End-Cretaceous Mass Extinction Event: Argument for Terrestrial Causation

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The end-Cretaceous mass extinctions were not a geologically instantaneous event and were selective in character. These features are incompatible with the original Alvarez hypothesis of their being caused by a single asteroid impact that produced a world-embracing dust cloud with devastating environmental consequences. By analysis of physical and chemical evidence from the stratigraphic record it is shown that a modified extraterrestrial model in which stepwise extinctions resulted from encounter with a comet shower is less plausible than one intrinsic to the earth, involving significant disturbance in the mantle.

JUDGED BY ITS HEURISTIC VALUE THE IMPACT HYPOTHESIS OF mass extinctions, published by Alvarez *et al.* in 1980 (*1*), has been a brilliant success. It has focused attention in an unprecedented way on a major scientific problem and stimulated an immense amount of fruitful research. Wider ramifications that have been explored as a direct consequence include nuclear winter scenarios and a more general extinction periodicity within the last 250 million years, perhaps induced by the impact of up to several extraterrestrial bodies within geologically short intervals of time. Judged, however, by the other criterion by which we assess scientific hypotheses, that of its truth, no decisive resolution has yet been achieved, and there exist legitimate grounds for doubt that it will survive even in a modified form.

Supporters of the Alvarez hypothesis may justifiably point to the establishment to general satisfaction of an iridium enrichment exactly at the Cretaceous-Tertiary (K/T) boundary on a global scale, in terrestrial as well as marine deposits, which cannot plausibly be explained by derivation from normal crustal rocks and which indicates that something very unusual and significant happened to the physical environment precisely at the end of the Cretaceous. Whereas adsorption on kerogen and low sedimentation rates have no doubt played a role in controlling the level of enrichment (*2*), they cannot by themselves account for the global phenomenon. Independent support has been proposed from the mineralogy of the boundary clay and the occurrence in it of tektite-like microspherules, soot, and shocked quartz (*3*), and doubts about the correlation of marine and terrestrial events appear to have been resolved (*4*). On the other hand, critics have accused supporters of impact of jumping too readily to conclusions without obtaining sufficient control data from elsewhere in the stratigraphic column and of inadequately evaluating any alternative. Many, indeed, prefer some kind of extinction scenario completely excluding any extraterrestrial influence, one based on the combined effects of sea-level and climate change with volcanism on a massive scale (*5*).

The Biotic Record

Some of the sharpest criticism of the original Alvarez hypothesis has come from paleontologists, on the grounds that the celebrated dust cloud scenario was altogether too drastic in its likely effects to account for the marked selectivity of end-Cretaceous extinctions, with a high proportion of both terrestrial and marine groups surviving with little or no change; also, many important extinctions had taken place before the iridium event. That the end-Cretaceous extinctions indeed involved more than the final catastrophe so clearly recorded in the plankton, was subsequently conceded by the original proponents of the impact hypothesis in conjunction with paleontologist colleagues (*6*). This leaves the impact supporters with two alternatives. Either the impact event was irrelevant to the extinction of many important groups, serving as no more than a final coup de grace, or there were several such extinction-inducing impact events closely spaced in time, such as might be produced if the earth encountered a shower of rogue comets whose orbits had been disturbed; this latter view seems to be the one currently favored by at least some impact supporters (*7*).

Without question the most striking mass extinction event at the K/T boundary was that affecting the planktonic forams and coccolithophorids in the oceanic realm (*8*). To a considerable extent the widespread occurrence of a boundary clay can be attributed to the sudden loss of the calcareous component of the bottom sediment as a consequence of mass extinction (*9*). Among the marine invertebrates the situation is more difficult to evaluate because the great majority inhabited the neritic zone and in consequence are extremely sparse in the stratigraphically more complete sections in deeper water pelagic facies rich in plankton. Because of the long-recognized marine regression at the end of the Cretaceous, sections in shallow-water marine facies across the K/T boundary are usually incomplete, being marked by hiatuses of varying magnitude (*10*). Despite sampling problems (*11*) it now seems clear that such important Cretaceous molluscan groups as ammonites, belemnites, inoceramids, and rudists underwent more or less progressive decline in diversity and numbers for a geologically appreciable period of time and were almost if not completely extinct by the time of the plankton "catastrophe" (*12*). Among other invertebrate groups, the brachiopods, cheilostome bryozoans, and some echinoderms exhibit a high rate of species turnover at the K/T boundary in Denmark (*13*). It appears probable that, in those cases where a sudden extinction event took place in bottom-living organisms at the end of the Cretaceous, no extra factor need be invoked beyond the plankton mass extinction, either, for example, the loss of food supply (*14*) or destruction of chalky substrate habitat (*15*).

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With regard to terrestrial vertebrates, dinosaurs were one of only a few groups to be seriously affected by the extinction event (*16*). Whereas Russell (*17*) has maintained that the dinosaurs were cut short in their prime, detailed work undertaken recently in Montana and neighbouring areas, taking full account of sampling and reworking problems, strongly suggests a more gradual decline (*18*). The other much discussed terrestrial biota are the plants. Shortly after publication of the impact hypothesis, Hickey (*19*) expressed what can perhaps be called the conventional view of paleobotanists, that there was no catastrophic event causing mass extinction at the end of the Cretaceous, but a more gradual increase in extinction rate, largely confined to the Northern Hemisphere and probably caused by climatic cooling. Investigators in the North American western interior have challenged this view; instead they favor a massive ecological disruption coincident locally with an iridium anomaly, with no significant Maastrichtian change preceding it (*20*). A similar K/T disturbance is also claimed for the boreal Far East (*4*).

To summarize, the biotic record suggests a compound scenario, with a more or less gradual increase in extinction rate for many groups of organisms followed by a culminating catastrophe lasting no more than a few tens of thousands of years and maybe less (*21, 22*). Especially because of sampling problems, it would seem to be extremely difficult to distinguish a stepwise series of sudden extinction events from a more uniform gradual pattern of extinction. In any case the demonstration of a sudden extinction event does not establish an extraterrestrial origin, which must be sought in physical and chemical evidence, a subject to which I now turn.

The Evidence Proposed for Impact

The evidence proposed in support of the impact hypothesis will be considered under several headings, with the most important being dealt with last.

Microspherules. Spherules in the general size range of 100 to 1000 micrometers, composed of sanidine and other minerals, were first recorded in the K/T boundary clay at Caravaca, southern Spain (*23*), and subsequently found at the same horizon at many other localities. Supporters of the impact scenario have proposed that they are mineralogically altered examples of microtektites formed by the cooling of droplets of impact melt. A detailed examination of the Gubbio section reveals, however, that although there is indeed a concentration of microspherules containing K-feldspar or K-feldspar and glauconite in the K/T boundary clay, they are not confined to this horizon but extend in stratigraphic range from mid-Cretaceous to Paleocene (*24*), so that they cannot be regarded as unique to the K/T boundary. Recent work in Denmark (*25*) involving dissolving the silicate material in hydrofluoric acid reveals that spherules identical to those interpreted as altered microtektites, including samples from Caravaca, are in fact the result of diagenetic infill of prasinophyte algae. Concentration in the boundary clay could simply signify that they represent "disaster" taxa like the opportunistic phytoplankton genera *Braarudosphaera* and *Thoracosphaera* (*26*). No doubt K/T microspherules have a variety of origins. Some could be volcanic, other iridium-rich examples could be micrometeorites as found throughout the stratigraphic column.

Mineralogy of the boundary clay. The boundary clay first studied at Gubbio and Stevns Klint has been treated by supporters of the Alvarez hypothesis as direct evidence of the fallout of material of the earth-embracing dust cloud produced by the impact event. A detailed mineralogical study of the boundary clay at Stevns Klint shows the middle part to be composed of pure smectite in contrast to the illite and mixed layer smectite-illite of the clay above and below; an impact melt rather than volcanic glass origin is claimed to be supported by major element chemistry (*27*).

However, a K/T boundary clay is not found in all marine sections (*21*). Where such a clay occurs, the most obvious explanation is that it marks a concentration of noncalcareous material following mass extinction of the plankton that supplied the calcareous component of the sediment, aided perhaps in some cases by post-sedimentation dissolution. In a number of examples that have been studied there is nothing unusual about the clay mineral composition, which varies from locality to locality in a way suggesting control by regional paleogeographic circumstances (*28*). With regard to the Stevns Klint boundary clay, the mineral smectite is most easily formed by the alteration of volcanic ash. The argument of Kastner *et al.* (*27*) contains a flaw. According to the impact scenario the meteorite component would have accounted for at most only 20% of the fallout dust and may be much less (*28*). Thus most of the boundary clay should be the alteration product of a mixture of earth rocks expelled from a huge crater, only a small fraction of which would have been melted on impact. Furthermore, no convincing evidence has been put forward that smectite is the normal product of impact melts. In the circumstances citation of chemical data seems rather meaningless.

Soot. Much publicity has been given to the discovery of soot in the organic fraction of the Fish Clay at the K/T boundary in Denmark by Wolbach *et al.* (*29*). The soot content is about four times as high as that of the clays above and below. On the assumption that the Alvarez hypothesis is correct, and that the boundary clay was deposited in less than a year, then the carbon flux during that year was 10^3 to 10^4 times the normal value. This has led Wolbach *et al.* to propose the occurrence of wildfires on a spectacular scale, which would have had devastating environmental effects globally, comparable to a nuclear winter. If, however, the sedimentation rate of the Fish Clay was similar to the clays above and below, and bearing in mind that it is relatively enriched in organic matter, there is nothing unusual about the presence of soot or charcoal, which is commonplace in the stratigraphic record, marking the persistent occurrence of forest fires on a modest scale. The Wolbach hypothesis depends implicitly on the assumption that the Alvarez hypothesis is correct, that the K/T boundary clay is exclusively post-impact fallout dust. The soot data cannot therefore be cited as independent evidence in support.

Shocked minerals. What appears on the face of it to be especially impressive evidence is the discovery at several K/T boundary localities around the world of so-called shocked quartz, with multiple laminar features held to be uniquely characteristic of impact deformation; the largest grains and highest proportions occur in the western United States, and a single impact event is favored (*30*). Shock mosaicism has been recognized, however, in plagioclase and biotite phenocrysts from the Toba caldera, Sumatra (*31*). Multiple laminar features are not likely to be found in volcanic minerals because of annealing at high temperatures, but might be expected to occur in country rock surrounding sites of highly explosive volcanicity. The question naturally arises as to whether explosive volcanicity can generate pressures of the extremely high order apparently required (a minimum of 90 kbar). Theoretical modeling based on the Mount St. Helens eruption suggests that this is indeed possible (*32*).

Acceptance of multiple laminar shocked quartz as evidence supporting K/T impact underlines a serious problem that cannot be lightly dismissed, namely the failure to locate a plausible site for the impact crater. If the impact took place somewhere on the continents, where is the huge crater of estimated diameter of 150 to 200 km? There are plenty of records of dated craters extending back through the Phanerozoic, so it is unlikely to have been subsequently buried by sediment or destroyed by erosion. If, on the other hand, the purported impact occurred somewhere on the ocean floor, where did all the shocked quartz come from? The sediment of the deep ocean is largely calcareous or argillaceous, interrupted at some horizons in the Atlantic by layers of turbiditic quartz sand. Much of this rock is incompletely consolidated, and it is difficult to see how impact stresses could be transmitted through such sediments to impose extreme shock deformation features on the quartz grains. Most of the expelled rock would in fact be quartz-free basalt. A possible way out of the dilemma posed is to invoke an impact site on the continental shelf, but this is statistically improbable because of the small area involved. Moreover it is highly unlikely that such a site would no longer be recognizable.

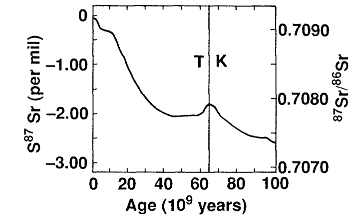
Iridium enrichment. The finding on a global scale of substantial iridium enrichment in the K/T boundary clay, compared with what could plausibly be derived from crustal rocks or normal micrometeorite background, initially supplied highly impressive evidence in favor of impact. The evidence became somewhat less impressive after publication of a report of an aerosol erupted at Kilauea, Hawaii, which had an enormous enrichment (10^5-fold) of iridium compared to normal Kilauean lavas, that apparently had been derived from the deep mantle (*33*). Provided that the appropriate mantle source could be tapped for an extended period of time, a global enrichment of iridium at the K/T boundary of the appropriate magnitude could be produced (*34*). That the period of time when unusually high quantities of iridium were distributed in the atmosphere and hydrosphere was significantly longer than the few weeks to months envisaged in the original impact scenario, more in the order of 10^5 to 10^6 years, is indicated by detailed analysis of a number of sections embracing both the K/T boundary and the strata immediately above and below, which sometimes reveal multiple anomalies (*21, 35*).

There are a number of geochemical grounds for suggesting that a terrestrial source for platinum-group element enrichment in the K/T boundary layers cannot be excluded. For example, the osmium isotope ratio in the Fish Clay at Stevns Klint, Denmark, is significantly higher than those of meteorites but corresponds very closely to that of the mantle-derived Bushveld Complex of South Africa (1.65 and 1.63, respectively). Furthermore, isotopic compositions of noble gases in the Danish Fish Clay are identical to those of the earth's atmosphere and do not record contamination by meteorite material. Most chalcophile elements (for example, copper, zinc, arsenic, antimony, and selenium) are much more enriched in the boundary clay than would be expected for a meteorite source. The considerable chemical heterogeneity of boundary clay at different localities is not consistent with settling of the clay from a globally dispersed dust cloud (*36*). The iridium enrichment over a 4-m stratigraphic interval now recognized at Gubbio, Italy, is not matched by a corresponding enrichment of palladium, platinum, or gold (*37*), suggesting that the iridium was concentrated in a light aerosol mantle differentiate as at Kilauea.

Isotopic and Other Data Relevant to End-Cretaceous Events

One of the most striking chemical signatures at the K/T boundary is a strong and short-term negative excursion of the carbon isotope ratio in coccoliths and planktonic forams in deep-sea cores, which is best explained in terms of a reduction in the $\delta^{13}C$ gradient between surface and deep ocean waters, such as would result from a drop in the global rate of photosynthesis over the ocean surface; this is of course what one could predict from a mass extinction event in the phytoplankton. The calcareous plankton oxygen isotope record reveals no such dramatic change, with several oscillations in oxygen

Fig. 1. Strontium isotope changes in seawater from the mid-Cretaceous to the present [based on Elderfield in (*40*), figure 6].



isotope ratio directly above and below the boundary being almost as marked as the small rise of 0.5 per mil immediately at the boundary (*38*). Whether such short-term oscillations represent environmental signals as opposed to diagenetic noise has not yet been clearly established. Longer term changes in carbon and oxygen isotope stratigraphy are suggested by a detailed analysis of the section at Zumaya, Spain, which reveals that the 2 per mil negative shift in both $\delta^{13}C$ and $\delta^{18}O$ at the K/T boundary is no greater than several preceding shifts in the late Maastrichtian time; the disappearance of ammonites and inoceramids coincides with these earlier isotope excursions, which are held to imply a direct relationship between warm surface water temperature and decrease in primary productivity (*39*).

The strontium isotope ratio ($^{87}Sr/^{86}Sr$) in seawater increased from the Late Cretaceous to the Recent in a regular way, but with a major interruption at the end of the Cretaceous, signified by a small but distinctive sharp rise followed by an equally sharp restoration to the original level (*40*) (Fig. 1). By far the likeliest reason for the increase in the ratio in the Cenozoic is the correlative fall of sea level, thereby increasing continental area and runoff (*41*). Applying the same reasoning to the end-Cretaceous event leads to the inference of a sea-level fall of a magnitude greater than for many millions of years previously, followed by a rapid rise to the earlier level.

It has indeed been widely acknowledged since the last century that the end of the Cretaceous was marked by a significant global fall of sea level, followed by a rise in the Paleocene. One important consequence of this is that, as noted earlier, continuous stratigraphic sections across the K/T boundary in shallow marine facies are extremely rare; hiatuses of varying magnitude are nearly always present. Figure 2 (*42*) shows three estimates of sea-level change in the latest Cretaceous. All three curves, based on different methods and a different degree of precision, show a notable regression immediately before the end of the Cretaceous. The strontium isotope data suggest that if anything the end-Cretaceous sea level fall and subsequent rise have been underestimated by the stratigraphers. One could predict that an event of such magnitude should be recognized by an influx of turbidites into the deep sea at the K/T boundary, and this is precisely what is recorded in both the North and South Atlantic (*43*). Although the strontium isotope data must record an event that lasted for a geologically significant period of time, rather than a mere "instant," their stratigraphic precision and ratio scatter are inadequate at present to allow further inference as regards duration (*44*). Some intriguing clay mineral data from Gubbio perhaps point the way to greater stratigraphic resolution. Johnsson and Reynolds (*45*) report a large influx of kaolinite in a 3-m-thick part of the section spanning the K/T boundary compared with the strata above and below, suggesting an environmental event lasting probably a few hundred thousand years. The authors confess themselves somewhat mystified by this phenomenon, but note the well-known fact that kaolinite tends to increase in abundance in nearshore facies, probably reflecting its coarse-grained nature and tendency to flocculate more readily than other clays. The simplest and most elegant explanation I can propose is that this kaolinite pulse in a pelagic-facies section reflects the end-Cretaceous regression recorded independently by stratigraphic and geochemical data.

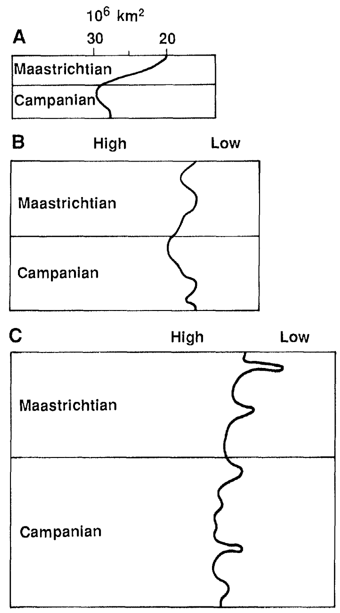


Fig. 2. Changes of sea level inferred for the two last stages of the Cretaceous (*42*). (**A**) Estimate based on area of continent covered by sea. (**B**) High and low stands of eustatic sea level based on classic stratigraphic methods. (**C**) High and low stands of eustatic sea level based on seismic stratigraphy.

The alternative possibility, that increased intensity of acid rain was the cause of both increased kaolinite production and strontium isotope ratio, fails to explain the independent evidence of regression. One would also need to invoke a greatly increased intensity for a much longer time than required to account for the paroxysmal event that caused mass extinction in the plankton and ecological disaster among the land plants.

There is a remarkably close correspondence between the Gubbio strata marking the kaolinite pulse and a zone of enrichment in both iridium and shocked quartz and feldspar (*46*), suggesting a striking conjunction of events (Fig. 3). Besides the flood basalt volcanism on an enormous scale in India, there is evidence of substantial explosive volcanicity at the K/T boundary in an extensive region from the South Atlantic to the Antarctic (*47*).

A Terrestrial Extinction Model

As indicated particularly by the Gubbio section, the last few hundred thousands years of the Cretaceous were marked by environmental changes more dramatic than experienced for a long time previously or subsequently. A substantial and rapid fall of sea level could have had both direct and indirect influence on the organic world. Notwithstanding Stanley's (*48*) reservations, and a causal relation that has as yet been inadequately worked out, marine regression seems to provide the best correlation with marine invertebrate mass extinction episodes throughout the Phanerozoic (*49*), presumably for reasons bound up with reduction in neritic habitat area. Sea-level fall would also have caused seasonal extremes of temperature on the continents to increase, thereby increasing environmental stress on the dinosaurs. Similarly, increased volcanism over an extended period would have had deleterious environmental consequences. It is known that flood basalt fissure eruptions that produce individual lava flows with volumes greater than 100 km^3 at very high mass eruption rates are capable of injecting large quantities of sulfate aerosols into the lower stratosphere, with potentially devastating atmospheric consequences (*50*). Such volatile emissions on a large enough scale would lead to the production of immense amounts of acid rain, reduction in alkalinity and *p*H of the surface ocean, global atmospheric cooling, and ozone layer depletion. Atmospheric cooling would be reinforced by ash expelled into the atmosphere by contemporary explosive volcanicity. The very end of the Cretaceous was marked by an episode of paroxysmal intensity, recorded by the iridium peak, which was the prime cause of the plankton extinction and ecological disaster among terrestrial plants (*21*).

It has recently become evident, to supporters as well as opponents of extraterrestrial causation, that a single bolide impact at the end of the Cretaceous cannot account for the gradual or stepwise extinction patterns of many groups of organisms, even the plankton, nor for the kinds of phenomena recorded by the latest work at Gubbio, the key locality where the impact story began. The only extraterrestrial hypothesis that can now be advanced with any plausibility is that involving a succession of impacts as a result of our planet encountering a comet shower, perhaps inducing large-scale volcanicity as a consequence. This hypothesis meets with at least four serious objections.

1) The iridium concentration in comets is probably about an order of magnitude less than the average for iron meteorites and one would need to invoke successive impacts of perhaps five iron meteorites of the necessary mass over a period of about a million years to account for the successive iridium peaks now recognized at Gubbio (*51*); this seems extremely improbable.

2) It is difficult to see how cometary impact can account for the end-Cretaceous strontium peak, the kaolinite pulse at Gubbio, and other evidence of a significant but not geologically instantaneous regression.

3) The problem of locating plausible impact craters is compounded if there were a succession of impacts.

4) It has been argued by a group of astronomers (*52*) that comet showers are not produced with either sufficient frequency or intensity by individual known bodies, whether stars or molecular clouds, to account for either periodic or episodic mass extinctions.

Rejection of the extraterrestrial option leaves us, of course, with the problem of putting forward a geologically plausible ultimate

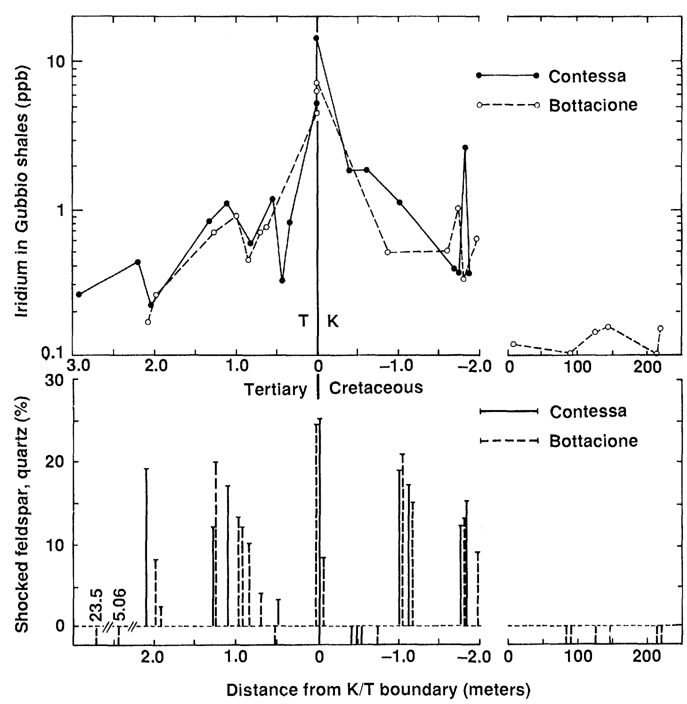


Fig. 3. Concentrations of iridium and shocked minerals over several meters of the two K/T boundary sections at Gubbio, Italy, with mineral occurrences and iridium peaks tending to show a positive correlation. Control samples taken at a greater distance from the boundary reveal only background levels of iridium and no shocked minerals. [Courtesy of N. L. Carter]

causation of dramatic sea-level fall and rise and concomitant increased volcanicity. Although trustworthy quantitative data are lacking, the rate of sea-level change was evidently too rapid to be accounted for by changes in the cubic capacity of the ocean basins controlled by, for instance, seafloor spreading (*53*). The freezing and melting of polar ice could effect marine regression and transgression at the appropriate rate, but there is no evidence of polar ice in any quantity before the Oligocene and plenty of biological evidence in favor of climatic equability in comparison with the present (*54*). The dilemma posed can be avoided if the regression and transgression are related to vertical tectonic movements on the continents. As any stratigrapher is aware, it is often difficult to disentangle global eustasy from regional epeirogeny if the regions in question are extensive.

Loper and McCartney (*55*) note that increased end-Cretaceous volcanism correlates with a significant change in the geomagnetic field, with a long Cretaceous reversal-free period coming to an abrupt end in the Maastrichtian. They propose a model involving periodic instability of the thermal boundary layer at the base of the mantle. This layer accepts heat from the core and transmits it upward by way of mantle plumes. As it thickens by thermal diffusion it becomes dynamically unstable and hot material erupts from it. Heat is extracted from the core at a greater rate, increasing the energy supply and hence the magnetic reversal frequency of the dynamo in the fluid outer core. Hot material rises through mantle plumes to the surface to give rise to volcanic activity. Both nonexplosive and explosive volcanism can be produced, depending on the condition of the lithosphere, which varies regionally. Exceptional plume events on a scale much greater than the largest volcanic events of historic time could explain some geological structures associated with extreme force, such as kimberlite intrusions and cryptoexplosion structures. Increased mantle plume activity also has the potential for causing uplift of extensive sectors of continents and hence regression of epicontinental seas, because present-day hot spots are associated with regional topographic bulges, so that it is reasonable to infer that most epeirogenic uplifts reflect hot, low density regions in the asthenosphere, derived from plume convection (*56*). Epeirogenic subsidence on the continents and marine transgression might be expected to follow episodes of substantial volcanic eruptions.

Although such a model is inevitably speculative it has more geological plausibility than the proposed extraterrestrial alternative and also has testable implications for other Phanerozoic mass extinction episodes. Meanwhile there remains much to be learned about the detailed regional and temporal pattern of change across the K/T boundary, a time that no one disputes was one of exceptional environmental disturbance.

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4. T. Saito, T. Yamanoi, K. Kaiho, *Nature (London)* **323**, 253 (1986). Note also that both plankton and dinosaur extinctions are placed in the same magnetic zone 29R.
5. See, for example, D. I. Axelrod, *Spec. Pap. Geol. Soc. Am.* **185**, 1 (1981); V. Courtillot and S. Cizowski, *Eos* **68**, 193 (1987); A. A. Ekdale and R. G. Bromley, *ibid.* **54**, 681 (1984); H. Jaeger, *Z. Geol. Wiss. Berlin* **14**, 629 (1986); M. L. Keith, *Geochim. Cosmochim. Acta.* **46**, 2621 (1982); D. M. McLean, *Cretaceous Res.* **6**, 235 (1985); C. B. Officer and C. L. Drake, *Science* **227**, 1161 (1985); C. B. Officer *et al.*, *Nature (London)* **326**, 163 (1987); J. E. Rich, G. L. Johnson, J. E. Jones, J. Campsie, *Paleoceanography* **1**, 85 (1986); P. R. Vogt, *Nature (London)* **240**, 338 (1972).
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7. P. Hut *et al.*, *Nature (London)* **329**, 118 (1987).
8. H. R. Thierstein, *Geol. Soc. Am. Spec. Pap.* **190**, 385 (1982); K. Perch-Nielsen [*Bull. Centre Rech. Explor. Prod. Elf Aquitaine* **10**, 421 (1986)] estimates that the taxonomic turnover of nannoplankton at the boundary is at least an order of magnitude higher than during the preceding Cretaceous.
9. The unusually thick and complete section across the boundary at El Kef, Tunisia, reveals that the plankton extinction event cannot be attributed to a "geological instant." Planktonic forams and coccolithophorids exhibit a different extinction-recovery pattern. Whereas both groups are considerably reduced at the level of the iridium anomaly, the nannoplankton experienced their main extinction well into the Tertiary, probably several thousand years later [J. Smit and A. J. T. Romein, *Earth Planet. Sci. Lett.* **74**, 155 (1985)]. According to S. D'Hondt and G. Keller [*Geol. Soc. Am. Abstr. Program* **17**, 557 (1985)], many species of planktonic forams disappeared 20 cm below the base of the boundary clay at El Kef, and these authors argue for a progressive, stepwise extinction of this group during the latest Maastrichtian. In marked contrast to the calcareous plankton, dinoflagellates and diatoms were evidently little affected by the end-Cretaceous mass extinction. J. A. Kitchell, D. L. Clark, and A. M. Gombos [*Palaios* **1**, 504 (1986)] relate the low rate of diatom extinction to a life history adapted locally to surviving stress by forming nonplanktonic resting spores. The same could well apply to the dinoflagellates.
10. In consequence the number of well-studied, more or less complete, sections is essentially confined to the following few examples: Nye Kløv and Stevns Klint, Denmark [T. Birkelund and E. Hakansson (*13*)]; Zumaya, Spain [P. Ward, J. Wiedmann, J. F. Mount, *Geology* **14**, 899 (1986)]; the Brazos River, Texas [T. A. Hansen, R. B. Ferrand, H. A. Montgomery, H. Billman, G. Blechschmidt, *Cretaceous Res.* **8**, 229 (1987); P. A. Meuller, J. R. Bryan, J. P. Dobson, J. E. T. Channell, J. C. Zachos, M. A. Arthur, *Geology* **15**, 311 (1987)]; and Seymour Island, Western Antarctica [W. J. Zinsmeister, *J. Geol. Soc.* **139**, 779 (1982)].
11. If there is a progressive decline in sampling quality approaching an extinction boundary, then even a razor-sharp, "instantaneous" extinction event will appear as a progressive decline smeared out in time [P. W. Signor and J. H. Lipps, *Geol. Soc. Am. Spec. Pap.* **190**, 291 (1982)]. On the other hand even a minor erosional hiatus, if not spotted, can serve to enhance the sharpness of the extinction event. As a result of facies changes correlative with, for example, shallowing of the sea, invertebrates may progressively disappear up a given latest Cretaceous section. It is hazardous to equate such disappearance with extinction, and indeed examples are known of taxa that reappear above an apparent extinction horizon, as a consequence of the restoration of the appropriate environment. These have been termed Lazarus taxa by D. Jablonski [in *Dynamics of Extinction*, D. K. Elliott, Ed. (Wiley, New York, 1986), p. 183].
12. Ammonites [J. Wiedmann, in *Global Bio-Events*, O. Walliser, Ed. (Springer-Verlag, Berlin, 1986), p. 397]; belemnites [W. K. Christensen, *Palaeontol. Z.* **50**, 113 (1976)]; inoceramids [A. V. Dhondt, *Zitteliana* **10**, 689 (1983)]; rudists [E. G. Kauffman, in *Catastrophes and Earth History*, W. A. Berggren and J. A. Van Couvering, Eds. (Princeton Univ. Press. Princeton, NJ, 1984), p. 151].
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Icosahedral Solids: A New Phase of Matter?

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Numerous examples of metallic alloys have been discovered, the atomic structures of which display an icosahedral symmetry that is impossible for ordinary periodic crystals. Recent experimental results support the hypothesis that the alloys are examples of a new "quasicrystal" phase of solid matter. Observed deviations from an ideal quasicrystal structure can be explained as "phason strains," a special class of defects predicted to be the dominant type of imperfection formed during solidification.

THE DISCOVERY OF SOLIDS WITH ICOSAHEDRAL SYMMETRY (1) has led to stimulating debate over the nature of their underlying atomic structure. The electron diffraction patterns of these alloys display sharp peaks, which indicates that the atoms are arranged in a highly ordered lattice, as in crystals; however, the patterns have an icosahedral symmetry that is impossible for periodic crystals (Fig. 1). The icosahedron (Fig. 2) includes fivefold symmetry axes that cannot be incorporated into any periodic, crystalline lattice according to established theorems of crystallography.

The challenge is to find a model for the atomic structure of the alloys that can explain the surprising diffraction pattern as shown in Fig. 1. Perhaps the most radical suggestion has been that the icosahedral solids are examples of "quasicrystals," a hypothetical phase of solid matter with long-range quasiperiodic positional ordering of the atoms in an arrangement with disallowed crystallographic rotational symmetry (2, 3). A second proposal, the "icosahedral glass model," assumes that the atoms are frozen in a dense but random arrangement (that is, there is no long-range positional

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