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Impact Theory: Is the Past the Key to the Future?

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Most geologists and biologists have never denied that there was a role for the unusual event or catastrophe in shaping the Earth's biota. The impact theory, however, has a different emphasis: it says not only that asteroid impacts could occasionally have an important effect, but in fact that they cause some of the most obvious patterns in life's history.

The "impact theory" views the history of life as punctuated by catastrophic mass extinctions caused by the impact of large extraterrestrial bodies, such as comets or asteroids (Fig. 1). The theory was originally developed to explain the well-known catastrophic mass extinctions around the Cretaceous-Tertiary boundary (65 MA) but it has now been extended to explain other apparent mass extinctions through the Phanerozoic (570 MA-present) as well. This is a seductive theory with profound philosophical as well as geological implications; it rightly stands as one of the more controversial theories of this century.

Cretaceous-Tertiary Boundary

It has long been recognized that a profound change in the Earth's biota occurred around the Cretaceous-Tertiary boundary. It was the magnitude of this transition and the Permian-Triassic (245 MA) boundary that prompted John Phillips' division of the Phanerozoic into Paleozoic (Old Life [570-245 MA]), Mesozoic (Middle Life [245-65 MA]), and Cenozoic (New Life [65 MA-present]) in the mid-19th century (Fig. 2). According to recent estimates by John Sepkoskie and Dale Russell 17% of all marine animal families, 20% of all genera of terrestrial animals, and 14% of all genera of lacustrine animals seem to have become extinct. The 17% extinction of marine families probably translates into perhaps 54% of the marine genera, and perhaps 85% of all marine species. Included among these extinctions were all ammonites, all belemnites, 55% of all genera of snails, 66% of all bivalve genera (including all rudists), perhaps all but one species of planktonic foraminifera, all non-flying dinosaurs (birds survived), all large marine reptiles, and all pterosaurs. On face value, this would certainly seem to be a catastrophic mass extinction.

The apparent synchronicity of the marine and terrestrial extinctions and the disappearance of the dinosaurs, previously dominated for 140 million years, has naturally prompted a wide range of explanations from geologists and paleontologists. These have included such gradualist explanations as slow global climatic warming or cooling, competition or predation from mammals, evolution of inedible plants, and lowering of sea level. Other catastrophic explanations have also been proffered, such as massive volcanism, a burst of radiation from a supernova or a magnetic reversal, and of course asteroid or comet impacts.

The gradualist and catastrophist sets of hypotheses make very different predictions about the distribution of extinctions through time around the Cretaceous-Tertiary boundary which should be testable in the fossil record. Unfortunately, the paleontological data available from most of the literature is compiled at level of the age (about 5-million-year intervals). Therefore, the extinctions listed above could actually have taken place anywhere in the 8-my duration of the terminal age of the Cretaceous — the Maastrictian (Fig. 3). If the extinctions were in fact spread through the entire duration of the Maastrictian Age, the total

Fig. 1: Large asteroids or comets have hit the earth repeatedly through geological time. This is the Manicouagan structure formed at or near the Triassic-Jurassic boundary (200 MA) by the impact of an approximately 10-km bolide into Grenville basement in Quebec. The inset shows the New York area at the same scale. The dark ring is a 70-km lake filling the most intensely fractured zone around the melted zone. The diameter of the structure is extended to 100 km by several additional fainter rings. At least 1 km of rock has been eroded since the time of impact. (Planetary Image Center, LPI [NASA]).

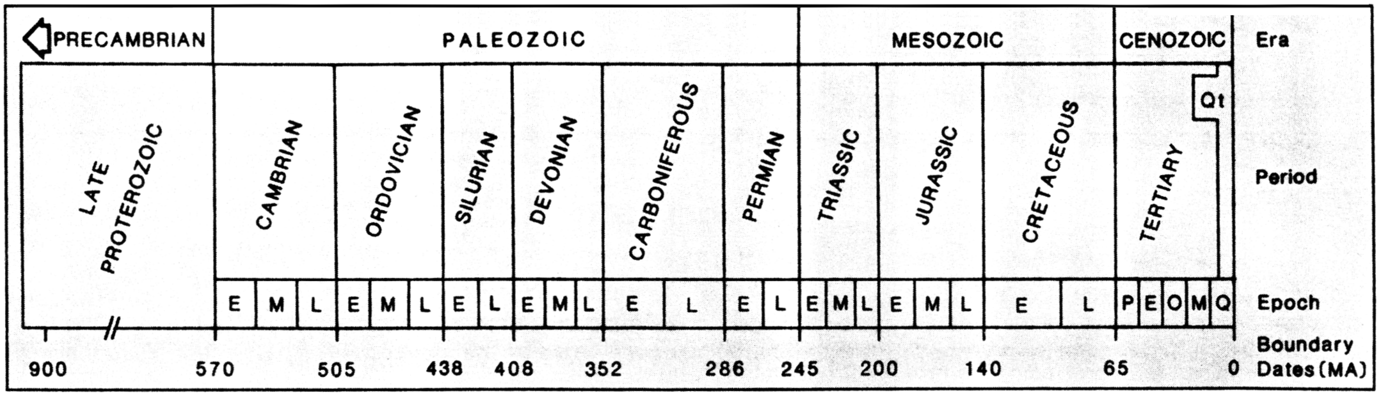

Fig. 2: Eras, periods, and epochs. Abbreviations in Tertiary as follows: QT, Quaternary Period; Q, Pliocene, Pleistocene, and Holocene epochs; P, Paleocene Epoch; E, Eocene Epoch; O, Oligocene Epoch; M, Miocene Epoch. Other abbreviations are: E, early; M, Middle; L, Late. Boundary dates modified from the Decade of North American Geology Time Scale.

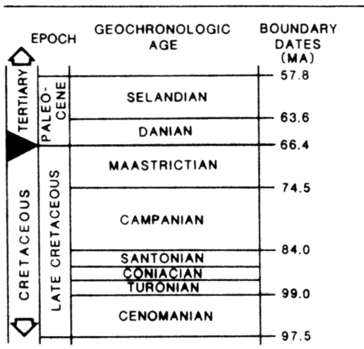

Fig. 3: Geologic time scale around Cretaceous-Tertiary boundary showing geochonologic ages, epochs, and periods as well as boundary dates (from the Decade of North American Geology 1983 Time Scale).

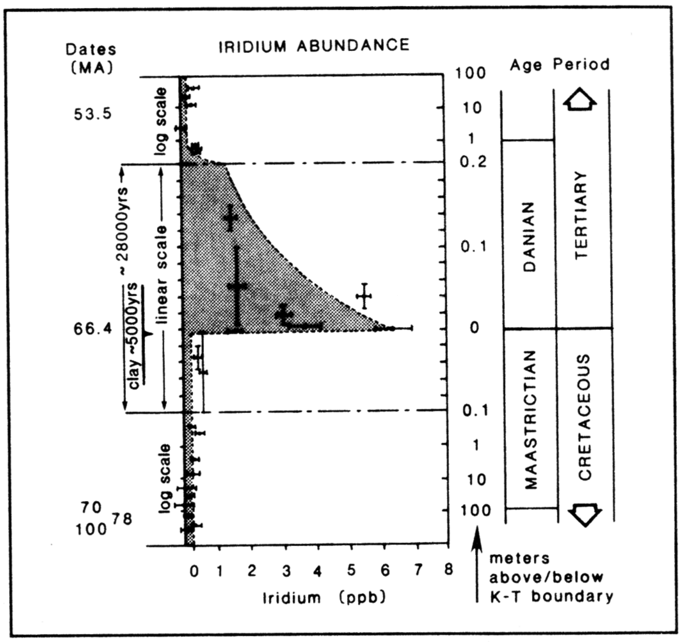

Fig. 4: Iridium abundances through Cretaceous-Tertiary boundary in pelagic limestones exposed in and near Gubbio, Italy. Abundances are per unit weight of acid-insoluble residues. Shaded area shows an "eyeball fit" (by the Alvarez group) exponential with a half life of 0.43 cm. (Figure adapted from Alvarez, Alvarez, Asaro, and Mitchel, 1982).

extinction event would certainly not qualify as catastrophic and probably not even as a mass extinction. As examined traditionally, the paleontological data have not provided clear-cut tests of any extinction model.

Physical evidence for some kind of catastrophic event was until quite recently similarly ambiguous. However, in 1980 Luis Alvarez, his son Walter Alvarez, Frank Asaro, and Helen Michel published evidence for an asteroid or comet impact at the Cretaceous-Tertiary boundary in exposed marine carbonate sequences at Gubbio Gorge in Italy, and Stevens Klint in Denmark. At exactly the interval that had been previously identified as the Cretaceous-Tertiary boundary by paleontologists, they found at a thin layer of clay which proved to contain levels of the platinum group element iridium 30 to 160 times the concentration in surrounding beds (Fig. 4). Because iridium is depleted in the Earth's crust, but relatively enriched in extraterrestrial material, the Alvarez group postulated an asteroid or comet origin for the iridium enrichment of the boundary clay. Over the last 5 years many researchers have found similar iridium anomalies at the Cretaceous-Tertiary boundary in many other localities, including deep-sea cores and continental deposits. The initial objections that the boundary anomaly could be explained as a purely diagenetic feature or that there might be iridium anomalies in other parts of the sections, have proved more or less unfounded.

More recently, spherules of what are interpreted as devitrified glass and/or feldspathic and mafic silicates have been identified in the boundary clay at a number of localities. These closely resemble glassy microtectites, long thought to be produced by the impact of meteors. These boundary spherules have a greater concentration of iridium than the surrounding matrix and may have been the major carrier of the element. In addition, shock-metamorphosed quartz occurs in the iridium anomaly layer in a number of terrestrial sequences in western North America. Shock-metamorphosed mineral grains are usually thought to be uniquely produced by extraterrestrial impacts. Recently, however, it has been suggested that both the boundary clay spherules and the shocked mineral grains could have been produced by volcanic eruptions.

With the discovery of physical evidence of a catastrophe at the Cretaceous-Tertiary boundary, it becomes necessary to re-evaluate the paleontological data, with particularly fine-scale scrutiny of the iridium anomaly-bearing sections themselves, since it was originally very unclear over what span of time the extinctions actually occurred. At Gubbio, Stevens Klint, other outcrops, and in many deep sea cores most extinctions have proved to occur at the boundary, although there are still some discrepancies. In the terrestrial sections in which an iridium anomaly occurs, dinosaurs disappear below it; they are never, however, sufficiently abundant to determine statistically if their disappearance directly coincides with the iridium layer.

The terrestrial plant record offers two different perspectives on the boundary, depending on the scale of examination. At the level of global compilations (geochronologic age), there is no dramatic break from the latest Cretaceous (Maastrictian Age) to the earliest Tertiary (Danian Age) (Fig. 3). However, at the sections where iridium anomalies have been identified, there is a dramatic break in the floral record with the extinction of a number of pollen forms just below the iridium anomaly, and a dramatic increase in fern spores just above (as shown by Robert Tschudy and colleagues). Ferns tend to colonize massively disturbed areas before any other major plant groups. Thus, although there are numerous dissenting views, the bulk of the fine-scale paleontological data seems in accord with a catastrophe at the Cretaceous-Tertiary boundary.

ALTERNATIVE EXPLANATIONS

There are at least two alternative catastrophic hypotheses which are also potentially compatible with the iridium anomalies. First, there is the supernova hypothesis of Dale Russell and others. The supernova of a relatively nearby star would send a shell of newly-formed heavy elements outwards, eventually passing the Earth and adding a large amount of fine extraterrestrial matter to the atmosphere. However, as pointed out by the Alvarez team, a significant ^{244}Pu anomaly should be associated with that iridium, but it is not. The second hypothesis considers the iridium to have a volcanic source, and this hypothesis cannot be so easily disposed of. Like extraterrestrial matter, the deep mantle and core of the Earth are relatively enriched in the platinum group metals, including iridium, and some sort of deep-seated explosive volcanism could be responsible.

The volcanism hypothesis has gained some support from the observation that iridium is enriched in airborne particulate matter from Kilauea Volcano of Hawaii, possibly from a mantle source, as described by William Zoller and his colleagues. In addition, the voluminous Deccan Plateau Basalts of India bracket the Cretaceous-Tertiary boundary, so there is a record of very large-scale volcanism. On the other hand, neither the Deccan nor the Hawaiian types of volcanism would be expected to send a large amount of matter into the atmosphere. There are, moreover, no examples of very large-scale deep-mantle explosive volcanism known, (which certainly does not mean they might not have occurred). Thus, we cannot rule out massive volcanism as a cause of both the Cretaceous-Tertiary extinctions and the iridium anomaly.

While there are no known examples of a volcanic eruption producing a sedimentary iridium anomaly, there is a well-documented example of an iridium anomaly produced by an asteroid. Last year Frank Kyte and D. Brownlee described unmelted meteoric particles from Antarctic deep-sea cores from within a Pliocene iridium anomaly, probably produced by the impact of a 100-m to 500-m small howarditic asteroid. The Pliocene anomaly is apparently not of worldwide extent, but the occurrence does demonstrate that asteroid impacts can and do produce iridium-enriched layers.

Based principally on models of iridium abundances at the time of impact and the frequency of asteroids which cross the Earth's orbit, the Alvarez group calculated that the asteroid responsible for the iridium anomaly would be roughly 10 ± 4 km in diameter. Such a bolide would release energy roughly equivalent to 100,000,000 megatons of TNT on impact with the Earth. The most commonly cited scenario envisioned for the actual cause of extinctions due to this impact involves the injection of large amounts of dust into the stratosphere, which would then block out all sunlight for a period ranging from several months to several years. This, in turn, would stop photosynthesis and collapse both the terrestrial and aquatic food chains for the duration of darkness. More recently Wendy Wolbach and others have proposed that continent-wide wildfires triggered by the asteroid impact would add very large amounts of soot to the atmosphere, adding to the sunlight-blocking effect of the dust produced by the impact itself. In addition, extinctions due to thermal stress, by either warming due to a greenhouse effect or cooling due to increased albedo and poisoning of the ocean and atmosphere, have also been proposed as deadly consequences of an impact.

There is little doubt that large asteroids or comets have struck the Earth in the geological past. There are appropriately sized impact sites of various ages identified over the globe. None large enough, however, have been found for the Cretaceous-Tertiary boundary, despite extensive searching. The apparent absence of a crater of the right size and age can be explained by burial by younger sediments, impact into a subducted portion of oceanic crust, or complete erosion of the impact site. Discovery of an impact structure of the appropriate size and age for the Tertiary-Boundary would certainly be a boost for the impact theory, but the absence of the structure cannot be taken as its disproof.

Triassic-Jurassic Boundary

While the Cretaceous-Tertiary boundary spawned the impact theory, there are other apparent catastrophic mass-extinctions which fit the same scenario. The best example is the Triassic-Jurassic boundary (200 MA). Tabulated at the chronostratigraphic age level (Figs. 2 and 5), 43% of all continental tetrapod families disappear in or at the end of the last age of the Late Triassic (the Norian [200-218 MA]). Even if we look only at the latest Norian, at least 50% of the tetrapod families are extinct by the Hettangian (ca. 197-200 MA). The dominant marine invertebrates were also strongly affected. All conodonts, nearly half of the bivalve genera and nearly all bivalve species, almost all nautiloid and ammonite families, and most brachiopods, disappeared at the Triassic-Jurassic boundary. This extinction is comparable in magnitude, if not larger, than that of the Cretaceous-Tertiary boundary.

Continental sediments in which the Triassic-Jurassic boundary has been identified abound on the East Coast of North America. These comprise the Newark Supergroup, remnants of the rifting stage of the present Atlantic passive margin. In the largest

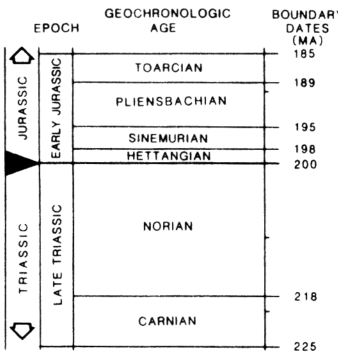

Fig. 5: Geologic time scale for interval around Triassic-Jurassic boundary showing geochronologic ages, epochs, and periods as well as boundary dates (adapted with revision from the Decade of North American Geology 1983 Time Scale).

exposed basin, the Newark basin of New York, New Jersey, and Pennsylvania, there are extensive extrusive basalt flows and interbedded sediments about 30 m or less above the paleontologically dated boundary. Contemporaneous with these flows are extensive diabase intrusions (among which is the Palisades Sill which underlies the Lamont-Doherty Geological Observatory). Similar lava flows and intrusions occur in many other Newark Supergroup basins. Collectively, these igneous rocks are earliest Jurassic in age (Hettangian [197-200 MA]), appear to span less than 500,000 (based on basalt fractionation rates and Milankovitch climate cycles) years, and yield K-Ar dates around 200 MA. The 200 MA date for the basalts is probably the best date for the Triassic-Jurassic boundary as well. The other Newark Supergroup basins, along with the Newark basin, preserve an extensive and well-preserved record of the continental Triassic-Jurassic extinctions. Critically, these tetrapod extinctions appear to be synchronous with globally extensive continental extinctions and contemporaneous with the massive marine invertebrate extinctions as well.

Nova Scotia Discoveries

Last year, in cooperation with a team headed by Neil Shubin from the Museum of Comparative Zoology at Harvard University, (funded by the National Geographic Society), I discovered a series of rich assemblages of reptiles in the Fundy basin of the Newark Supergroup of Nova Scotia, Canada which helps document the magnitude and timing of these Triassic-Jurassic extinctions. The assemblages are probably less than 500,000 years younger than the Triassic-Jurassic boundary (early Hettangian) and consist of an abundant and diverse set of dinosaurs, crocodilians, mammal-like reptiles, lizard-like sphenodonts, and possibly amphibians. It is especially interesting that, although all "typical" Triassic forms are absent, the assemblage consists only of survivors of the Triassic and no new taxa.

This pattern of only survivors after the boundary is exactly the kind of transition that would be expected of a catastrophic extinction event such as that proposed for the Cretaceous-Tertiary boundary. One would not expect to find in the immediate aftermath (within 500,000 years) of a catastrophe the origination of new families. Rather the "day after" communities should be composed of survivors — exactly the pattern seen in the early Hettangian Nova Scotian faunules. Such a pattern of survivors has already been described for the Cretaceous-Tertiary boundary. These new discoveries strongly support the hypothesis of a sudden and dramatic extinction event at the Triassic-Jurassic boundary, affecting both marine and terrestrial assemblages.

As for the Cretaceous-Tertiary extinction, numerous causal explanations of the Triassic-Jurassic extinction event have been proposed. These range from ecological explanations which argue for competitive extinction of "primitive" by "advanced" forms, to geomorphic changes involving massive marine trangressions and loss of continental relief. None of these arguments explain the abruptness of the transition. Again an extraterrestrial origin for the event is a plausible hypothesis, and in this case there is a well documented major impact structure of appropriate age.

MANICOUAGAN IMPACT STRUCTURE

The Manicouagan impact structure (Fig. 1) of Quebec is dated at 210±4 by K-Ar methods which is within the uncertainty around the Triassic-Jurassic boundary. The impact structure is 70 km in diameter and was probably produced by a 10 km or larger bolide. The astrobleme is less than 500 km from the reptile-producing units in Nova Scotia. At present the possible correlation of an impact event with the extinctions can only be regarded as tantalizing, because no direct internal evidence, such as an iridium anomaly or shocked quartz, has ever been identified in strata encompassing the Triassic-Jurassic boundary (although Mark Anders, a student of Walter Alvarez, is currently looking for just such evidence in Triassic and Jurassic rocks in Nova Scotia). The biological data seem to favor the type of scenario envisioned for the Cretaceous-Tertiary extinction by a catastrophic event more than any other.

Periodicity of Catastrophic Mass Extinctions

When extinction rates are plotted against time (Fig. 6) a cyclical and suggestively quasi-periodic pattern is apparent. In addition to the Cretaceous-Tertiary and Triassic-Jurassic boundary extinction events, there is at least one mass extinction of even greater magnitude which occurs at the Permian-Triassic boundary (245 MA), and 10 or so mass extinctions of considerably lesser magnitude. Recently, the impact theory has gone one more step forward with the recent suggestion by David Raup and John Sepkoskie and Michael Rampino and Richard Stothers that these 13 or so extinction events occur with a periodicity of between 26 and 33 million years, and that this periodicity correlates both in phase and frequency with the pattern of bolide impacts on the Earth. While there can be little doubt that large asteroid or comets have repeatedly struck the Earth, perhaps with catastrophic results to the Earth's biota, both the apparent periodicity of the extinctions and their correlation are hotly contested and cannot be considered very robust, as has been cogently discussed by Antoni Hoffman of Lamont. The main problems involve the definition of mass extinctions as distinct from "normal" background levels of extinction, differences among competing time scales, artifacts of correlation, and the very coarse scale at which the extinctions have been examined. The supposed periodicity in extinctions and bolide impacts has spawned a variety of astronomical hypotheses, including the presence of a binary twin to our own sun ("Nemesis" or the "Death Star") disturbing the Oort cloud, (as proposed by Walter Alvarez and Richard Muller), the presence of an additional, unseen planet ("Planet X" of Daniel Whitmire and Albert Matese), and a supposed correlation with the oscillation of our solar system through

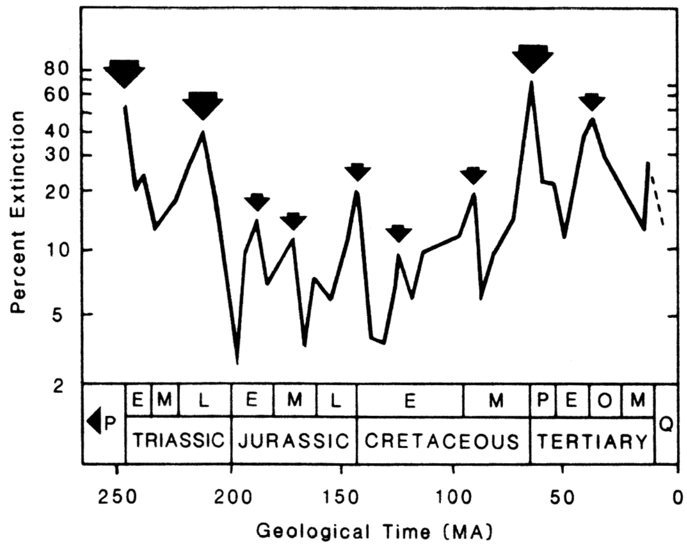

Fig. 6: Percent extinction of marine families of invertebrates from the Permian-Triassic boundary to the Miocene-Pliocene boundary at the chronstratigraphic age level (approximately 5 million year invervals) showing quasi-periodic pattern of peaks. Here, extinction is expressed as the number of families which have their last appearance in an age, divided by the total number of families present in that age. Large arrows show the most important extinction events, and smaller arrows show less significant peaks in extinction. Abbreviations as in Fig. 2, except that the P at the left represents the Permian Period. (Adapted with time scale revision from Raup and Stanley, 1984).

the galactic plane (as originally proposed by S.M.V. Clube), all of which would oscillate with a periodicity of around 30 million years. These extremely creative and heuristically valuable hypotheses have received mixed reviews from various astrophysicists, but I do not think the hypotheses can yet be discarded.

Impact Theory and the Nuclear Winter Model

Shortly after the proposal of the impact hypothesis and its mechanism of extinction, a similar scenario was developed for the consequences of a modern thermonuclear holocaust by Richard Turco, Carl Sagan, Paul Ehrlich and others. In this "Nuclear Winter" model, even a modest nuclear exchange with detonation of warheads above cities and forests would raise large clouds of dust and produce extensive firestorms, resulting in the injection of something like 225 million tons of smoke into the atmosphere. As in the Alvarez group's model the consequence would be a reduction of sunlight to less than several percent of normal with a dramatic lowering of temperature, perhaps down to −23° to −50° C after the war. The consequences for the global ecosystem would be quite like those proposed for the Cretaceous-Tertiary boundary. The Nuclear Winter model yields predictions of devastation far greater than the usually accepted, terrible consequences; the total yield of the present world arsenal of nuclear weapons is on the order of 14,000 megatons of TNT, roughly four orders of magnitude less than the calculated "yield" of an impact of a 10-km-asteroid (100,000,000 megatons).

Evolutionary Consequences of Catastrophic Mass Extinctions

The effects of a large asteroid impact or nuclear holocaust on the world's biota would not be the same as a scaling up of smaller perturbations. Organisms respond to a hierarchy of environmental perturbations and different sorts of effects occur at each level. At the lower levels, organisms must adapt to change on the scale of days and years. These time scales are short compared to the lifespan of the organisms and they can adapt their behavior and morphology through evolution to anticipate predictable changes. On longer time scales it may be difficult for organisms to evolve anticipatory adaptations, but there can still be an evolutionary response by speciation and extinction.

Analyses of modern, Pleistocene (0.01-1.6 MA) and early Mesozoic (185-225 MA) lakes, fossil lacustrine sequences and their contained fish show that this is the case for the response of organisms to environmental changes operating within the higher-frequency elements of the Milankovitch Climate Cycles (e.g., 21,000-yr cycle). Enormous numbers of species evolve and go extinct as wet-dry and warm-cold cycles dramatically alter the size and quality of habitat areas. For the lower-frequency elements of Milankovitch Cycles (e.g., 100,000- and 400,000-year cycles) there seems to be a response at the genus and family level, probably through species selection. Pleistocene sea-level changes, glacial and interglacial alternations, and dry intervals lasting tens of thousands of years fall into this level. At even lower frequencies, on the order of millions of years, we have repeated if not periodic catastrophes such as proposed by the impact theory. These perturbations presumably act far more arbitrarily on the global ecosystem and act to disrupt any long term cumulative effects of the lower level perturbations. At even longer time scales, on the order of hundreds of millions of years, we have the effects of continental drift and ultimately the cosmological evolution of the Earth, solar system and the universe itself. Each level of this hierarchy has elements which have origins at least in part independent from lower levels, but the effects of each level may strongly depend on the precise state of the lower-level perturbations. It may very strongly matter, for example, whether an asteroid hits during a time of low sea level rather than high.

What kind of evolutionary scenario might we develop for the type of catastrophic mass extinction predicted by the impact theory? The initial effect of either the cessation of photosynthesis or thermal stress lasting perhaps less than a year to a few years, would be mass extermination of most of the macroscopic animals on earth. As a consequence many animal species would become extinct, most likely those which were large and relatively high in the food chain and incapable of surviving torpor, estivation, or hibernation. No animal with a body weight of greater than 25 kg seems to have survived the Cretaceous-Tertiary Boundary, for example, Among terrestrial animals, those which could burrow and hibernate would be most likely to survive, and in the marine realm benthic and/or environmentally unspecialized animals without a planktonic larval stage would seem to have the best chance for survival. Land plants would be much less affected. Not only are many seeds capable of surviving long periods of darkness and thermal stress (especially if buried), but so are trunk, rhizome, and root systems, and this greatly increases the survival rate of individual plants as well as species.

The taxonomic recovery after the Triassic-Jurassic extinction differed in many ways from that of the Cretaceous-Tertiary. Seventy-five million years followed the Late Triassic extinction event before the family level diversity of terrestrial vertebrates surpassed Late Triassic levels. In contrast, it took less than 10 million years for the number of Tertiary terrestrial vertebrate families to recover to their Late Cretaceous levels. On the other hand, the recovery times for marine invertebrates was roughly 20 million years for both extinction events. The reasons for the difference between the recovery times of the terrestrial vertebrate patterns of the end-Triassic and end-Cretaceous extinctions are not at all apparent. Perhaps they have something to do with the extremely uniform Jurassic and Early Cretaceous global flora, which contrasts with the much more provincial flora of the Tertiary. Or perhaps they are due to the different speciation patterns of the dominant groups: dinosaurs and gymospermous plants were dominant after the Triassic extinctions, but mammals and angiospermous plants were dominant after the Cretaceous.

Our understanding of the evolutionary patterns of the recovery period following a catastrophe is very poor at the population and species levels. However, we might gain some insight by analogy with the microcosm of the evolutionary patterns seen in fishes of Lakes Kariba, Victoria, Tanganyika, and Malawi of East Africa on which the following scenario is based. Within the first few thousand years of the catastrophe, the world biota would consist only of the remaining survivor species, but the numbers of individuals would increase exponentially as the base of the food chain recovered. Presumably, individual populations and species dominance would be highly unstable and subject to occasional crashes. However, within a few tens of thousands of years, certain of these surviving species would radiate explosively into hundreds and thousands of new morphologicaly rather similar species, filling the newly vacated ecological space with more specialized, and more stable occupants. Other forms would speciate at lower rates, some changing little, others showing considerable change. Eventually, on the scale of several million years, we might expect some groups of species to have become so different from their ancestors that we would recognize them as new higher taxa such as families. Much more specialized members of these new, more distantly related families might after 10 or more million years crowd out the opportunistically speciating groups and eventually surpass the pre-catastrophe levels of family diversity. Of course, the precise response would ultimately depend on the intrinsic properties of the surviving groups and the phase relations and magnitude of effect of the other levels in the hierarchy of environmental perturbations.

Philosophical Considerations

The impact theory differs from most scientific explanations of Earth and biological processes in at least three ways. First, its effect supposedly operates at a much higher scale than other processes, cutting across the traditionally accepted levels of environmental perturbations — it implies a hierarchical view of effects. I have already commented on this aspect of the theory. Second, it is the ultimate in abrupt rather than gradualist causes; its effect is measured in years rather than millenia. Finally, it is a special explanation, invoking a unique extrinsic cause which is not part of "normal" Earth history.

As has been commented on by Stephen Gould and others, the impact theory is a recent and powerful challenge to the long-dominant Lyell-Darwin view in which small-scale, short-term changes are extrapolated to the grand scale through an "insensibly graded series" of events. It is a methodologically uniformitarian theory, but it calls on past causes we cannot observe in operation, and can only infer. Philosophically, the theory hearkens back to the late 18th- and early 19th-century, pre-Darwinian concepts of repeated catastrophes and special creations of Georges Cuvier. Cuvier, a pioneer of stratigraphical paleontology, as well as comparative anatomy, regarded the fossil record as proof that the biological world was repeatedly wiped out by some sort of, "Revolution," as he called it, and rebuilt from scratch — a convenient biostratigraphic approach — and his best example was the Cretaceous-Tertiary boundary. Interestingly, Cuvier, who was born in 1769, was a young man through the French Revolution (1789-1799), an event that must have impressed him deeply. Through the natural theology of William Buckland, Alcide d'Orbingny, and Louis Agassiz the catastrophism of Cuvier became less and less gentle and more and more the hand of God. This theological catastrophism was more or less replaced by the end of the 19th century by the evolutionary gradualism of Lyell and Darwin, which now finds itself under attack on several fronts. Most geologists and biologists have never denied that there was a role for the unusual event or catastrophe in shaping the Earth's biota. The impact theory, however, has a different emphasis: it says not only that asteroid impacts could occasionally have an important effect, but in fact that they cause some of the most obvious patterns in life's history.

Scientific theories are not divorced from society's norms and common philosophy. We have lived for 40 years with the concept of nuclear holocaust and the immediate intensity of interest with which the impact theory has been greeted almost certainly has been affected by our fear and fascination with the possibility of our own imminent annihilation. The impact theory fits our rather new view of the ultimate destructive and uncontrollable control by catastrophes unrelated to our day to day activities. The parallel and intertwined development of the impact theory and Nuclear Winter scenarios is a rather striking demonstration of how comfortable the impact theory is with current popular concerns. While I do not wish to push the issue too strongly, as Cuvier's catastrophism and Darwin's theory of evolution were during the 19th century, the asteroid impact theory is symptomatic of society's current philosophical milieu. This is quite independent of the correctness of the theory. Hopefully that will be judged by its correspondence to reality as judged by critical tests.