot et al., 1988. (6) Baksi, 1989. (7) Mahoney et al., 1991. (8) Duncan and Richards, 1991. (9) Baksi, 1986. (10) Baksi, 1988. (11) Renne et al., 1992. (12) Fleck et al., 1977. (13) Heimann et al., 1992. (14) Sebai et al., 1991. (15) Dunning and Hodych, 1990. (16) Richards et al., 1991. (17) Dalrymple et al., 1991. (18) Renne and Basu, 1991. (19) Baksi and Farrar, 1991. (20) Campbell et al., 1992.

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TABLE 2. Ages of Major Extinction Events

Geologic stage	Upper boundary age (Myr)	References*
Pliocene	1.64 ± 0.03	1,2,3
Middle Miocene	10.5 ± 1	1,2,3
Upper Eocene	35 ± 1	1,2,3,4,5
Maastrichtian	65 ± 1	1,2,3
Cenomanian	91 ± 1	1,2,6
Aptian	110 ± 3	1,2,6
Tithonian	141 ± 4	1,2,7,8
Bajocian	171 ± 4	1,2,6,9
Pliensbachian	190 ± 4	1,2,6,9
Rhaetian	204 ± 4	1,2,10
Dzulfian (Changxingian)	250 ± 3	1,2,11

*(1) Harland et al., 1990. (2) Haq et al., 1987. (3) Berggren et al., 1985. (4) Montanari et al., 1985. (5) Swisher and Prothero, 1990. (6) Kent and Gradstein, 1985. (7) Lowrie and Ogg, 1986. (8) Bralower et al., 1990. (9) Westermann, 1984. (10) Dunning and Hodych, 1990. (11) Claoué-Long et al., 1991.

on the background, but a fifth (Bajocian) stands out quite strongly on the extinction time curve and is included here. In all cases, the mass extinctions are assumed to have occurred at the ends of the geologic stages, because that is how many of the stages were historically established in the first place. In this view, the ages of the mass extinctions have actually not been artificially constrained by the geologic time scale. Dating of the stage boundaries in Table 2 is based, where possible, on the most recent radiometric age determinations. An average of the various standard and recently published age determinations for each boundary is provided in the table; the estimated 1σ gaussian error in each case is large enough to embrace, more or less, all of the listed individual ages for that boundary. It also encompasses most of the uncertainty regarding the duration and internal stage location of the extinction event (Sepkoski, 1989).

The formal estimated error in each case follows from considering the internal error of the most accurate published date, an intercomparison of the various published dates (which are not entirely independent), and an inspection of the working chronogram in Harland et al. (1990). The very large chronogram errors appearing in Harland et al. for the Tithonian, Pliensbachian, Rhaetian, and Dzulfian upper boundaries significantly exceed the estimated errors listed in Table 2. But three of these chronogram errors have been superseded by the results of more recent dating, and therefore only the Pliensbachian upper boundary has an estimated error that may be too small. Although the age of the terminal Pliensbachian must be biostratigraphically interpolated between two widely spaced tie-points, the results are quite similar whether one assumes equal durations of stages (Harland et al., 1982) or of substage biozones (Westermann, 1984; Harland et al., 1990), or even if one uses glauconites to date the tie-points (Odin, 1982). At any rate, an estimated age error of ±4 Myr is certainly more realistic than the physically impossible value of ±15 Myr from the chronogram.

Method of Cross-Correlation

To cross-correlate the two statistically independent time series, differences between nearest times in overlapped segments of the two series are used here, as in other linear data analysis techniques for point series. From these numerical differences, the rms difference (or else, to minimize the effect of outliers, the median absolute difference) is calculated and employed as a correlation measure. If the observed times in one or both of the time series possess quantifiable errors, a large set of slightly perturbed (pseudo-randomized) time series can be adopted instead of the original time series themselves. A uniform phase shift of one series with respect to the other can be easily incorporated into the analysis as in the case of a standard cross-correlation analysis.

Monte Carlo simulations may be performed in order to estimate the significance level at the position (or, in the case of a large number of slight perturbations of the original time series, the average position) of the best phase match. The times in a random simulation time series consist of N ordered, uniformly distributed random deviates, falling inside the same preassigned time interval as the N observed times in the original time series that is chosen to be the "target" series (here, the sequence of mass extinctions). The estimated significance level follows as the percentage of random correlations that are better than the observed correlation, within a symmetrical range of possible phase match positions extending up to the observed best position.

Cross-Correlation Results

Inspection of Tables 1 and 2 reveals that major extinction events seem indeed to be correlated with continental flood basalts, at least roughly. Cross-correlation of the two time series, using the flood basalt time series as a template over the interval from the near-present (3 Myr) to the mid-Permian (270 Myr), confirms that the correlation measure drops to a sharp minimum at a phase lag close to zero. Randomly introducing gaussian errors into the ages yields a statistically more realistic estimate of the correlation measure. Results are presented in Table 3 for two sets of major extinction events: the entire set of 11 events of Table 2 and a reduced set of 8 events, omitting the less certain Pliocene, Aptian, and Bajocian events. Note, however, that the Pliocene event does not contribute in either case, because it lies outside the overlapped interval.

Without employing pseudo-randomization of the observed ages, the null hypothesis that the ages of major extinction events arise from a uniform distribution of random times can be rejected at the 1% significance level. Perturbing the observed ages within their gaussian error distributions increases the significance level to about 4%. In all cases, the average phase lag is statistically indistinguishable from zero, being much smaller than the associated average residual of ~4 Myr (rms) or ~2 Myr (median).

The obvious inference is that major extinction events might have been caused by continental flood basalt eruptions (or, perhaps, by whatever triggers these eruptions). It appears, however, that not all continental flood basalts led to major extinction events. For example, the Brito-Arctic and Wrangellian eruptions apparently did not. Nor did the large, well-dated oceanic flood basalt Ontong-Java (121 ± 3 Myr) (Tarduno et al., 1991). Nevertheless, it remains true that every known major extinction event, except for two events, is seen to match up with a continental flood basalt eruption, at least within the estimated 1σ errors of the ages. The two apparent exceptions are the Pliocene and middle Miocene events. However, the Pliocene extinctions were only regional (Stanley, 1986), occurring mainly at the species and genus levels, and they constituted only a "possible" event according to Raup and Sepkoski (1986). In the case of the middle Miocene event, the extinctions may be

TABLE 3. Cross-Correlation of Major Extinction Events and Continental Flood Basalts

Extinction events	Dates randomized?	Residual type	Significance level (%)
Eleven	no	rms	0.5
	no	median	0.6
	yes	rms	3.8
	yes	median	2.9
Eight	no	rms	0.4
	no	median	1.3
	yes	rms	4.0
	yes	median	4.4

a delayed response to very slow environmental deterioration initiated by the Columbia River eruption, or perhaps the extinctions occurred at the Langhian/Serravallian boundary (15 Myr) rather than at the Serravallian/Tortonian boundary (10.5 Myr).

The total number of continental and oceanic flood basalts during the past 250 Myr has been estimated as ~40, using either a simple geographical extrapolation based on the observed number of continental flood basalts or a physical association with the observed number of upper mantle hotspots (Stothers, 1993). If each of these eruptions led to detectable extinctions of at least some regionally or globally abundant marine species, then a similar number of geologic stages would be expected to occur in the geologic record. In fact, the observed number of geologic stages is about 48 (Harland, et al., 1990), most of them having been defined by some marine species extinctions. This suggests that oceanic flood basalts do not occur exclusively, or even preferentially, at the times of continental eruptions. Since most oceanic flood basalts also cover less area and produce a smaller subaerial component, their destructive effects on global marine life would be expected to be different from and not as severe as for continental eruptions. Mass extinctions, consequently, ought to be mainly associated with continental flood basalts.

The average interval between nonsimultaneous continental flood basalts is 21 Myr. Since these eruptions comprise only a small geographical subset of all flood basalts, the average geologic stage length of ~5 Myr, rather than a longer cycle of ~21 Myr, could be the largest meaningful unit of Cenozoic and Mesozoic time. This line of argument would suggest that the periodicity of 26 Myr previously detected in mass extinctions (Raup and Sepkoski, 1984, 1986; Sepkoski, 1989) might be only a statistical artifact. The improved dates in Tables 1 and 2 are certainly not significantly periodic.

Conclusions

An objective method of cross-correlating two point series has been used to demonstrate a statistically significant correlation between major biotic extinction events and continental flood basalt eruptions of the past 250 Myr. The present approach avoids all questions of periodicity and explicitly incorporates the maximum likely errors of the assigned dates in the two time series. There remains a possibility that the immediate cause of the extinction event is not the flood basalt eruption itself, in which case the relative phasing of the two phenomena is not easily predictable, and the extinction event could conceivably precede the eruption, although this is unlikely. At any rate, possible lags and leads are buried in the noise of the gaussian errors of the dates.

The significance level of the derived correlation is 1% to 4%, depending on the assumptions made about possible age errors. It appears that all major mass extinctions could be associated with continental flood basalts, but that the converse is not true. Some flood basalts (especially the mostly smaller, but more frequent oceanic ones) may, however, have produced less-important marine extinction events, and therefore may be responsible for having terminated at least some of the other geologic stages. This argument suggests the need to search further for possible physical associations at the stage level, as has already been done near the period boundaries (Officer et al., 1987; Dunning and Hodych, 1990; Renne and Basu, 1991; Renne et al., 1992; Campbell et al., 1992).

It would not be profitable, at the moment, to investigate possible correlations between flood basalt eruptions and other major geologic phenomena that, like mass extinctions, are largely or wholly dated by association with stage boundaries and therefore by the use of a standard geologic time scale. Since such time-scale-dependent time series are not independent, they could not at present contribute useful new information.

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