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A COMPOUND SCENARIO FOR THE END-CRETACEOUS MASS EXTINCTIONS

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ABSTRACT

Two major controversies have arisen in research on the end-Cretaceous mass extinctions, concerning the extent to which they were sudden or gradual, and terrestrially or extraterrestrially induced. A review of recent work supports more or less gradual extinction for a number of terrestrial and marine groups such as dinosaurs and ammonites, but the spectacular crash of the calcareous plankton and correlative ecological disaster in land plants in part of the northern hemisphere suggest a short-term catastrophic event. With regard to extinction selectivity in the marine realm, tropical groups and suspension feeders dependent on phytoplankton were relatively vulnerable, while on the continents large terrestrial reptiles were more prone to extinction than their freshwater relatives, while plants in western North America and eastern Asia suffered more severely than elsewhere.

Chemical and physical signatures of the Cretaceous-Tertiary boundary, including iridium anomalies, shocked quartz, microspherules and carbon, oxygen and strontium isotopes, are discussed and the evidence for and against a bolide impact-induced or volcanic catastrophe is reviewed, with the conclusion that it is not yet decisive either way. Evidence for longer-term changes is also cited, with strontium-isotope data supporting that from stratigraphy in suggesting a significant fall in sea level shortly before the end of the Cretaceous. A large body of evidence also supports a latest Cretaceous fall in seawater and air temperature, but this has recently been disputed for western North America on the basis of leaf studies. It is concluded that both longer term causes, intrinsic to this planet, and a final catastrophe either involving bolide impact or volcanism on a spectacular scale, or perhaps a combination of the two, are required to account for the pattern of end-Cretaceous extinctions.

Keywords: Mass extinction. Cretaceous-Tertiary boundary. Geochemical anomalies. Sea level. Meteoritic impacts. Volcanism.

RESUMEN

En la investigación de la extinción en masa del final del Cretácico han surgido dos controversias importantes, acerca de si fue gradual o súbita y si fue de origen terrestre o extraterrestre, respectivamente. La revisión de los últimos trabajos apoya una extinción más o menos gradual para ciertos grupos terrestres y marinos tales como los dinosaurios y los ammonites, pero la crisis espectacular del plancton calcáreo y el desastre, ecológicamente correlativo, de las plantas terrestres en parte del hemisferio norte sugieren un acontecimiento catastrófico de corta duración. Respecto a la selectividad de la extinción en el mar, los grupos tropicales y los organismos filtrantes dependientes del fitoplancton fueron relativamente vulnerables, mientras que sobre los continentes los grandes reptiles terrestres fueron más propensos a extinguirse que sus correspondientes de agua dulce, igualmente las plantas en Norteamérica y el este de Asia sufrieron los efectos más que en otros sitios.

Se discuten las anomalías geoquímicas y físicas del límite Cretácico-Terciario, incluidas las del Ir, cuarzo de impacto, microesferas y carbono, isótopos del O y Sr y se revisan las evidencias, a favor y en contra, del impacto de un meteorito y de una catástrofe volcánica, con la conclusión de que no hay nada aún definitivo. Se citan también datos de cambios de largo período, como los isótopos del Sr sugiriendo una caída del nivel del mar muy poco antes del final del Cretácico. También hay otras muchas evidencias que soportan una caída del nivel del mar y de la temperatura en el Cretacico terminal, pero esto ha sido contradicho por los estudios sobre hojas fósiles en el oeste de Norteamérica. Se concluye que ambas causas, de largo período, intrínsecas a este planeta, y catastróficas, tanto si fue un bólido como si fue un fenómeno volcánico de gran escala, o quizás una combinación de ellas, son requeridas para explicar el modelo de las extinciones del final del Cretácico.

Palabras clave: Extinción en masa. Límite Cretácico-Terciario. Anomalías geoquímicas. Nivel del mar. Impacto meteorítico. Volcanismo.

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INTRODUCTION

The great interest stimulated by the asteroid impact hypothesis of Alvarez *et al.* (1980), based on the discovery of an anomalous enrichment of iridium in the Cretaceous-Tertiary boundary clay, is reflected in a huge literature which cannot be adequately summarised here. For comprehensive literature citations the reader is referred to Silver and Schulz (1982), Van Valen (1984), Alvarez (1986), Jaeger (1986) and Officer *et al.* (1987). In this article these will be for the most part a concentration on more recent work; where there is no citation the material is thought to be sufficiently familiar not to require it, but in any case the above-listed references should provide appropriate sources.

Much of the literature deals with controversial matters. An early controversy concerned whether or not dinosaurs and calcareous plankton suffered mass extinction at exactly the same time, as demanded by the Alvarez hypothesis. It soom became established to general satisfaction that both terrestrial and marine extinction events took place during the same magnetic interval, 29 R, but there could still have been a difference in timing of up to about half a million years. Recently, however, Saito *et al.* (1986) claim to have recognised in Hokkaido a sudden change in pollen and spore composition precisely at the base of the Cretaceous-Tertiary boundary clay as determined by planktonic foraminifera. This is held to correspond to the horizon of the so-called fern spike in the Western Interior of North America, which coincides with an iridium-rich layer taken by palynologists on the basis of floral turnover as the Cretaceous-Tertiary boundary in terrestrial sequences (Tschudy *et al.,* 1984). Acceptance of the Japanese workers' findings would mean that the marine and continental Cretaceous-Tertiary boundaries are indeed precisely coincident in time.

Two other major controversies persist. Many palaeontologists have challenged the Alvarez assumption of a geologically instantaneous mass extinction event, and argued for gradual changes extending from at least several thousand to as much as a few million years, most probably bound up with changes of sea level and/or climate, the most plausible events causing significant environmental change on a global scale over prolonged periods of time. Secondly, to account for the iridium anomaly and other distinctive features of the Cretaceous-Tertiary boundary layer, volcanism on a catastrophic scale has been invoked as an alternative to bolide impact. In the ensuing account an attempt is made to evaluate the evidence for and against these conflicting views and a scenario is presented in outline that invokes a multiplicity of interacting factors.

THE PATTERN OF BIOTIC CHANGE THROUGH THE LATEST CRETACEOUS

Two of the most important questions that must be addressed initially concern (1) the extent to which the extinctions were gradual or sudden and (2) extinction selectivity. In other words, were extinction rates for particular groups of organism already increasing before the final demise, or was there no hint of change before a catastrophic event at the very end of the period? To what extent can a differential effect be discerned in the vulnerability to extinction of different groups? Answers to these questions will obviously have a critical bearing on which environmental scenario is favoured.

Before these questions are addressed the problem of sampling quality must be noted. Thus Signor and Lipps (1982) point out that 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. (On the other hand even a minor erosional hiatus, if not spotted, can serve to enhance the apparent sharpness of the extinction event). The sampling problem becomes particularly acute with large organisms, which are rarer than small organisms in accordance with the so-called Biomass Law. Thus in a terrestrial sequence without adequate palynological control should the Cretaceous-Tertiary boundary be drawn at the horizon of the highest dinosaur? Sampling considerations suggest that an error of up to several metres of section should be incorporated in the estimate.

Another consideration that should be borne in mind is that taxon counts alone are insufficient to give an adequate assessment of an extinction event. Thus if a particular group has gradually been reduced from many to merely one species before its final disappearance, a simple plot of species number against time will suggest a progressive decline, with the extinction of the last species being a trivial event calling for no special explanation. But if that last species was present in huge numbers of individuals until the end, then a phenomenon of potentially great significance would be missed by simply recording taxon number. The fairly recent disappearance of the Passenger Pigeon from North America might be considered a case in point. Therefore culling of the literature for records of the stratigraphic distribution of species or higher taxa, while undoubtedly a valuable and necessary exercise, must be supplemented by careful observation of the stratigraphic distribution of numbers of individuals.

EXTINCTION-SUDDEN OR GRADUAL?

Attention will be concentrated on some of the most discussed groups of organisms that suffered extinction, and on research that takes due note of the sampling problems noted above. For many familiar groups of organisms that became extinct by the end of the Cretaceous, such as the reptilian plesiosaurs, ichthyosaurs, mosasaurs and pterosaurs, and various marine benthic invertebrates, there are either severe sampling problems or the available data are insufficient to allow any generalisation.

Calcareous plankton

Without question the most striking mass extinction event at the Cretaceous-Tertiary boundary was that affecting the planktonic foraminifera and coccolithophorids in the oceanic realm (Thierstein, 1981, 1982). This is clearly expressed both in the drastic reduction in numbers of individuals and taxon diversity. Thus it is easy to locate the boundary at a classic section such as Gubbio, Italy by the sudden disappearance of numerous forams which are just discernible with the naked eye. Perch-Nielsen (1986) estimates that the taxonomic turnover at the boundary of nannoplankton (mainly coccolithophorids) is at least an order of magnitude higher than during the preceding Cretaceous. 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.

Detailed examination of the unusually thick and complete section across the boundary at El Kef, Tunisia, reveals however 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 (Smit and Romein, 1985). According to D'Hondt and Keller (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. Lamolda (1987) reaches a similar conclusion for sections in the Basque Country of Spain, including Zumaya. According to Lamolda the loss of forams below the boundary cannot plausibly be attributed to dissolution effects, as in some deep sea cores, because the Maastrichtian deposits are more calcareous than the overlying Danian.

Marine molluses

It has long been recognised that some of the most familiar Mesozoic groups such as ammonites, belemnites, and inoceramid and rudist bivalves became extinct at or shortly before the end of the Cretaceous. Because of their greater individual size, and also possible facies restrictions, these groups pose more of a sampling problem for precise stratigraphic analysis than the calcareous plankton, and the number of well exposed, mollusc-bearing, biostratigraphically well controlled and complete sections across the Maastrichtian-Damian boundary is very restricted. It is therefore not possible to make pronouncements with the same degree of confidence as for the plankton but there are a number of clear pointers to some general conclusions.

The apparently complete section that has received the most attention is that at Zumaya, northern Spain (Ward *et al.*, 1986; Wiedmann, 1986). Ammonite diversity and numbers decreased more or less gradually through the course of the Maastrichtian; no new groups appear in the late Maastrichtian. Despite intensive search in suitable facies, no ammonites have been found in the top 13 m, corresponding to a time interval of approximately 130 thousand years. Thus the ammonite might have gone extinct well before the end of the Cretaceous. Although ammonites persist to the top of the Cretaceous at the well known localitv of Stevns Klint, Denmark, there is a dissolution hiatus at the level of the Fish Clay (Ekdale and Bromley, 1984). At Mons Klint nearby, where there is no such feature, the last ammonites are found a short distance below the boundary.

The other molluscan groups were apparently all in decline before the end of the Cretaceous (Dhondt, 1986; Christensen, 1976; Kauffman, 1984). Thus true inoceramids went extinct at the end of the early Maastrichtian, with only one related genus of doubtful affinities, *Tenuipteria*, persisting until the end of the stage, while rudists underwent a drastic reduction in numbers and diversity early in the late Maastrichtian.

Dinosaurs

Although they attract the greatest popular interest dinosaurs are one of the least satisfactory groups for this kind of study, because of the paucity of suitable stratal sections and the comparative scarcity of fossil material. Virtually all the conclusions that have been drawn about the final dinosaur extinction episode derive from a few sections in western North America. For all we know, the group might well have gone extinct in other parts of the world before the end of the Cretaceous, or even locally have persisted into the Palaeocene. At any event too much has been made of the end-Cretaceous dinosaur mass extinction as a unique event. In fact, as Padian and Clemens (1985) point out, the dinosaur generic turnover rate was exceptionally high throughout the group's history, and the most unusual feature of the end-Createaceous event was the failure of a new replacive group of dinosaurs to emerge. The implication of the high generic turnover rate is that dinosaurs were always relatively vulnerable to extinction throughout their long history, and that no environmental event of exceptional magnitude need necessarily be invoked.

Whereas Russell (1979) maintains that the dinosaurs were cut short in their prime, with the group exhibiting no decline from a high late Cretaceous diversity level at the end of the period, some detailed work reported on recently suggests otherwise. Carpenter and Breithaupt (1986) studied the latest occurrence of nodosaurid ankylosaurs in Wyoming and Montana, using the relative abundance of teeth as a good measure of species abundance, and inferred a real decrease in population levels during the late Maastrichtian, with the group going extinct well before the end of the stage. That this pattern is likely to be true of dinosaurs in general is suggested by the more comprehensive work of Sloan *et al.* (1986). According to these authors, who take into account the discovery of articulated bones to eliminate the possibility of reworking, dinosaur extinction in Wyoming, Montana and Alberta was a gradual affair, beginning about 7 million years before the end of the Creataceous and accelerating rapidly in the last 0.3 million years. This decline up the succession cannot apparently be dismissed as an artifact; there is more outcrop available for examination in the top 30 m of the Cretaceous in the Montana section that an equivalent thickness of strata below, where more dinosaur remains have been found. The rapid reduction through time of both diversity and individual abundance is attributed to a combination of environmental deterioration and more tentatively to competition from immigrant ungulate mammals. Sloan *et al.* also make the more controversial claim (see discussion in *Science* 234, 1170) that a dinosaur "genera" (best interpreted as species) persisted into the early Palaeocene in Montana, with only 4 disappearing at the end of the Maastrichtian. The fossil teeth on which this claim is based occur in doubted Palaeocene strata, above the local iridium anomaly and correlated palynological change, but in stream channel sediments which raise the possibility of derivation by reworking from Maastrichtian strata. Sloan *et al.* discount this on the grounds that (a) the teeth bear no signs of abrasion and (b) dinosaurs are less common than mammals in the Maastrichtian sediments through which the channel is cut, yet no mammals have been found with dinosaurs in the channel deposits.

Terrestrial plants

For this group as well as the dinosaurs, one has to depend on North American data for the type of detailed information required. What can be called the conventional view, as reviewed by Hickey (1984), is that, while the rate of floral turnover increased in the latest Cretaceous, with a decline in angiosperm diversity, there was no catastrophic end-Cretaceous extinction event. This view has recently been challenged by Wolfe and Upchurch (1986) on the basis of detailed leaf studies over an extensive region in the Western Interior from New Mexico to Alberta. They see no evidence of any major floral change through the late Maastrichtian, but record a sharp and dramatic change at the Cretaceous-Tertiary boundary, with mesothermal evergreen vegetation suffering major extinction in the northern High Plains region. An episode of significant ecological disruption at the boundary, which consistently occurs coincident with an iridium anomaly, had earlier been recognised from palynological data, which indicated a drastic decline of angiosperms and gymnosperms at the expense of ferns-the socalled fern spike (Tschudy *et al.*, 1984). A comparable event has been recorded for Japan by Saito *et al.* (1986). That this was more an ecological disturbance than a major extinction event is indicated by the reappearance of many taxa in the early Palaeocene, indicating that refugia must have existed, and the disruption to plant life was only temporary (Tschudy and Tschudy, 1986).

EXTINCTION SELECTIVITY

Within the marine plankton, dinoflagellates were evidently little affected by the end-Cretaceous extinction events, in marked contrast to the calcareous plankton, and the same applies to benthic as opposed to planktonic forams. Whereas, according to Thierstein (1982) the generic extinction was 92 % for planktonic forams, 85 % for radiolaria and 73 % for coccoliths, it was only 23 % for diatoms (Kitchell *et al.*, 1986). Kitchell *et al.* relate this low rate of extinction compared with other elements of the plankton to a life history cycle adapted locally to surviving stress by forming non-planktonic resting spores. The same could well apply to the dinoflagellates. With regard to the macrobenthos, study of the section along the Brazos River, Texas suggest that suspension feeders, most notably epifaunal bivalves, were relatively vulnerable to extinction (Sheehan and Hansen, 1986).

It has been stated that on the continents animals over 25 kg in weight were the most extinction-vulnerable (Russell, 1979) but it should be noted that some dinosaur taxa were quite small and that, although nearly all end-Cretaceous mammals were small in size, the marsupials were much more severely affected than the placentals (Padian and Clemens, 1985). Freshwater vertebrates such as crocodiles, turtles and champsosaurs survived with little change, as evidently did the birds; while of course the fossil record of this last group is relatively poor it has improved greatly in recent years and the inference is probably soundly based (M. Howgate, personal communication).

Because of the existence of seeds, spores, pollen and rhizome systems, terrestrial plants should be more resistant in the long term to severe environmental disturbance than many animal groups (Knoll, 1984) and the pollen data reported by Tschudy and Tschudy (1986) appear to bear this out, as indicating rapid recovery of angiosperms following a short-term ecological disaster. Nevertheless there was a high rate of extinction in the Aquillapollenites Province of western North America and eastern Siberia, with angiosperms being more vulnerable than conifers in mid to high latitudes. Floral turnover in the Normapolles Province of eastern North America and Europe was less pronounced and in the southern hemisphere little or no change has been recorded across the Cretaceous-Tertiary boundary (Collinson, 1986).

A number of general conclusions have been drawn on the basis of comparison of various groups. By studying evolutionary patterns among late Cretaceous bivalves and gastropods Jablonski (1986a) argues that the end Cretaceous extinctions involved more than an intensification of normal "background" extinction. Factors that enhanced survivorship during normal times, such as planktotrophic larval developments, broad geographic species range and high species richness, were ineffectual during the mass extinction phase, but broad geographic range of an entire lineage, regardless of the ranges of its constituent species, evidently correlates with reduced vulnerability to extinction.

Stanley (1987) perceives a climatic theme, with tropical taxa in the marine realm being relatively vulnerable to extinction (cf. Kauffman (1984) for bivalves). Thus cool-adapted species of planktonic forams, with a simple globigerine shape, migrated to low latitudes within the last few thousand years of the Cretaceous, replacing warm-adapted species with ornate skeletons that suffered extinction (Gerstel *et al.*, 1986). Similarly, gastropods that lived in cool northern waters in the late Cretaceous migrated to North Africa at the end of the Cretaceous, replacing tropical gastropods (Kollman, 1979). It is of course well known that low latitude organisms such as reef corals and rudists have been relatively vulnerable to extinction, but it should be borne in mind before a simple temperature decline scenario is adopted, that tropical groups are generally stenotopic and hence potentially vulnerable to a variety of environmental disturbance. They are also more taxon-rich, and it remains to be demonstrated with quantitative rigour that there is a significant differential effect between low and high latitudes which involves proportion rather than absolute numbers of taxa that went extinct.

Sheehan and Hansen (1986) put forward a hypothesis of great generality embracing both marine and continental realms. They observe that the marine phytoplankton, because of its low biomass at a given time and short life history, is very vulnerable to environmental disturbance. A model is generated whereby organisms dependent on living plant material are more vulnerable than those that feed on detritus or scavenge for their food. The fauna of the Brazos River section supports the model, because suspension feeders dependent on plankton were more affected by the end Cretaceous extinction than deposit feeders such as nuculanid bivalves, and carnivores. As regards the continents, it is argued that the herbivorous dinosaurs probably depended for their food on living plants, while placental mammals were probably insectivores. Freshwater ecosystems, however, are based fundamentally on land-derived detritus, which would have enabled the vertebrates to survive. The Sheehan and Hansen hypothesis is, of course, only relevant to the short-term catastrophic type of scenario presented by Alvarez *et al.* (1980) and not to any longer-term events lasting thousands of years or more.

CHEMICAL AND PHYSICAL SIGNATURES OF THE CRETACEOUS-TERTIARY BOUNDARY

The evidence supporting the impact hypothesis has been eloquently reviewed recently by Alvarez *père et fils* (L. W. Alvarez, 1987; W. Alvarez, 1986) and need not be gone into in detail here. The key discovery was made at the end of the 1970s. A clay layer at Gubbio, Italy, identified by micropalaeontologists as marking exactly the Cretaceous-Tertiary boundary, was found to be greatly enriched in the platinum-group trace element iridium, by a factor of 30 compared to the normal background. Subsequently an iridium anomaly, signified by a more or less pronounced "spike", has been found at the boundary across the globe at over 75 localities, including a few in sections of continental sediments. The high iridium concentration, and that of other siderophile trace elements, is much too great for crustal rocks but matches that of chondritic meteorites. Concentration of micrometeorite background material at a time of exceptionally low sedimentation rate appears to be inadequate to account for the size and extent of the anomaly, though without much doubt condensation factors have played a role in controlling the level of iridium recorded locally (e.g. Ekdale and Bromley, 1984). Similarly the fact that kerogen can preferentially absorb a variety of metallic elements of their compounds may help to explain the exceptionally high iridium level in the kerogen-rich Fish Clay at Stevns Klint, but there is no general correlation of the iridium anomaly with black shales, nor have iridium enrichments of comparable magnitude been recognised in organic-rich deposits of other ages. A possible concentration by marine organisms that were subsequently buried by bottom sediment fails to explain the existence of iridium anomalies in continental sections in North America.

Independent evidence supporting the Alvarez hypothesis is claimed on the basis of two discoveries in clay layers at the Cretaceous-Tertiary boundary. The first discovery, which seems to be impressive, is of so-called shocked quartz, with multiple laminar features held to be uniquely characteristic of impact events; it has been recorded at several localities in North America and Eurasia (Bohor *et al.*, 1984; Izett and Pillmore, 1985; Badjakov *et al.*, 1986). The second discovery is of spherules in the general size range 100-1000 μm, composed of sanidine and other minerals, first recorded at Caravaca, southern Spain by Smit and Klaver (1981) and subsequently found at many other localities. These are believed by some workers including the above-named authors to be mineralogically altered examples of microtektites formed by the cooling of droplets of impact melt.

Much publicity has also been given to the discovery of soot in the organic fraction of the Fish Clay at the Cretaceous-Tertiary boundary in Denmark (Wolbach *et al.*, 1985). The soot content is about four times higher than 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 is 10^3-10^4 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 Cretaceous-Tertiary boundary clay is exclusively post-impact fallout of dust, and the soot data cannot therefore be cited as independent evidence in support (see discussion in *Science* **234**, 261-4).

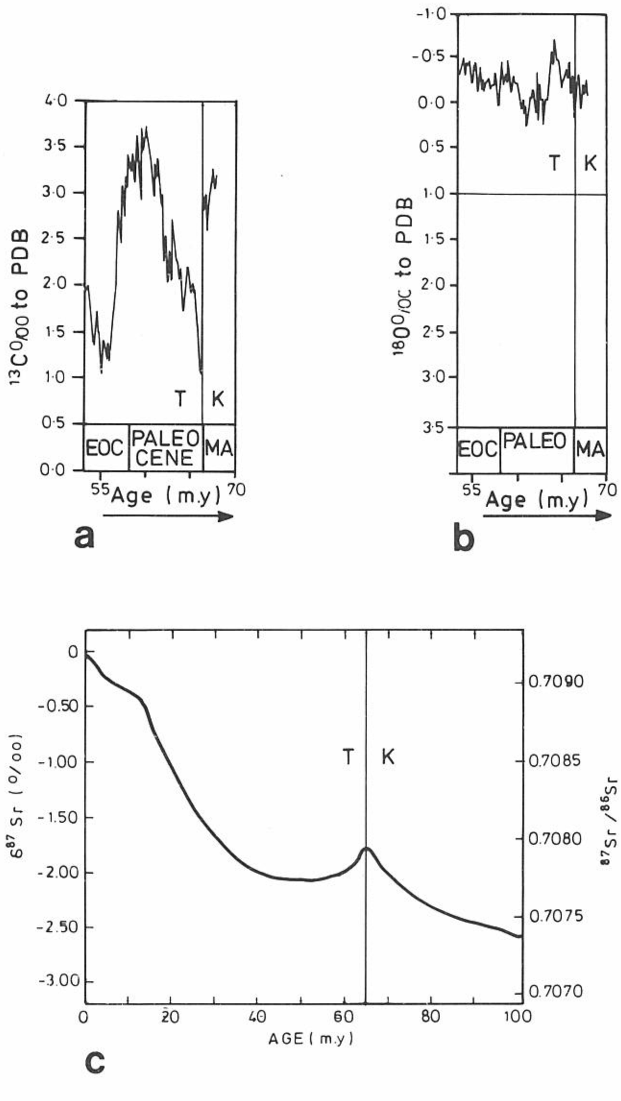

Figure 1. Isotopic changes across the Cretaceous (K)-Tertiary (T) boundary,

a) carbon isotope data for bulk sediment in a number of DSDP sites. Based on fig. 3 of Shackleton (1986).
b) oxygen isotope data for bulk sediment in a number of DSDP sites. Based on fig. 3 of Shackleton (1986).
c) strontium isotope changes in seawater from the mid Cretaceous to the present. Based on fig. 6 of Elderfield (1986).

With regard to other chemical signatures at the Cretaceous-Tertiary boundary other than the iridium anomaly, the most striking is a strong and short-term negative excursion of $\delta^{13}C$ in coccoliths and planktonic forams in deep-sea cores (Fig. 1a), which is best explained in terms of a reduction in the ^{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 (Shackleton, 1986). 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 (Fig. 1b), with several oscillations in $\delta^{18}O$ directly above and below the boundary being almost as marked as the small rise of 0.5 immediately at the boundary (Shackleton, 1986). Whether such short-term oscillations represent environmental signals as opposed to diagenetic noise has not yet been clearly established. The $^{87}Sr/^{86}Sr$ ratio increases from the late Cretaceous to the Recent in a regular way that promises well for stratigraphic correlation, but with a major interruption at the end of the Cretaceous, signified by a small but distinctive sharp rise followed by a restoration to the original level (Fig. 1c; Koepnick *et al.*, 1985; Hess et al., 1986; Elderfield, 1986).

An analysis of the Cretaceous-Tertiary boundary clay at several localities revealed a different clay mineral composition in each, with no exotic mineralogy; all samples were typical of normal marine Cretaceous clay (Rampino and Reynolds, 1983; cf. Preisinger *et al.*, 1986).

COMPARISON OF THE IMPACT AND VOLCANIC HYPOTHESES FOR THE END CRETACEOUS CATASTROPHE

Whatever the ultimate cause, there now seems to be little doubt that the Cretaceous period ended in a geologically short-term event or rapid succession of events of catastrophic magnitude and more or less global extent. Within the biosphere this event is recorded by mass extinction of the marine calcareous plankton and by an ecological disaster in at least much of the northern hemisphere among the more evolved land plants. Contemporary extinctions in animal life most probably reflect a devastating disturbance to primary food production and may therefore require no special explanation. Directly following the catastrophe, marine deposits record a short-term population explosion of the opportunistic phytoplankton genera *Braarudosphaera* and *Thoracosphaera* in the oceans (Thierstein, 1981), and of ferns on at least two continents, followed by the gradual restoration of angiosperms along the lines of an ecological succession. The striking and globally widespread iridium anomaly, and associated occurrence of shocked quartz and microspherules, has not been matched at any other generally accepted mass extinction horizon and may yet prove to be unique to the Phanerozoic (Donovan, 1987).

Given this array of evidence, there appear to be only two plausible causes that can be invoked to account for such a catastrophe, bolide impact or volcanicity on an exceptional scale. Rival hypotheses based on these alternatives give rise to quite similar environmental scenarios.

The impact scenario as first put forward by Alvarez, *et al.* (1980) and subsequently modified somewhat (Alvarez, 1987) is that a 10 km diameter bolide hit the earth, creating a crater about 150-200 km in diameter and expelling a huge quantity of pulverised rock. The earth was in consequence enveloped by an opaque blanket of dust, which for a period of months blotted out sunlight and thereby stopped photosynthesis, leading to the mass starvation of animal life. The dust eventually settled to form the Cretaceous-Tertiary boundary clay, laced with iridium-enriched material from the bolide remnants. Significant short-term temperature changes would have ensued, probably an initial drastic fall followed by a rise because of the greenhouse effect. Perhaps the most important killing mechanism would derive from the shock heating of the atmosphere by the expanding fireball. This would give rise to the production of huge amounts of nitrogen oxides in the atmosphere, leading to highly acidic rain. The acid rain would lower the pH of oceanic surface waters sufficient to dissolve calcareous material such as plankton skeletons.

The volcanic scenario proposed by Officer *et al.* (1987) differs in that the events in question extended over at least 10,000 years. 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 sulphate aerosols into the lower stratosphere, with potentially devastating atmospheric consequences (Stothers *et al.*, 1986). Such volatile emissions on a large enough scale would lead to the production of immense amounts of acid rain, reduction in alkalinity and pH of the surface ocean, global atmospheric cooling and ozone layer depletion.

It is clear that the environmental consequences envisaged for either the bolide impact or the volcanic scenario are essentially similar, but with the latter being much more extended in time because no individual episode of volcanism could match the devastating effect of a large bolide impact. In deciding, therefore, which is the better supported by evidence, it is of crucial importance to establish as precisely as possible the time spans signified by the horizon of abnormal iridium enrichment and correlative biotic changes. Because the time interval for either scenario falls well within the finest resolution available by conventional means of stratigraphic correlation or age determination, this is not a straightforward matter.

I give below a personal assessment of the evidence for and against the alternative scenarios, abreviated to I (impact) and V (volcanic).

1. Iridium enrichment

I. The substantial enrichment of iridium (and other siderophile elements) in the Cretaceous-Tertiary boundary clay matches the composition of chondritic meteorites but not that of the earth's crustal rocks. The global distribution signifies an event of major significance and the intimate coincidence with mass extinction of the plankton is remarkable. Simple calculations based on iridium concentrations in the boundary clay lead to the inference of a bolide 10 km in diameter, whose impact with the earth would have deleterious consequences of the appropriate magnitude. Although much of the earth's mantle has a composition similar to that of chondritic meteorites, it is implausible to invoke a mantle source because of (a) the global extent and amount of iridium, (b) the iridium-enriched aerosol erupted recently at Kilauea was a light mantle differentiate. The iridium/platinum ratio of the Cretaceous-Tertiary boundary clay signifies, in contrast, no such differentiation (F. Asaro, personal communication).

V. The composition of the aerosol erupted at Kilauea, with an enormous enrichment of iridium compared to normal Kilauean lavas (Zoller *et al.*, 1984) weakens the case for excluding a terrestrial source for the Cretaceous-Tertiary boundary clay iridium, especially as the ratios of iridium to arsenic and antimony of the boundary clay resemble those of the Kilauea eruption but differ significantly from those of meteorites (Officer and Drake, 1985). Provided the appropriate mantle source could be tapped for an extended period of time, a global enrichment of iridium of the appropriate magnitude of the Cretaceous-Tertiary boundary could be produced.

2. Stratal distribution of iridium

V. A number of profiles of the Cretaceous-Tertiary boundary clay indicate that the zone of iridium enrichment often extends over a thickness of strata indicating, according to reasonable estimates of sedimentation rate, a time duration of at least several thousand and perhaps several tens of thousand years, which is inconsistent with the prediction of the impact hypothesis. In several cases multiple iridium enrichments have been recorded (Officer *et al.*, 1987; Wiedmann, 1986). It is implausible to invoke bioturbational smearing up and dow the section, because such disturbance would substantially diminish the iridium anomaly. In addition, some classic sections such as Stevns Klint do not show bioturbation at the critital horizon.

I. Careful cm by cm sampling of Cretaceous-Tertiary boundary sections in the Gosau Basin of Austria shows a sharp rise to the maximum value of iridium, followed by a gradual diminution over a thicker portion of section back to normal values (Preisinger *et al.,* 1986). Similar patterns have been discerned at Gubbio and Caravaca and can best be interpreted as due to iridium deposition due to impact, followed by redeposition over a longer time interval of iridium-enriched material from elsewhere.

3. Shocked quartz

I. The shocked quartz found at the Cretaceous-Tertiary boundary at a number of widely scattered localities in three continents has the highly distinctive features of impact deformation in the form of multiple sets of laminae. These have not been recognised in any volcanic rocks.

V. The recognition of shock features, many of which are subtle and present only in small grains, in volcanic rocks requires specialised skills and the subject has not hitherto been studied intensively. Shock features have now been recognised in plagioclase and biotite phenocrysts erupted from the Toba caldera, Sumatra (Carter *et al.*, 1986). Shocked features in minerals are also known to occur in the Bishop's Tuff of California. It is admitted that, so far, no shocked quartz grains of the distinctive type described by Bohor *et al.* (1984) have been recognised, but even in the Cretaceous-Tertiary boundary clay only a small minority of the quartz grains fall into this category. Discovery of shocked quartz grains at horizons other than the boundary clay would weaken the case for associating them with an impact event that caused mass extinction. (See discussion between Carter *et al.* and Izett and Bohor, *Geology* **15**, 90-92).

4. Microspherules

I. The microspherules found at the Cretaceous-Tertiary boundary in many localities around the world are most reasonably interpreted as the low temperature alteration products of droplets of impact melt.

V. A detailed examination of the Gubbio sectin reveals that, while there is indeed a concentration of microspherules containing K-feldspar or K-feldspar and glauconite, in the Cretaceous-Tertiary boundary clay, they are not unique to this horizon, but extend over a stratigraphic range from Turonian to Palaeocene (Naslund *et al.*, 1986), so that they cannot be regarded as unique to the Cretaceous-Tertiary boundary. Spherules of the appropriate size range of clearly volcanic origin are known to occur, so the concentration in the boundary clay could signify a peak of volcanism at that time. Recent Danish work (Hansen *et al.*, 1986) suggests that the spherules have nothing to do with either impact or volcanism, but are the result of diagenetic infill of prasinophyte algae.

5. The Cretaceous-Tertiary boundary clay

I. The boundary clay first studied at Gubbio and subsequently found in other parts of the world is 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 Stevens Klint shows the central part to be composed of pure smectite in contrast to the illite and mixed layer smectite/illite of the clays above and below. An impact melt rather than volcanic glass origin is supported by major element chemistry (Kastner *et al.*, 1984).

V. A Cretaceous-Tertiary boundary clay is by no means found in all marine sections (Officer *et al.*, 1987). Where such a clay occurs, the most obvious explanation for it is that it makes a concentration of non-calcareous material following mass extinction of the planktonic organisms 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 palaeogeographic circumstances (Rampino and Reynolds, 1983). With regard to the Stevns Klint boundary clay, the mineral smectite is most easily formed by the alteration of volcanic ash. A layer of pure smectite in the midst of normal detrital clays is usually a clear indication of a bentonite. This argument was used to propose a volcanic origin for distinctive fuller's earth clays in the Jurassic and Cretaceous of Southern England (Hallam and Sellwood, 1968), an interpretation confirmed by the subsequent discovery of a diagnostic suite of minerals and relict glass shards (Jeans *et al.*, 1977).

Kastner *et al.*'s argument contains a flaw. According to the impact scenario, the meteorite component would have comprised at most only 20 % of the fallout dust and may be much less (Rampino and Reynolds, 1983). 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 this 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 major element chemical data seems rather meaningless.

6. The site of the impact crater

I. It is disappointing rather than devastating to the impact hypothesis that no convincing crater of the appropriate age has yet been recognised. If the impact took place on a continent, perhaps it has subsequently been buried by sediment or destroyed by erosion. The buried Manson crater of Iowa seems to be of the right age to account for the occurrence of shocked quartz of sand grade in the U.S. Western Interior. It is statistically more probable, however, that impact took place somewhere in the oceans.

V. The Manson crater, with an estimated diameter of about 30 km, is far too small to be invoked for the devastating environmental scenario required by the impact hypothesis. There are plenty of records of dated craters extending back througn the Phanerozoic. A continental crater as young as end-Cretaceous and of the large size required, is unlikely to have been destroyed by erosion or buried without trace. If the impact took place 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 sediment to impose 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 recognisable. An impact anywhere in the marine realm should have generated tsunamis on an enormous scale, which should have created significant disturbance to the sedimentary record across the Cretaceous-Tertiary boundary. Although slumping seems to have occurred in a few sections, this has not been tied to a Cretaceous-Tertiary boundary event.

7. Appropriate volcanism

V. There is evidence from various parts of the world of substantial volcanism at the end of the Cretaceous, the most striking example being the emplacement of the Deccan lavas of India. With a minimum estimated volume of 10^6 km^3 they are the largest continental flood basalt eruptions of the post 200 million years and the most recent determination of their date of eruption suggests that it all took place within magnetic interval 29 R, with a duration of about 600 thousand years and embracing the Cretaceous-Tertiary boundary (Courtillot *et al.*, 1986). It would be an astonishing coincidence if volcanicity on such an immense scale was totally independent of the Cretaceous-Tertiary boundary mass extinction event. Modelling calculations based on the volume of lavas and the injection of mantle-derived material into the atmosphere and stratosphere suggest that it is plausible to invoke the Deccan Traps to account for the end-Cretaceous catastrophic disruption to the biosphere (Officer *et al.*, 1987).

I. It is implausible to invoke the Deccan Traps or any other localised volcanic source to account for the global distribution of iridium, on the basis of the small Kilauean gas eruption, and no other iridium-enriched volcanic rocks are known. No iridium-enriched layer has been found in sediments associated with the Deccan Traps. The presence of shocked quartz implies explosive volcanism if an impact origin is to be rejected, whereas the Deccan Traps are flood basalts.

8. The biotic response

I. From the initial work at Gubbio, where an intimate correlation was first demonstrated between the iridium anomaly and mass extinction of the calcareous plankton, a strong association of the two has been repeatedly demonstrated. Allowing for sampling and preservational problems it is highly likely that many animal groups went extinct at the same time. The work of Wolfe and Upchurch (1986) on angiosperm floras in North America points to a single geologically very short-lived disturbance event coincident with an iridium anomaly, which is more consistent with bolide impact than more prolonged volcanism.

V. When sections signifying an unusually high sedimentation rate are studied, such as El Kef, it can be demonstrated that the main planktonic foram and coccolith extinction phases were not coincident in time, but separated by up to a few thousand years, and the extinction rate among the forams was already increasing before the end of the Cretaceous. The impact scenario is too drastic to account for the selective nature of the end-Cretaceous extinctions, with many groups of organisms surviving into the Palaeocene with little or no change.

From the foregoing evaluation it should be apparent that both scenarios have their shortcomings as regards evidential support, and more research is required to resolve the issue decisively. Meanwhile the possibility must not be discounted that bolide impact triggered large-scale volcanism, though such a circumstance could confuse attempts to devise critical tests of clear-cut alternative hypotheses. Moreover, the Deccan Traps volcanism started before the end of the Cretaceous (Courtillot and Cizowski, 1987).

EVIDENCE FOR LONGER-TERM ENVIRONMENTAL CHANGES

Before the impact hypothesis was put forward it was customary to relate the end-Mesozoic extinctions to either fall of sea-level or climatic cooling, or a combination of the two, climate and sea-level being, with volcanism, the only earth-bound phenomena that could influence environment on a global scale. Their influence would be felt, however, over a longer period of time than the paroxysmal effects discussed in the previous section, ranging probably from hundreds of thousands to a few million years. Evidence for sea-level and climatic changes of this time span is reviewed below.

Sea-level change

It has 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 Palaeocene. One important consequence of this is that stratigraphic sections across the Cretaceous-Tertiary boundary in shallow marine facies are extremely rare; hiatuses of varying magnitude are virtually always present. However, precision about the amount and rate of sea-level change has been lacking, though the situation has improved in recent years.

Fig. 2 presents three different estimates of sea-level change in the latest Cretaceous. Sliter's curve (Fig. 2a) is based on the amount of continental area covered by sea and is therefore very approximate; it also makes no distinction between different divisions within the stage and merely indicates a progressive Maastrichtian decline correlative with sea-level fall. Kauffman's curve (2b), though only a qualitative estimate, is more precise stratigraphically and is based on changes in sedimentary successions as well as areal changes; it indicates a late Maastrichtian sea-level rise followed by a fall to the end of the stage, after a mid Maastrichtian fall. The revised curve of the Exxon group (2c), based on seismic stratigraphy, offer even more stratigraphic precision. As with the Kauffman curve, a mid Maastrichtian fall is followed by an early late Maastrichtian rise, after which there is a rapid and pronounced fall immediately before the end of the stage. Thereafter there is an equally rapid rise, which more or less ceases across the Cretaceous-Tertiary boundary. All three curves, derived using different methods and of a different degree of precision, agree on a notable sea-level fall shortly before the end of the Cretaceous. The claim by Haq *et al.* (1987) that the minimum sea-level was reached not at but immediately before the end of the period is based on microfossil correlations that have not been published, so that the evidence in support cannot be assessed. The subject is sufficiently important to warrant independent investigation.

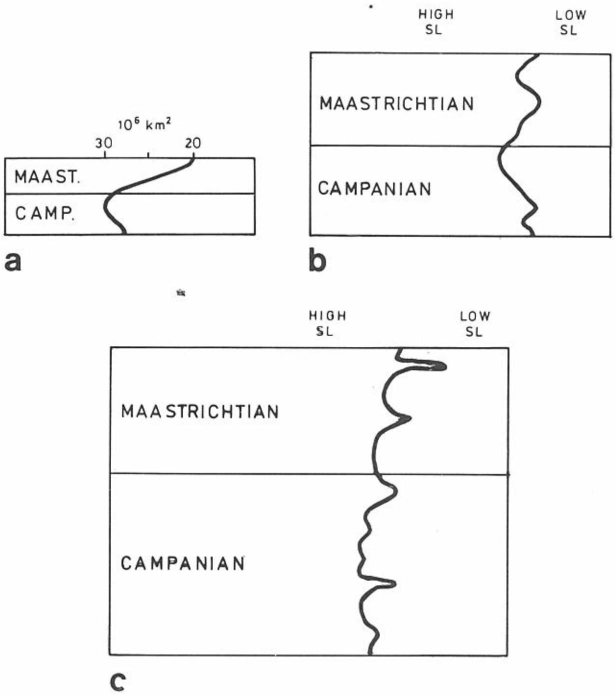

Figure 2. Changes of sea-level inferred for the two last stages of the Cretaceous,
a) estimate based on area of continent caused by sea, after Sliter (1976).
b) high and low stands of eustatic sea-level based on classic stratigraphic methods, after Kauffman (1979).
c) high and low stands of eustatic sea-level based on seismic stratigraphy, after Haq *et al.* (1987).

Stratigraphic data are sometimes criticised as being both imprecise and difficult to quantify in an illuminating way, so it is gratifying that independent geochemical evidence can be cited that apparently bears on the question of sea-level change. As noted earlier, there is a clearly discernible positive excursion of the $^{87}Sr/^{86}Sr$ ratio across the Cretaceous-Tertiary boundary (Fig. 1c), indicating an increase in continental influence of the sort recorded progressively throught the Cenozoic to reach the present-day abnormally high level of 0.709. By far the likeliest reason for this Cenozoic change is the correlative fall of sea level, thereby increasing continental area and runoff (Koepnick *et al.*, 1985). Applying the same reasoning to the end-Cretaceous event leads to the inference of a sealevel fall of a magnitude greater than for many millions of years previously, followed by a rapid rise to the earlier level.

While 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 inferences as regards duration. Some intriguing clay mineral data from Gubbio perhaps point the way to greater stratigraphic resolution. Johnsson and Reynolds (1986) report a large influx of kaolinite over a 3 m thick part of the section spanning the Cretaceous-Tertiary boundary, compared with the strata above and below, suggesting an environmental event lasting probably a few hundreds of thousands of 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 offer is that this kaolinite pulse in a pelagic facies section reflects the end-Cretaceous sea-level fall recorded independently by stratigraphic and geochemical data.

Jones *et al.* (1987) record facies evidence of a marine regression within the last 300,000 years of the Cretaceous, in a section near Braggs, Alabama, and a correlative rise in the strontium isotope ratio, while an injection of sand and silt turbidites into the deep Atlantic off New Jersey, precisely at the Cretaceous-Tertiary boundary, is reported by Van Hinte *et al.* (1985a, b). The authors relate this event to an impact-induced tsunami, but it could just as well signify a marked fall of sea level.

Climatic change

The best record of oceanic temperatures comes from oxygen isotope data obtained from planktonic and benthic forams, principally in the Pacific (Savin, 1982). Both surface and bottom waters apparently underwent a more or less steady post-Coniacian temperature decline which was arrested only at the end or immediately before the end of the Maastrichtian (Fig. 3).A detailed analysis of Upper Maastrichtian carbon and oxygen isotope stratigraphy at Zumaya, Spain, using bulk sediment derived from the plankton, has been undertaken by Mount *et al.* (1986). They find that the 2 per mil negative shift in both ^{13}C and ^{18}O at the Cretaceous-Tertiary boundary is no greater than several preceding shifts in the Upper Maastrichtian. The disappearance of ammonites and inoceramids coincides with these earlier isotope excursions. The striking similarity of the $\delta^{13}C$ and $\delta^{18}O$ curves is held to imply a direct relationship between warm surface water temperature and decrease in primary productivity. The implication of a succession of El Niño-type warming episodes is thought to be consistent with a volcanic scenario, with injection of CO_2 in the hydrophere and atmosphere leading to rise of oceanic CCD and greenhouse warming. Clearly such intriguing results need to be confirmed by comparable analysis of

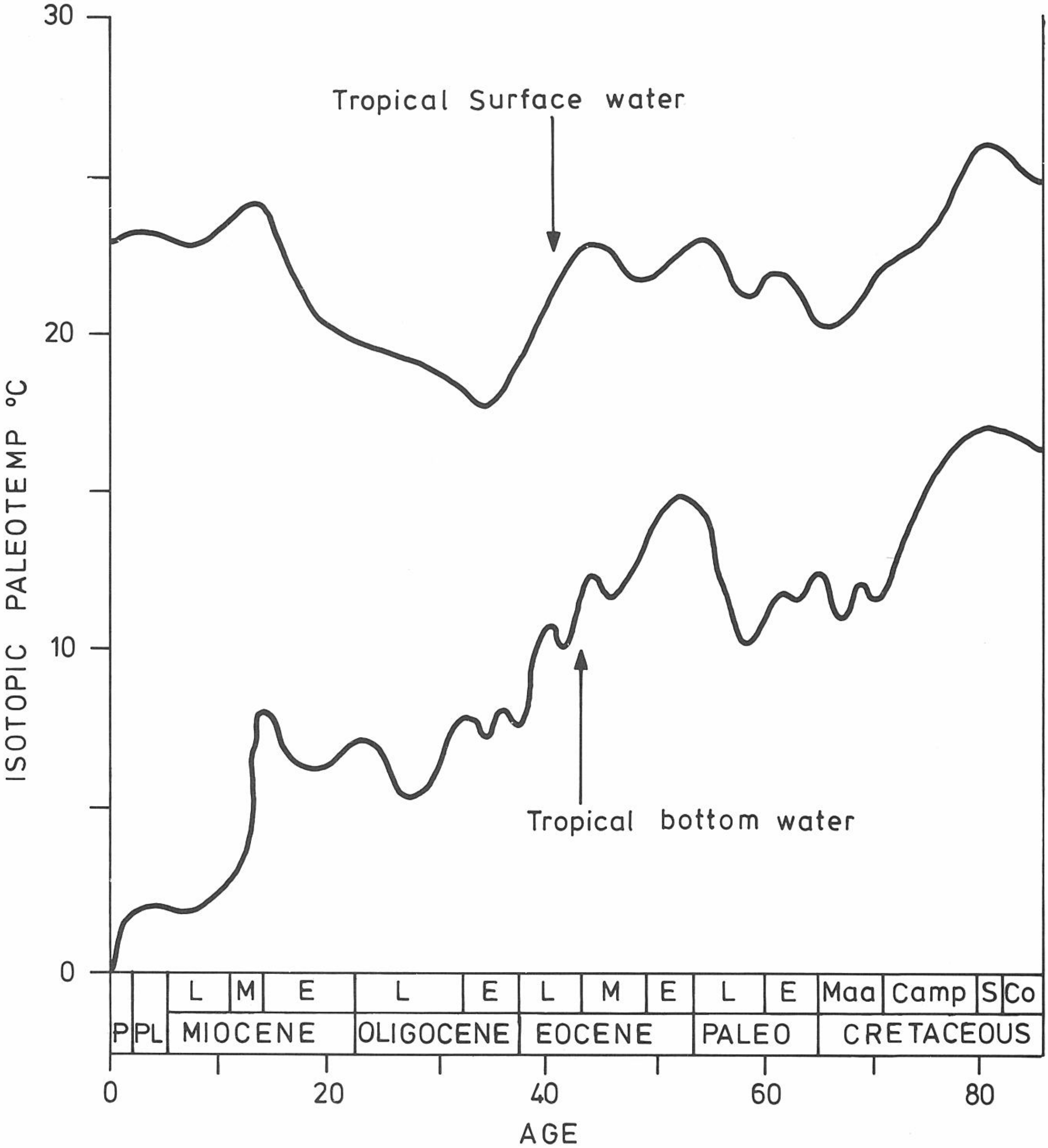

Figure 3. Estimated palaeotemperature curves for low latitude oceanic waters from the late Cretaceous to the present, based on oxygen isotope data from planktonic and benthic foraminifera. Based on Savin (1982, Fig. 18.1).

other stratigraphic sections, and a more positive demonstration that true oceanographic as opposed to diagenetic signals are being recorded.

If one accepts the arguments of Kauffman (1984) and Stanley (1987) concerning the relative extinction vulnerability of tropical marine organisms, then there is independent evidence of climatic cooling towards the end of the Cretaceous.

There has also been a general consensus about a late Cretaceous decline of air temperatures, based on the record of terrestrial plants (Savin, 1977; Hickey, 1984) but this view has been challenged for the North American Western Interior by Wolfe and Upchurch (1986). From angiosperm leaf studies they find no evidence of climatic cooling through the late Maastrichtian (indeed, Fig. 6 of Upchurch and Wolfe (in press) suggests the reverse) but infer a major long-term increase in precipitation starting at the Cretaceous-Tertiary boundary, following the brief episode of ecological disruption discussed earlier. Because such conflicting results have been obtained from the analysis of leaf margins (Hickey, 1980; Wolfe and Upchurch, 1986) there is doubt as to how to interpret them and the matter needs urgently to be resolved.

CONCLUSIONS

A substantial and rapid sea-level fall would severely restrict habitat area. Notwithstanding Stanley's (1987) reservations, and a causal relationship that has as yet been inadequately worked out, marine regression seems to provide the best correlation with mass extinction episodes throughout the Phanerozoic (Jablonski, 1986b). Consider for example the ammonites; throughout their history, diversity peaks correlate with sea-level high stands and diversity troughs, leading in extreme cases to extinction or near extinction of the whole group, with sea-level low stands. Kennedy's graph (1977, fig. 33) suggests strongly that, regardless of any bolide-induced catastrophe, ammonites would have gone extinct by the end of the Cretaceous. Sea-level fall would, of course, increase continental habitat area, but seasonal temperature extremes would increase as the climate became more "continental" and this might have been sufficient to cause the extinction of large (probable) ectotherms with low population density, such as the dinosaurs. It appears likely, however, that climate was deteriorating towards the end of the Cretaceous, independent of tectonically-induced sea-level change. If, indeed, temperatures fell by a sufficient amount, small polar ice caps could have been established, that would induce rapid sea-level fall. Subsequent early Palaeocene climatic amelioration would cause these to disappear and the sea level to rise with comparable rapidity. So far no evidence has been discovered that such ice caps actually formed.

It seems clear, however, that a combination of sea-level and temperature fall is insufficient to account for the catastrophic end-Cretaceous plankton extinctions and short-lived ecological disaster among terrestrial plants, so that a final, paroxysmal, disturbance needs to be invoked in addition, due either to bolide impact or volcanicity on a spectacular scale rare in earth history. There has been a temptation for some supporters of the impact hypothesis to accept the phenomenon of stepwise extinction extending over a period of up to a million years or more, and explain it by the collision with the earth of a shower of comets that might leave no chemical signature (Alvarez, 1986). It has now been argued, however, by a group of astronomers (Bailey *et al.*, in press) 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. One of the great strengths of the original Alvarez hypothesis was its testability. The comet shower hypothesis is weak because it seems impossible to falsify it by data from the stratigraphic record. Taking due note of the astronomers' scepticism, it appears to be a wiser strategy to adopt an extinction scenario derived from events intrinsic to this planet, perhaps with the exception of a single bolide impact *coup de grâce* to an already wilting biosphere.

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