

A scale of greatness and causal classification of mass extinctions: Implications for mechanisms

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A quantitative scale for measuring greatness, G , of mass extinctions is proposed on the basis of rate of biodiversity diminution expressed as the product of the loss of biodiversity, called magnitude (M), and the inverse of time in which that loss occurs, designated as intensity (I). On this scale, the catastrophic Cretaceous–Tertiary (K-T) extinction appears as the greatest since the Ordovician and the only one with a probable extraterrestrial cause. The end-Permian extinction was less great but with a large magnitude (M) and smaller intensity (I); only some of its individual episodes involved some semblance of catastrophe. Other extinctions during the Phanerozoic, with the possible exception of the end-Silurian diversity plunge, were parts of a forced oscillatory phenomenon and seem caused by marine- and land-habitat destruction during continental assemblies that led to elimination of shelves and (after the Devonian) rain forests and enlargement of deserts. Glaciations and orogenies that shortened and thickened the continental crust only exacerbated these effects. During the Mesozoic and Cainozoic, the evolution of life was linearly progressive, interrupted catastrophically only at the K-T boundary. The end-Triassic extinction was more like the Paleozoic extinctions in nature and probably also in its cause. By contrast, the current extinction resembles none of the earlier ones and may end up being the greatest of all.

greatness scale | intensity | magnitude | mass dying | shelf destruction

Following J. C. Rosenmüller's remarkable demonstration in 1794, on the basis of comparative osteology, that *Ursus spelaeus* Rosenmüller was an extinct species (1–3), Georges Cuvier showed that a whole fauna, including mammoths and woolly rhinoceroses, had become extinct “before the empire of man” had become established (4–6). John Phillips later documented that two major minima had characterized Phanerozoic terrestrial biodiversity, one at the end of Magnesian Limestone time (end-Permian) and another at the end of Chalk time (end-Cretaceous). Phillips considered these minima suitable to subdivide the then-known fossiliferous record into three major eras (7, 8). These minima were later ascribed to episodes of pervasive decimation of the terrestrial fauna variously called “universal extinctions” (9), “massive extinctions” (10), “mass extinctions” (11), or “diversity crashes” (12), and ever since, they have troubled earth and life scientists alike (refs. 11 and 13–34; for general overviews, see refs. 35–48). Alcide d'Orbigny (49) used the decimation, indeed as he believed the total extinction, of entire faunas to define what we today call stratigraphic systems. James D. Dana (9) quickly became his enthusiastic supporter.

In one way or another, what we today generally call extinctions have played a vital role in the creation of a geological calendar. Because of that it is of some practical necessity to know how extensive they have been, both geographically and taxonomically, and how fast they altered the size and the composition of the terrestrial biota. Since Cuvier's 1812 book (6), the geological and biological communities have had little reason to question that entire faunas did indeed disappear in the geological past, but ever since Constant Prévost's (50) and Paul Deshayes's (51) work that profoundly influenced the later and similar ideas of Lyell (52, 53), it has remained controversial as to how completely and how fast those disappearances occurred. Interpretations about the nature and origin of these fluctuations in the progression of life have long been

bedeviled by uncertainties as to what constitutes a mass extinction and which mass extinction is “greater” or “lesser” than any other. This difficulty of interpretation has had both taxonomic and stratigraphic reasons. The so-called end-Permian extinction, for example, has long been considered the greatest of all extinctions of the Phanerozoic Eon, “a nearly complete destruction of all life” (see p. 49 of ref. 36), a time at which “life nearly died” (43), but in what time span all that happened is still contentious. Moreover, not all “mass extinctions” are comparable in terms of the effect they had on the biota of the planet: some seem to have threatened all life, whereas others threatened only a part of it (either certain taxa or those in a certain environment), and some came after a protracted span of time during which a slow diminution of biodiversity and/or number of individuals took place, whereas others were rapid.

To talk about what has been called mass extinctions in a sensible way and compare them with each other and with other extinctions generally subsumed under the lump term “background extinction,” a quantitative scale is required on the basis of a rigorous definition of what quantities are measured. It is not contended that quantification will bring any improved accuracy into the data concerning extinctions. We only contend that it will enable researchers to ask the same questions and compare their results rigorously. Such a procedure will help to reduce the number of overly elastic statements concerning timing and taxa concerned, because a precise account will have to be given of what is being counted. It is the purpose of this article to provide a scale of greatness, which we indicate with G , and to compare the Phanerozoic extinctions with one another on the basis of how much they threatened all marine animal life. The scale we propose can be used for any group of taxa, however. The only reason we chose marine animal life is because a convenient and familiar database happens to be in existence (54) and was recently treated in a way we find most suitable in illustrating the nature of our proposed scale (34). When such an objective scale is provided, the ranking of Phanerozoic extinctions in its light appears somewhat different from what one expects from the current discussions. After erecting what we believe to be an objective scale of extinctions, we propose a causal classification of mass extinctions to determine whether the ranking we propose has any relation to general causes.

Extinction Greatness as a Function of Extinction Magnitude and Extinction Intensity

To rank mass extinctions, we propose three quantities, namely magnitude (M), intensity (I), and greatness (G); although two of the terms we use, namely magnitude and intensity, have commonly been used in the literature, they have never, to our knowledge, been rigorously defined, and the meanings attached to them have been inconsistent, with some authors using intensity for what others consider magnitude.

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around the mean. This is clearly a driven oscillator that has the frequency characteristics of the forcing that drives it, because the frequency structure of the extinction intervals between 450 and 250 Ma ago is very different from the pre-450 Ma ago structure (34, 54) and from the structure that follows it (Fig. 1). The two biodiversity curve structures before and after Sepkoski's Paleozoic fauna biodiversity curve (63) structure are, in turn, distinct from one another. Thus, at least two of these curve patterns are unlikely to represent the natural oscillations of the terrestrial biodiversity. Therefore, whatever may have caused the oscillations in the Paleozoic was most likely a common mechanism (or a group of mechanisms) with common characters likely outside the biosphere (with the end-Silurian exception, in the sense that it had a mechanism different from the other post-450 Ma Paleozoic fluctuations). However, when a new evolutionary sequence commences (i.e., a sequence of genera in a certain time period in which the genera time series shows a behavior different from the others, especially the one that predates it), the sensitivity of the system on this new "initial" condition might be different from the sensitivity of the previous system. Characteristics such as the sexual parities of species and their dependence on external conditions (e.g., temperature as in some reptiles), the birth–death proportions of different species belonging to the same sequence, swiftness and range of disease propagations (e.g., avian influenza), etc. are also likely to be different. Therefore, it is impractical to make a one-to-one comparison of the states of systems, which, at certain periods of their duration, might include exactly the same number of genera.

The left-hand (post-Permian) side of the curve in Fig. 1 can be represented by almost a linear fit, save for the sudden diminution of biodiversity corresponding to the K-T decay and a fairly significant diminution at ≈ 210 Ma that was the first serious biodiversity decrease after the recovery from the Permian extinction. However, the 210 plunge is now known to extend beyond the 200 Ma mark when the nonmarine record is also taken into account and not correlatable with any fast geological event such as catastrophic basalt effusion in 1 Ma or less (65). The post-Permian part of the biodiversity curve has a small variance around a nearly linearly increasing trend (as just pointed out, apart from the K-T diminution that most likely has an origin different from the rest of the oscillations of the post-Permian portion of the curve). If, on the other hand, the M value of the Permian extinction is reduced from 1,184 to 947 just for argument's sake, then the 450–250 Ma trend would include the Triassic extinction, and the minimum, dividing the time-series curve, would have been reached only during that extinction. In opposition to the conclusions of Bambach *et al.* (33), the causes of the extinctions from 450 to 210 Ma ago, as judged only on the basis of the curve in Fig. 1, seem most likely to be similar to one another with an additional cause during the end-Permian extinction that considerably increased its magnitude. One important question, therefore, is the following: After the Triassic extinction, how did the number of genera increase so regularly without being subject to the strong oscillations that predated the Triassic extinction? This question immediately leads to another: What drove the oscillations before the Triassic extinction, and, within that oscillating system, what made the Permian extinction so special?

A Causal Classification of Extinctions

A consideration of the proposed causes of extinctions shows that there may be three classes: (i) those that take place because of environmental change resulting from physical processes indigenous to the planet [i.e., the patriagenic (i.e., in-house) extinctions]; (ii) those that take place because of extraterrestrial interference [i.e., the xenogenic (i.e., out-sourced) extinctions]; and (iii) those that take place because of events within the biosphere [i.e., the emfy-

lostasiogenic[§] (i.e., civil-war) extinctions]. These three categories are not intended as exclusive classes but are meant to illustrate only the triggering mechanisms.

For the patriagenic extinctions, the following processes, listed together with the orders of magnitude of their durations in years, have thus far been held responsible, singly or in various combinations, including the desperate "murder on the Orient express" scenario holding all of them together responsible (47, 48): (a) global warming [at the fastest 10^2 -year (the fastest version, however, is known only from anthropogenic causes) to 10^7 -year scale]; (b) glaciations [i.e., global cooling (10^3 to 10^5 years)]; (c) large volcanic eruptions in very short time intervals such as those of Deccan and Tunguska (allegedly $\leq 10^6$ years, but as data accumulate, they are seen to spread over 4- to 5-Ma durations or more: e.g., for the Deccan, see ref. 67; for the Tunguska, see ref. 41, p. 136, and the isotopic ages at www.le.ac.uk/gl/ads/SiberianTraps/Dating.html seen on December 15, 2007; for the Paraná-Etendeka traps, see ref. 67); (d) great regressions (10^7 years); (e) anoxia in the oceans and attendant phenomena (10^4 to 10^7 years); and (f) formation of pangeas (10^8 years). The xenogenic extinctions, whether caused by meteorites or comets, are triggered literally in seconds to minutes, but their effects are spread over at least thousands to tens of thousands of years. Finally, the emfylostasiogenic extinctions, those being triggered entirely by the biosphere, may range from thousands of years, as the current anthropogenic extinction shows, to hundreds of millions of years, as the increase in O_2 in the Precambrian atmosphere by organisms indicates (68).

Of the classes of mass extinction listed above, only those with extraterrestrial origin are known to be triggered literally with lightening speed, and their deadly repercussions are felt within a time frame of 10^4 to 10^5 years. All others take hundreds of thousands to millions of years, except, so far, the current extinction. From this we conclude that the ultrafast events of the Cretaceous and the Quaternary correspond to phenomena that remain probably unique in kind in earth history. The G and cG values of all others seem to cluster among themselves, and their causes are probably tied to indigenous processes of our planet that influence life with similar comprehensiveness and similar speed.

What Is Special About the Permian Extinction?

Why, then, has the Permian extinction been singled out as being special? Obviously, because it has been thought so severe to be singular in the Phanerozoic. Its "severity," however, has never been properly defined but assumed to be prodigious because of the terribly low level to which the terrestrial biodiversity had plunged by Induan to Olenekian time (251–245 Ma ago). Which processes acted in such a way as to harm marine animal (and also terrestrial, for that matter) biodiversity between the Ordovician and the Olenekian?

One obvious candidate is continental assembly, as emphasized by many before. Since 450 Ma ago, the previously dispersed continents progressively gathered into smaller numbers of assemblies, finally culminating in a single body, namely the end-Paleozoic Pangea. As continents become less in number and existing ones greater in area, biodiversity diminishes both on land and in the seas in consequence of habitat, especially continental shelf (after the Devonian, also rain forest), destruction. As Suess (13–15) pointed out long ago and Purdy (34) reiterated recently, sea-level drop (a function of continental assembly) correlates with the negative trend of marine animal biodiversity because of destruction of marine habitats in the most vital part of the ocean, namely the continental shelves. Glaciations and orogenies simply exacerbate the amplitudes of sea-level lowerings and exposure of continental shelves, leading to

[§]"Emfylostasiogenic" is a new word we created from the classical Greek words *ἐμφύλιος* (emfylos), meaning kinsfolk, tribe; *στάσις* (stasis), meaning sedition, discord; and *γέννησις* (genesis), meaning producing, engendering.

increased continentality on land (69). Increasing continentality naturally reduces another habitat rich in biodiversity, namely rain forests that had become widespread in the Carboniferous and declined with the progressive tightening of and consequent elimination of internal seaways in the Pangea. Therefore, a serious low in marine and terrestrial animal biodiversity was not unexpected toward the end of the Permian. The *coup de grâce* at the end of the Permian was delivered, we think, by the Ptolemaic condition of the earth, that is, the total isolation of Paleo-Tethys from Panthalassa and its development, since the late Carboniferous, into a major anoxic basin that, at the end of the Permian, overflowed into the peri-Pangean Panthalassa in the Northern Hemisphere (ref. 70, ¶). This not only poisoned major volumes of the world ocean close to continents, but probable gas eruptions of Paleo-Tethys most likely also eliminated a vast section of the terrestrial biomass including insects and plants, as suggested by a 2000-km-wide halo of fungal spikes around it (ref. 70, ¶). The magnitude of the total biosphere elimination by the end of the Permian cannot be assessed appropriately unless one takes it as the difference between the biodiversity 450 Ma ago and that at the end of the Permian. However, the intensity represented by this immense time interval is so small that the product of $M \times I$ cannot make the end-Permian squalor of the biosphere the result of the “greatest” extinction. Its causes were most likely entirely Lyellian, with the exception of the final Cuvierian anoxic catastrophe(s) (ref. 70, ¶).

Diversity blooms occurred when the opposite of what we just described happened at times in the Paleozoic by the growth of Turkeic-type orogens that generated vast shelf areas on juvenile continental crust (69). However, in the Paleozoic, shelf destruction and sea-level lowering always held the upper hand eventually (69).

By contrast, the Mesozoic-Cainozoic world was a world of progressive increase in marine animal biodiversity together with increases in atmospheric oxygen, continental dispersion, and sea-level rise. Thus, no observer at the end of the Cretaceous could have foreseen the disaster that was about to hit the biosphere at that time. It was an unexpected affair that happened with immense swiftness and ferocity, eliminating a huge number of genera within a time interval shorter than the time constant of most indigenous processes of the earth to affect the entire biosphere. It was truly a Cuvierian catastrophe, “the most spectacular” mass extinction event in the Phanerozoic (ref. 45, p. 33), but it was also the deadliest. As Hallam (ref. 71, p. 213) reminded us, “Something very unusual appeared to have happened at the end of the Cretaceous, and opinion is growing that it might have involved an event unique in the Phanerozoic.”

From the arguments presented in this articles, it seems as if the Permian extinction was the last straw that broke the camel's back, whereas the end-Cretaceous extinction was the stray mouse that choked the healthy elephant.

The present extinction, which seems greater than any thus far, has elements of those of both the Cretaceous and Permian. It represents a virtual Pangea formation by providing human-caused transfer of organisms world-wide simulating a world with no oceanic barriers, leading to increased competition without opening new niches and the introduction of a global annihilating agent, namely humans, that creates functional deserts for much of the rest of the biosphere (human dwellings) at a rate unknown in the history of the biosphere during the Phanerozoic. It is a Lyellian event accelerated and magnified to Cuvierian dimensions. If unchecked, the present extinction threatens to be the greatest killer of all time.

Conclusions

Extinctions may be ranked according to their greatness, G , defined as the product of the portion of the biosphere affected (M), proxied by biodiversity decline, with the inverse of the time in which the biodiversity plunged, used as a proxy to the intensity (I) of the extinction. Mass extinctions have affected large volumes of the biosphere during intense killing episodes. If biosphere volume diminution takes a long time, the extinction may not be great at all but simply of considerable magnitude. By contrast, intense extinctions may cut deep but narrow slices out of the biosphere that may be swiftly refilled by a subsequent diversification bloom. Therefore, the size of mass extinctions, if they are to be worthy of that name, must be expressed by objective G numbers expressing the general threat to all life at any one time. An extinction with a large G number may be arrested before running its full course and, thus, may never achieve a large M number, but it would still represent a process with a potential of mass killing (such as the present extinction), and we would like to know about it.

Great extinctions are generally less catastrophic than widely thought: they are generally Lyellian, only exceptionally Cuvierian. When they are Cuvierian, as the end-Cretaceous extinction so obviously was, and as the present one so alarmingly is, they stand out among the other, more mundane, Lyellian ones. It is not profitable to study extinctions in isolation, among few taxa, in few sections and in limited time frames. They are simply parts of one continuous evolution of the entire earth system and must be studied as such.

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