THE CRETACEOUS-TERTIARY BOUNDARY PROBLEM

by

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Speculation on the causes of some of the dramatic geological and faunal changes during the Cretaceous-Tertiary transition continues to grow. Two hypotheses are explored here in the light of recent isotopic evidence. The article stresses the need for interdisciplinary collaboration and research if a satisfactory solution to the problem is to be found.

The end of the Mesozoic Era, and with it the extinction of the ammonites, cycadeoids and dinosaurs, has fascinated earth scientists since the major divisions of Phanerozoic time were recognized. For many decades, the problem of separating the highest stratigraphic levels of the Cretaceous System from the lowest levels of the Tertiary was clouded by the dubious biostratigraphic relationships of the Danian Stage. In recent years, however, microfossil evidence has persuaded many stratigraphers that Tertiary time began with the initiation of Danian deposition. The debate has now shifted to whether the biostratigraphic peculiarities of the Cretaceous-Tertiary boundary are better explained by gradualistic (often terrestrial) or by catastrophic (often extra-terrestrial) mechanisms.

An area of consensus does exist. Most specialists concur that the Cretaceous-Tertiary boundary can be identified in local sections with relative ease and often with great precision (for example, in the Mendez Formation near Tampico, Mexico, the Scaglia Rossa near Gubbio, Italy, the El Haria Formation in Tunisia, the Gaj River section in Pakistan, and the contacts between the Kanguk and Eureka Sound Formations in Arctic Canada, between the Wurno and Dange formations in Nigeria, and between the Gramame and Maria Farinha Formations in Brazil). It coincides with an extinction datum of greater than usual importance and often a lithologic change as well. The duration of the extinctions was geochronologically brief, and estimates range between 1,000 years and 1.5 Ma. Within this framework, however, there is much disagreement. So far, more effort has been expended on defending the plausibility of hypotheses than on testing them to assess their predictive value.

The Cretaceous-Tertiary boundary problem thus continues to be an unusually fertile area of research. Accordingly, it may be timely to point out some of the problems which have previously obscured our appreciation of the nature of the Cretaceous-Tertiary transition. Several of these, pertaining to paleontological, chronological and environmental factors, are considered below. Possible courses for future investigation are then suggested for two models currently under discussion - one gradualistic and the other catastrophic.

Problems for Paleontologists

The process of sampling the fossil record can present difficulties of a practical order, and detailed dinosaur collecting programmes have not been initiated to examine faunal trends toward the close of Cretaceous time. An average dinosaur skeleton is about one-third complete and could be considered to contain the same amount of biostratigraphic information as does one palynomorph. A palynomorph slide preparation, derived from fine-grained terrestrial sediments of late Cretaceous age, usually contains about 20,000 grains. It can be prepared at a cost of \$100 (Cdn.), including less than a week of one person's time in the laboratory. To collect and prepare 20,000 fragmentary dinosaur skeletons for study, \$260,000,000 (Cdn.) and the equivalent of 15,000 years of one person's time would be required (excluding transportation and storage costs).

Approximately 5,000 such skeletons have been collected from Mesozoic strata around the world, the richest fossil field

having yielded slightly more than 300 specimens. Existing collections, however, do not support the view that dinosaurs were declining in diversity through late Cretaceous time.

In order to reduce the awesome scope of the paleontological record to manageable segments, paleontologists have tended to specialize, usually restricting their areas of investigation to one taxonomic group of organisms and one interval of geological time. Thus, the response of different groups of organisms to the Cretaceous-Tertiary transition tends to

The Cretaceous-Tertiary boundary, here postulated to be at the base of a pink sandstone below the Barre du Cengle on the southern flank of Mt. St. Victoire, near Aix-en-Provence, France. The red shales in the lower part of the section contain fragments of dinosaur egg shells, and the white ledge higher on the slope is the "calcaire formant toit" of Paleocene age. The crest of the hill is formed from the Poudingue de la Galante. Tertiary deposition is inferred to have begun with the pale pink sandstone sequence immediately above the red shales. The author is digging a trench along the postulated erathem boundary.

affect different specialists' judgement of the importance of the extinctions. For example, students of dinosaurs and marsupalian mammals are often more impressed by the terminal Cretaceous extinctions than are students of crocodilians and placental mammals. Furthermore, paleontological studies tend to terminate with the end of Cretaceous time, or begin with the initiation of the Tertiary, so that a continuity of perspective is lost at the erathem boundary.

Diversity trends for two groups of planktonic marine microorganisms through Cretaceous and early Tertiary time. The dinoflagellates (D) show no unusual decline in specific diversity through the terminal Cretaceous crisis, although a spectacular decline is evident in the case of calcareous nannoplankton (C). Diversity in hundreds of species (SP), is plotted against time measured in millions of years before the present (MYBP), according to data obtained by Jonathan Bujak and Graham Williams (Atlantic Geoscience Centre, Geological Survey of Canada), and by Bilal Ul Haq (Woods Hole Oceanographic Institution, U.S.A.).

From a paleobiological point of view, detection of the stresses which drove certain organisms to extinction is difficult. Obviously, the survivors were not eliminated, and it may be possible to identify some of the advantageous characteristics they shared. In the case of organisms becoming extinct, some may have been exterminated as a direct result of the stresses, while others could have withstood them but vanished as a result of the disappearance of vulnerable organisms upon which they were ecologically dependent. It may not always be possible to distinguish "primary" from "secondary" extinctions. Reconstructions and analyses of the behaviour of ecosystems through the Cretaceous-Tertiary boundary crisis will provide a stimulating and rewarding area for study.

It is apparent that, despite a possible loss of biostratigraphic precision due to reworking, paleobiological information can most abundantly and economically be obtained through microfossil studies. These have already clarified the global nature of the Cretaceous-Tertiary boundary crisis, and will provide an easily accessible source of data for cross-disciplinary research involving paleontological materials. The problem of specialization can be overcome through informal colloquia, and encyclopedic reviews such as the *Treatise on Invertebrate Paleontology*. On the basis of existing literature, a case can be made for the extinctions having been extraordinarily severe.

Chronological Resolution

In many sections (for example, along the Barranco del Gredero in Spain, and in the Lance Creek Basin of Wyoming, U.S.A.) the biotic change associated with the Cretaceous-Tertiary boundary took place within a vertical interval comparable to the thickness of the smallest lithologic subdivisions, implying the presence of a hiatus or a biological crisis of short duration. If the extinction datum were found to be diachronous on a global scale, a gradualistic explanation

for the phenomenon would be supported. If it were found to represent a globally synchronous event, a catastrophic mechanism would be favoured. Chronologic resolution by radioisotopic means is thought to be about 500,000 years for the period considered, about 63 Ma (Lerbekmo et al., 1979). Biostratigraphic resolution is also of this order (Alvarez et al., 1977).

In order to improve chronologic resolution, magnetostratigraphic surveys have been carried out during the last few years across the Cretaceous-Tertiary boundary in Italy, Spain, U.S.A. and Canada, yielding conflicting interpretations of the synchronous or diachronous nature of the extinctions. For short intervals of time (~ thousands of years) the uncertainty is generated by fluctuations in sedimentary rates and the existence of otherwise undetected hiatuses. Assuming that the terrestrial magnetosphere can reverse itself within about 1,000 years, chronostratigraphic resolution of this order is possible under conditions of rapid and uniform deposition. As suitable sections are identified, geomagnetic techniques will be of great utility in determining the global duration of the Cretaceous-Tertiary boundary crisis.

The Cretaceous-Tertiary boundary in pelagic marine carbonates as exposed on Woodside Creek (Mead Hill Formation) near Ward, South Island, New Zealand, established on the basis of foraminiferal guide fossils. Dr. Percy Strong, New Zealand Geological Survey, points toward the erathem boundary. The small holes result from removal of cores, taken for paleomagnetic analysis.

Physical Environmental Indicators

A few years ago, Thomas Worsley (University of Washington, U.S.A.) postulated that the carbonate compensation depth in the oceans may have risen at the end of the Cretaceous, producing a world-wide hiatus in pelagic carbonate sequences. More recently, Hans Thierstein (Scripps Institution of Oceanography, U.S.A.) and Hisataka Okada (Yamagata University, Japan), have shown that fluctuation in patterns of carbonate compensation depth surfaces varied in different ocean basins through late Cretaceous and early Tertiary time, showing no indication of a global carbonate solution event coinciding with the erathem boundary.

There is, nevertheless, a sedimentological dimension to the Cretaceous-Tertiary boundary problem. In several terrestrial and shallow marine sections, higher-energy environments of deposition appear to be associated with the beginning of Paleocene time. This is often evident in the northern interior of the United States, where basal Paleocene sediments also appear to be more oxidized and better stratified than Cretaceous sediments below. Parenthetically, it may be noted that in this region the extinction datum lies at the same horizon in both continental and marine facies, instead of being offset 30 to 80 m by prevailing depositional rates, as would have been the case had the continental extinctions followed those in marine environments by 0.5 to 1.5 Ma (this has been suggested by Robert Butler and his colleagues at the University of Arizona, U.S.A.).

Table 1

Characteristics of the Cretaceous-Tertiary Environment Crisis

Duration:

between - 1,000 and 1,500,000 years

Discontinuities:

Extirmination of - 75% of species on planet

Coincident with crisis:

- higher-energy environment of sedimentation
- changes in colour of sediments
- increases in concentrations of heavy elements

Following the crisis:

- increase in amount of lighter isotope of carbon in marine organisms

Continuities:

- Absence of excursion in marine paleotemperatures through crisis
- Survival of most species inhabiting freshwater ecosystems

The environmental implications of this change in sedimentation have not been studied. Could extinctions of arbore-scent plants in elevated regions, as described by Valentin Krassilov (Vladivostok Institute of Biology and Pedology, U.S.S.R.), have resulted in rapid runoffs and a change in the mode of continental weathering (Davies et al., 1977)? Or could the dramatic terminal Cretaceous coccolith extinctions have temporarily suspended carbonate deposition on continental shelves, resulting in the accumulation of a thin, relatively pure deposit of terrigenous material? The influences of the biosphere, tectonism and climate on sedimentary processes are well appreciated, but is it possible to discern which of these three categories of variables was most effective in producing sedimentological changes at the erathem boundary?

The absence of change in certain environmental indicators may not imply environmental stability. For example, an increase in cosmic radiation would stimulate production of light-absorbing nitrogen oxides and cause a global decline in temperatures (Reid et al., 1978). An abrupt reduction in planktonic algal floras in the oceans would release CO₂ into the atmosphere, producing a global warming which would be further enhanced by a reduction in the solubility of CO₂ in marine waters (McLean, 1978). The absence of a clearly defined paleo-temperature trend across the Cretaceous-Tertiary boundary does not necessarily indicate that neither of these events occurred. In combination, they may have been incapable of producing a clearly defined thermal excursion.

As in the case of organisms which became extinct, the nature of stress may not be revealed by a change in the behaviour of a paleoenvironmental indicator. Theirstein and his colleagues have documented an increase in isotopically light carbon in pelagic marine sediments immediately above the erathem boundary. This may be taken as evidence of a surficial water layer of reduced salinity, or of a sudden increase in the photosynthetic productivity of terrestrial plants relative to that of planktonic marine algae.

Two Hypotheses

No other interval of geological time has been so fecund a source for speculation as has the Cretaceous-Tertiary transition. The number of hypotheses advanced to explain the extinctions is legion. Several, including the effects of a collapse of marine phytoplankton communities through nutritional deficiencies, a huge injection of fresh water into the world ocean, and atmospheric effects of volcanic dust veils, are objects of current interest. In Russell (1979) there is a general review of speculation on the terminal Cretaceous extinctions, but the possible implications for further research in two of the models are discussed here.

Giant waves and rapid changes in sea level are viewed as terrestrial catastrophes (not unlike floods generated by hurricanes); rapid marine regressions are regarded as agents of destruction for marine communities on continental shelves. A geologically brief but profound terminal Cretaceous regression of the seas is frequently invoked to explain the biotic crisis at the Cretaceous-Tertiary boundary.

A surprisingly small body of information is available on the physical properties of this regression, and it has seldom been studied apart from its biostratigraphic context. For example, emersion has been inferred because of the abrupt change between late Cretaceous and early Tertiary faunas, and the presence of hardgrounds at or near the erathem boundary. The former could also be a reflection of the rapidity of the extinctions, and the latter could contain a balance of carbon isotopes indicative of submarine solution. There is a danger of reasoning "in circles" here - assuming that because extinctions were severe, regression must have been profound, and vice-versa.

The terminal Cretaceous regression should be studied on the basis of physical criteria alone. Its vertical amplitude and geographic distribution should be plotted. If it can be shown to have been an extraordinary and approximately synchronous event, then environmental pressures which decimated marine faunas of the continental shelves will stand in higher relief. Computer models of oceanic and atmospheric circulation, as well as of global heat budgets, based upon preregression and regression paleogeographies, may be examined for temperature and rainfall changes which would be sufficient to simultaneously exterminate large vertebrates on expanding, biologically productive coastal plains. Factors such as rate of continental erosion and marine circulation could be analyzed to reveal changes leading to catastrophic declines in phytoplankton populations in the open oceans.

The Cretaceous-Tertiary boundary in Makoshika State Park, near Glendive, Montana, U.S.A. Grey fluviatile sediments of the Hell Creek Formation (Cretaceous) are overlain by laminated lignitic siltstones of the Tullock Formation (Tertiary). The erathem boundary, identified palynologically at this site, coincides with a 2-3 cm regolith containing root casts.

In selecting their preferred hypothesis to account for the terminal Cretaceous extinctions, paleontologists have sometimes applied the principle of "minimum astonishment" to the detriment of the uniformitarianism principle - as the latter applies to extra-terrestrial sources of environmental stress. It is abundantly evident that surficial planetary environments are affected by matter and energy from space. The biosphere of the Earth will disintegrate as the Sun enters a red giant phase five Ga hence. Extraordinarily violent but

geochronologically brief stellar explosions, termed supernovae, have a distribution in time and space which is of great cosmological significance. Their astrophysical and, ultimately, biological importance have been described during the last decade in interdisciplinary journals such as *Nature*, *Science* and *Scientific American*.

A nearby supernova could produce increases in cosmic, gamma and ultraviolet radiation at the surface of Earth, as well as decreases in temperature, rainfall and illumination in visible wavelengths. These effects might be maintained for tens to thousands of years. The possible severity of the stresses is not understood, but detailed information on the properties of supernova ejecta and the effects of their passage through interstellar space and the terrestrial atmosphere will determine their amplitude. The influence of changes in temperature, rainfall and illumination (whether generated by a supernova or some other agent) on terrestrial and marine ecosystems is relatively well documented, and a growing body of information on the effects of high energy radiation on communities of organisms is available. The global response of the biosphere to higher levels of ultraviolet radiation is largely unpredictable, although many marine organisms are currently living close to the limits of their UV tolerance.

Thus, disturbances within the biosphere during the Cretaceous-Tertiary transition cannot be viewed as evidence only of the simultaneous explosion of a nearby supernova. It would be more useful, instead, to examine rapidly and continuously deposited sedimentary successions for residues of supernova ejecta, such as enrichments in Mg^{26} (derived from Al^{26}), I^{129} (with its decay product Xe^{129}) and Pu^{244} , all of which are created in supernova explosions. Similarly, indications of unusually intense cosmic ray interactions in the atmosphere may be detected by enrichments of B^{10} (from Be^{10} , in turn derived through nitrogen spallation) and Mg^{26} (from Al^{26} , in turn derived through argon spallation). Interactions of supernova ejecta with other surface materials on Earth may also leave identifiable residues. Preliminary surveys have already been made for evidence of ancient supernovae in the stratigraphic record (Higdon and Lingenfelter, 1973).

Walter Alvarez and his colleagues in the University of California at Berkeley, U.S.A., are carrying out a programme of isotopic studies across the Cretaceous-Tertiary boundary. Preliminary findings suggest that anomalously high concentrations of iridium at the boundary contain an Ir^{191}/Ir^{193} ratio similar to that prevailing within the solar system. These data, together with the absence of a corresponding increase in Pu^{244} , do not appear to indicate a supernova origin (Alvarez et al., 1979). Attention is currently being focussed on the effects of the collision of a planetesimal to account for the paleontological and paleoisotopic record during the extinction interval (Napier and Clube, in press; L. Alvarez, personal communication, 1979).

Broad Approach

Not so long ago, the pernicious effects of egg-eating mammals, competition for food resources with lepidopteran larvae and poisonous alkaloids in flowering plants, were considered as possible explanations for the disappearance of the dino-

sosaurs. These factors no longer seem to be of great consequence, in view of the geographical and ecological pervasiveness of the biotic crisis in which the dinosaurs vanished. Hypotheses are now required to accommodate a much broader range of paleobiological data.

Furthermore, a problem which has traditionally been paleontological is attracting the attention of an increasingly diversified range of scientists. This will surely be beneficial, for paleontologists may never be able to satisfactorily resolve the Cretaceous-Tertiary boundary problem, just as they were unable to form a consensus regarding the possibility of continental drift before the concept began to receive geophysical support some fifteen years ago. The new inferences gleaned from the record of the Cretaceous-Tertiary passage by atmospheric and isotopic physicists, geomagneticians, marine geochemists and palynologists force those who have specialized in the morphology and evolution of the great Mesozoic reptiles to broaden their appreciation of the possibilities and limitations of "sister" disciplines. The converse is also true.

It has been suggested that the terminal Cretaceous extinctions occurred when several ordinary stresses coincided with mutually reinforcing and catastrophic effects. It is equally possible that a single extraordinary stress produced a shower of biologically significant secondary stresses. In either case it is difficult to comprehend the full scope of the problem. The scientific challenge lies in the task of devising programmes of interdisciplinary research which will lead to a better understanding of a time when the biosphere of Earth was convulsed in a very peculiar way.

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