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STRUCTURE AND DATING ERRORS IN THE GEOLOGIC TIME SCALE AND PERIODICITY IN MASS EXTINCTIONS

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Abstract. Structure in the geologic time scale reflects a partly paleontological origin. As a result, ages of Cenozoic and Mesozoic stage boundaries exhibit a weak 28-Myr periodicity that is similar to the strong 26-Myr periodicity detected in mass extinctions of marine life by Raup and Sepkoski. Radiometric dating errors in the geologic time scale, to which the mass extinctions are stratigraphically tied, do not necessarily lessen the likelihood of a significant periodicity in mass extinctions, but do spread the acceptable values of the period over the range 25-27 Myr for the Harland et al. time scale or 25-30 Myr for the DNAG time scale. If the Odin time scale is adopted, acceptable periods fall between 24 and 33 Myr, but are not robust against dating errors. Some indirect evidence from independently-dated flood-basalt volcanic horizons tends to favor the Odin time scale.

Introduction

Mass extinctions of marine species during the Cenozoic and Mesozoic Eras seem to have occurred in regular (or quasi-regular) cycles. The mean period of these cycles is given by Raup and Sepkoski (1984, 1986) as 26 Myr, although a few authors prefer 30 to 32 Myr (Thomson, 1976; Fischer and Arthur, 1977; Rampino and Stothers, 1984; Kitchell and Pena, 1984). Still others reject the finding of periodicity, since they either question the identifications and stratigraphic locations of the major extinctions (Hoffman and Ghiold, 1985; Hoffman, 1985; Patterson and Smith, 1987) or argue that the periodicity is a chance effect occurring in a short record (e.g. Tremaine, 1986; Stigler and Wagner, 1987).

It is widely, though tacitly, believed that any dating errors arising from random and systematic errors in the geologic time scale do not significantly affect the value of the period (see Raup and Sepkoski, 1988, and references therein). A few authors propose that the period may even be an artifact of the geologic time scale itself (Hoffman, 1985; Stigler and Wagner, 1987). These two aspects of the geologic time scale will be addressed here in connection with the question of periodicity in mass extinctions.

Geological Data

An important assumption made by essentially all authors is that all accepted mass extinctions took place at the ends of the stratigraphic stages in which these events were identified. This assumption probably involves little error because at least some mass extinctions are known to have been relatively rapid events and, historically, many stage boundaries have been defined by recognizing the presence of significant changes in biota. Accordingly, Raup and Sepkoski (1986) determined that the eight most reliably determined mass extinctions during the Cenozoic and Mesozoic Eras (roughly the last 250 Myr) occurred at the ends of the following stages: Middle Miocene, Late Eocene, Maastrichtian, Cenomanian, Tithonian, Pliensbachian, Norian, and Dzulfian (see also Sepkoski, 1987; Raup and Boyajian, 1988). They listed in their Table 1 the chronometric ages of the upper stage boundaries according to three different time scales: Harland et al. (1982), Odin (1982), and DNAG (Palmer 1983). Raup and Sepkoski's three sets of ages will be used here as bases for calculation, since the more recent Snelling (1985) time scale can be regarded as a hybrid of the Harland et al. and Odin time scales.

Authors still argue about the definitions of "mass extinction" and "extinction event". To avoid confusion, all extinction maxima regarded by Raup and Sepkoski as being significantly above the background are referred to here as "mass extinctions".

Method of Time-Series Analysis

To analyze the adopted series of dates for possible periodicity, the method of linear spectral analysis (Stothers, 1979) will be used, in which the observed dates t_i ($i = 1,2,\ldots,N$) are matched to predicted times from a linear model $t = t_0 + nP + \epsilon$, where P is a trial period, t_0 is a trial phase, and n is an integer. Goodness of fit for a trial period P is evaluated from a "residuals index" $(\sigma_c - \sigma)/P$, where $N\sigma^2$ is the sum of the squares of the residuals and $\sigma_c /P = [(N^2 - 1)/12N^2]^{1/2}$. Control tests indicate that this method tolerates well a moderate amount of irregularity in the periodicity as well as some noise and random gaps in the series of dates. It has been used, in one form or another, for many of the previous studies of periodicity in mass extinctions. (The simple linear model itself goes back to Galileo's analysis of pendulum motion.)

Periodicity in the Geologic Time Scale

Since many stage boundaries were first defined by abrupt changes in marine biota, it can be expected that the geologic time scale itself should show a weak preference for a period close to 26 Myr. A direct spectral analysis of all 48 Cenozoic and Mesozoic stage-boundary ages listed in the DNAG chronology (Palmer, 1983) yields the spectrum of residuals indices shown in Figure 1. The highest spectral peak occurs at a period of 28 Myr (amid considerable noise). It arises from a tendency for the few stages immediately following a mass-extinction event to have slightly shorter durations than do the preceding stages.

When Stigler and Wagner (1987) used random extinction curves in a real stratigraphic framework for their Monte Carlo simulations of Raup and Sepkoski's (1984) mass-extinction time series, they found a similar bias toward a period of 26 Myr, caused apparently by the geologic time scale. However, by not recognizing the time scale's largely paleontological origin (Raup and Sepkoski, 1988), they improperly concluded that the nonuniform lengths of the stages might be helping to contribute "artificially" to the peri-

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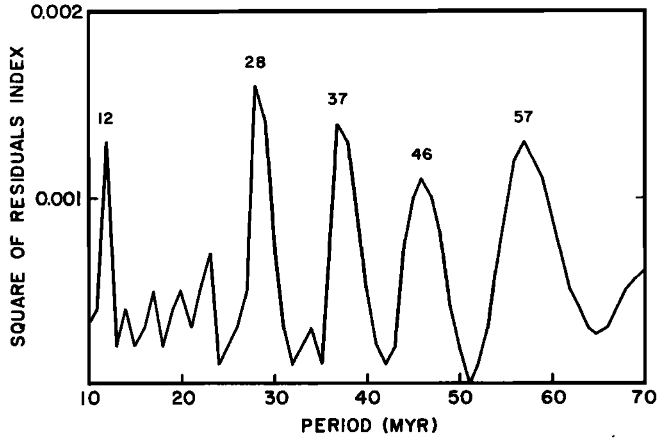

Fig. 1. Spectral analysis of the DNAG stage-boundary ages that fall within the Cenozoic and Mesozoic Eras. The square of the residuals index (defined in the text) is a measure of goodness of fit to an assumed, perfectly periodic time series.

odicity in mass extinctions. Stigler and Wagner's other objections to the 26-Myr periodicity are not strictly tied to any actual geologic time scale and so will not be discussed here (but see Raup and Sepkoski, 1988; Stigler and Wagner, 1988).

Periodicity in Mass Extinctions

To test formally for statistical significance of the 26-Myr period, the null hypothesis that has usually been adopted is complete randomness of the extinction events. Different authors, however, have obtained different results depending on how the random dates were generated. For example, Raup and Sepkoski (1986) placed a set of eight extinction events randomly on the 48 stage boundaries of Cenozoic and Mesozoic time, and derived a formal confidence level of over 99.9%. However, by placing eight events randomly in time anywhere within the Cenozoic and Mesozoic Eras, Tremaine (1986) obtained only 50% confidence.

The reason for the surprising difference in results (despite the fact that both results were based on multiple testing of periods) is that even comparatively small changes of dates in the mass-extinction time series can lead to large shifts in the height of the main spectral peak (Raup and Sepkoski, 1986). What is needed is a confidence test that utilizes the estimated errors of the observed dates themselves directly in the observed time series, without resorting to the use of purely random time series. A further reason for dispensing with the latter is that the true mass-extinction time series may be intrinsically quasi-periodic with a complex structure not known *a priori* (Rampino and Stothers, 1984). In such cases, there may be a real, even though approximate, period for which the absolute height of the corresponding spectral peak is not a very good indicator of the period's presence; this peak is not even necessarily the highest one in the spectrum (Stothers, 1985). Hence a valid test of statistical significance would be difficult, if not impossible, to construct, unless the time series were much longer.

Robustness of the period against possible errors in the dates, however, may be tested for. Since the observed mass-extinction time series is not perfectly periodic, it serves as a very conservative starting series for the suggested perturbation studies. The indicator of robustness then becomes the number of times the highest spectral peak (regardless of its absolute height) occurs at the same period when calculations are done using a large number of appropriately perturbed time series. Each perturbed time series, of course, is to be regarded as a valid alternative representation of the observed time series.

Harland et al. (1982) have estimated the possible errors of the published radiometric ages of tie-points that were used in constructing the modern geologic time scales. For the Cenozoic, they did not estimate the possible errors, but intercomparison of various published time scales suggests maximum errors of $\pm1\%$ to $\pm5\%$ of the published stage-boundary ages. For the Mesozoic, the published error estimates at the tie-points can be very roughly expressed as maximum errors equal to $\pm3\%$ of the published tie-point ages. Stage boundaries that lie between tie-points certainly cannot have true random dating errors that are significantly bigger than this or, otherwise, Mesozoic stage boundaries would theoretically be able to invert in a chronometric sense. Since, however, the ages of these intermediate stage boundaries are partially correlated, systematic errors due to the process of interpolation (such as the assumption by Harland et al. of approximately equal stage lengths between the mid-Triassic and mid-Cretaceous tie-points) can be larger than $\pm3\%$. Even so, the extreme errors of $\pm10\%$ believed possible for early and middle Jurassic times are probably not realizable in practice. Support for a lower percentage error comes from the new radiometric age determinations on lowermost Cretaceous rocks by J. Obradovich (Roth, 1987). Additional, though indirect, support is provided by the independently-derived chronology for major outbreaks of flood-basalt volcanism, which have radiometric dating errors of about $\pm4\%$ and approximately agree in time with the episodes of mass extinctions dated in the conventional stratigraphic way (Rampino and Stothers, 1988). Assuming a close physical association between flood-basalt outbreaks and mass extinctions and also a correct identification of the stratigraphic stages involved, estimated maximum errors of the stage-boundary ages between mid-Triassic and mid-Cretaceous are $\pm3\%$ for the Odin time scale and $\pm6\%$ for the Harland et al. and DNAG time scales, if the flood-basalt time scale is correct.

If the combined random and systematic errors for all the stage-boundary ages, including those at the tie-points, should happen to be perfectly correlated, the derived time-series spectra would remain invariant except for horizontal scale. In that case, the best-fit period would vary by no more than about $\pm3\%$, which is a negligible amount. The true errors, however, cannot be perfectly correlated, and so, to have a more realistic representation of these errors, a uniform error distribution spanning the range from -3% to $+3\%$ of the assigned age is allocated to each of Raup and Sepkoski's (1986) tabulated ages. Such an assumption of fully independent errors for all ages is actually reasonable because for the eight mass extinctions all eight ages are uncorrelated for the Odin time scale (no more than one age is bracketed by adjacent tie-points), while six of the eight ages are uncorrelated for the Harland et al. and DNAG time scales.

The proposed test based on these assumed errors begins with the generation of 1000 perturbed time series in which each of the observed dates is randomly shifted from its mean assigned value within the allowed error range. Spectral analysis is then performed on each of the time series, and the period at which the highest spectral peak occurs is recorded. Trial periods are chosen to run from the shortest effectively resolvable period, 16 Myr (half the mean interval between extinction events), to 100 Myr. The number of times the highest spectral peak occurs at each period is displayed in a histogram.

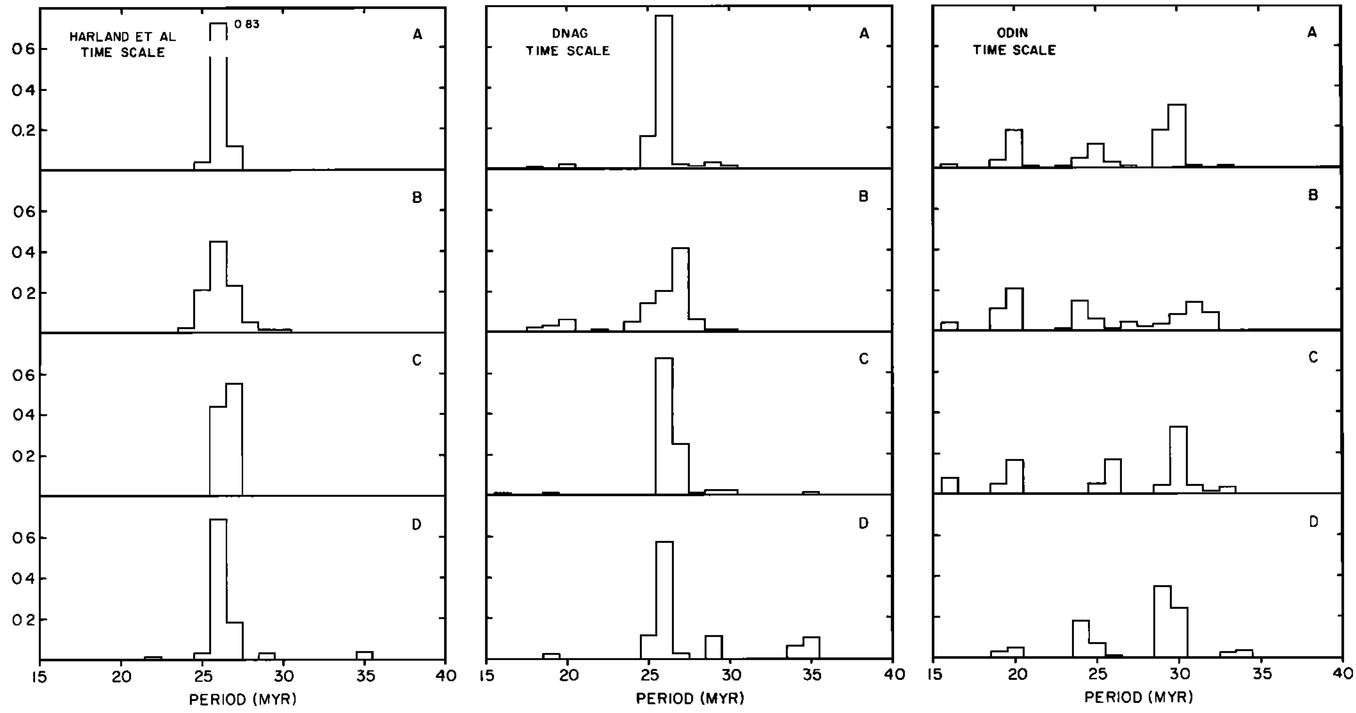

Fig. 2. Histogram of the periods at which the highest spectral peak occurs in a set of 1000 perturbed time series for Cenozoic and Mesozoic marine mass extinctions. Case A, eight extinction events. Case B, eight extinction events with different assigned mean dates for the two oldest events. Case C, ten extinction events. Case D, six extinction events.

Numerical experiments, using as a starting series a perfectly periodic sequence of eight dates successively separated by 26 Myr or a similar sequence punctuated by one or more 26-Myr gaps, yield histograms that contain a large bunching of periods around 25-27 Myr and a small, incipient bunching around periods shorter than 21 Myr, which, however, grows in size as the percentage error of the dates is allowed to increase. These results indicate that the group of shorter periods is due to high-frequency noise in the randomly perturbed time series and should be ignored.

Histograms are plotted in Figure 2 for the four geological cases of greatest interest (Raup and Sepkoski, 1986). Case A refers to the eight most reliably determined mass extinctions at the family level. Case B replaces the Dzulfian and Norian (the tentatively assigned stratigraphic stages of the two oldest mass extinctions) by the Guadalupian and Rhaetian. Case C adds the Aptian and Pliocene extinction events, which are possible mass extinctions at the genus level; but the two oldest family-level mass extinctions have been assumed again to be the Dzulfian and Norian. Case D omits the two possible genus-level events as well as the two least-conspicuous family-level events during the Mesozoic, namely, the Pliensbachian and Cenomanian extinctions. The case D time series exhibits a qualitative similarity to Benton's (1985, 1986) coarse stratigraphic series of mass extinctions of non-marine tetrapods, which have occasionally been associated with the periodic marine mass extinctions (Thomson, 1976; Rampino and Stothers, 1986; Rampino, 1988).

The highest spectral peaks in all of the cases A, B, C, and D occur at periods that are unexpectedly sensitive to the choice of geologic time scale (Figure 2). Superficially, the three time scales agree closely since they deviate from a formal mean time scale by less than $\pm 3\%$, except at one stage boundary, the terminal Tithonian, for which Odin gives 130 Myr BP as compared to 144 Myr BP on the Harland et al. and DNAG reckonings (Hallam, 1984). But if the Harland et al. time scale is chosen for the starting mass-extinction time series in the three cases A, B, and C of greatest interest, the highest spectral peak occurs in a very narrow period range of 25-27 Myr for 89-99% of the randomized series, with other periods being scarcely represented, while the corresponding result for the DNAG time scale is 76-92%, because an additional 5-8% exhibit the highest spectral peak at slightly longer periods of 28-30 Myr. For the Odin time scale, on the other hand, the percentage is only 24-66% for periods in the range 25-30 Myr. Therefore, the existence of a robust periodicity in the case of the Odin time scale may be seriously questioned. As already noted, however, robustness is not the same thing as statistical significance, and so it cannot be concluded that the Odin time scale precludes the existence of a statistically significant periodicity somewhere in the range 24-33 Myr.

The present tests show that the true value of the mass-extinction period, if any period exists, is not yet known with a high precision, although it is likely to lie between 24 Myr and 33 Myr. In fact, these results are very conservative, because the dating errors of some of the stage boundaries might exceed $\pm 3\%$ and because some of the extinction events might not fall at the ends of the assigned stages. Until the extinction time scale is much better known, the question of periodicity remains open.

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