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Mass Mortality and Its Environmental and Evolutionary Consequences

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That many species of animals and plants became extinct near the end of the Cretaceous is a matter of geological record, although there remains considerable dispute concerning the causes, tempos, and modes of this unusual geologic event (*1*). Certain groups of organisms, such as planktonic foraminifera and calcareous nannoplanktons, were almost completely eliminated during a very brief span of geologic time (*2–4*). Significant physical and chemical changes of the oceans at the end of the Cretaceous have been revealed by analyses of the lithology (*5*) and of the stable-isotope compositions of fossil calcareous plankton in deep-sea drilling cores (*6–8*). However, it has not always been clear if the changes were the causes or the effects of mass mortality.

Several recent postulates have related the terminal Cretaceous extinctions to an extraterrestrial cause (*9–12*), primarily on the basis of anomalously rich traces of iridium being found in sediments directly above the Cretaceous-Tertiary (C-T) boundary. The assumptions of a fallen asteroid or a disintegrated comet seemed to offer the best explanations for the iridium anomaly, but the various scenarios have not produced convincing arguments that meteor impact should cause a selective extinction at the end of the Cretaceous as registered by the paleontological record (*13, 14*). One of us (K.J.H.) attempted to invoke cometary impact to explain the selective extinction on the basis of geochemical anomalies of the boundary layer above the C-T contact (*15, 16*). These efforts, however, have been hampered by the fact that deep-sea drilled sections, which contain the clearest stable isotopic records, exhibit a hiatus at the C-T boundary or sedimentation rates that are too low to provide a detailed record of the event.

In this article, we present results relating the environmental changes to the mass mortality in the oceans and discuss several theories that are in accordance with these new data.

Stratigraphy at Site 524

Deep Sea Drilling Project (DSDP) site 524 was located at 29°29′S, 3°31′E at 4805 meters depth in Cape Basin (Fig. 1). The hole was drilled into a submarine fan at the mouth of a submarine canyon cut into the Walvis Ridge. Lower Eocene sediments crop out here where younger sediments have not been deposited or have been eroded. The uppermost Cretaceous and lower Tertiary sediments have been buried at such a shallow depth that there is little evidence of postdepositional changes that might have altered their isotopic compositions. Those sediments constitute a continuously deposited sequence from the Maastrichtian to the Lower Eocene (Fig. 2).

Since no magnetic subdivisions (chrons) have yet been defined for Paleogene and Cretaceous sediment or rock sequences, we adopted a convention during the expedition which will be formalized elsewhere. Our convention defines a Paleogene magnetic chron as extending between the youngest reversal boundaries of numbered magnetic anomalies as defined by Heirtzler *et al.* (*17*) and refined by LaBrecque *et al.* (*18*). Chrons are distinguished by a letter C prefix to the associated anomaly number, and may be subdivided into subchrons by the addition of an N or R suffix which refers to the predominantly normal or reversed segment of the chron. Shipboard analyses by three of us (L.T., P.T., and N.P.) provided a magnetostratigraphic time framework for the sedimentary sequence, which allows us to compare our magnetostratigraphy results with results from other sequences of the same time period. Magnetozones correlated to chrons C27 to C31 (corresponding to magnetic anomalies 27 to 31) have been positively identified. The C-T boundary was recognized at 203.54 m subbottom, in core 20, section 3, within the reversed subchron C29R (Fig. 3). Thus the C-T boundary at site 524 occurs within the same magnetic subchron as at the Gubbio section in Italy (*19*).

Biostratigraphically, the sequence at site 524 yielded Maastrichtian as well as Tertiary fossils from foraminiferal zones P-1 to P-7/8 and from nannofossil zones

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NP-1 to NP-12. The sediments include nannofossil oozes, nannofossil marls, and bioclastic and volcanoclastic sands, with basalt flows and sills intercalated in the lowest (Maastrichtian) part of the section (Fig. 2). The origin of the basaltic rocks is related to the genesis of the Walvis Ridge. The basement was not cored at site 524.

The volcanoclastic components, derived from the nearby Walvis Ridge, are present both in the turbidites and in hemipelagic sediments, accounting for the rapid sedimentation rate of about 30 m per million years for the Maastrichtian and Paleocene. The sediments of the subchron C29R were deposited at a slightly slower rate of 28 m per million years, but still several times faster than the rate at Gubbio or at other DSDP sites. Samples of hemipelagic sediments from this expanded sedimentary record permit us to reconstruct the record of environmental and biostratigraphic changes during the critical period of C-T transition.

Summary. The latest Mesozoic and earliest Tertiary sediments at Deep Sea Drilling Project site 524 provide an amplified record of environmental and biostratographic changes at the end of Cretaceous. Closely spaced samples, representing time intervals as short as 10^2 or 10^3 years, were analyzed for their bulk carbonate and trace-metal compositions, and for oxygen and carbon isotopic compositions. The data indicate that at the end of Cretaceous, when a high proportion of the ocean's planktic organisms were eliminated, an associated reduction in productivity led to a partial transfer of dissolved carbon dioxide from the oceans to the atmosphere. This resulted in a large increase of the atmospheric carbon dioxide during the next 50,000 years, which is believed to have caused a temperature rise revealed by the oxygen-isotope data. The lowermost Tertiary sediments at site 524 include fossils with Cretaceous affinities, which may include both reworked individuals and some forms that survived for a while after the catastrophe. Our data indicate that many of the Cretaceous pelagic organisms became extinct over a period of a few tens of thousands of years, and do not contradict the scenario of cometary impact as a cause of mass mortality in the oceans, as suggested by an iridium anomaly at the Cretaceous-Tertiary boundary.

Detailed investigations of the nannofossils have been carried out by two of us (S.F.P. and K.P.-N.). The C-T boundary (bottom of NP-1) was placed at the level 203.54 m subbottom, recognized in this hole on the basis of the first occurrences of the "Tertiary nannofossils" *Markalius astroporus*, *M. reinhardtii*, *Zygodiscus sigmoides*, and *Thoracosphaera* species. As in other DSDP holes, a transitional interval above the C-T boundary includes nannofossils that have been considered exclusively Cretaceous species. We define this transitional interval as occurring after the C-T boundary and having sediments containing abundant to common "Cretaceous nannofossils." These Cretaceous nannofossils are either the remains of the last "survivors" which soon became extinct, or they represent Cretaceous microfossils reworked from older sediments. At site 524 the samples directly above the C-T boundary contain more than 90 percent of typically Cretaceous taxa. This decreases to less than 50 percent at 1.2 m and to less than 20 percent at 1.9 m above the boundary (Fig. 3). Most common are species with robust skeletons from middle latitudes, namely, *Micula staurophora*, *Arkhangelskiella cymbiformis*, *Eiffellithus turriseiffelii*, and *Watznaueria barnesae*. However, some species less resistant to dissolution are common (*Prediscosphaera cretacea*) or rare (*Micula prinsii*). The transitional interval ends at about 2 m above the C-T boundary when Cretaceous taxa become very rare.

The planktonic foraminiferal faunas near the C-T boundary have been much dissolved. Typical Tertiary forms, such as *Globigerina eugubina* and *"Globigerina" pseudobulloides*, were found in the sediments 1 to 2 m above the boundary. Also present in the transitional zone are some typical Cretaceous taxa, such as *Globotruncana*.

Geochemical Anomalies

More than 200 samples from site 524 have been analyzed for their calcium carbonate content (percentage by weight) by means of a combustion-titration apparatus. The lower Paleocene sediments are marly oozes with an average $CaCO_3$ content of about 40 percent (Fig. 3). The uppermost Maastrichtian sediments are also marly oozes with a $CaCO_3$ content between 30 and 40 percent. However, as in every continuously deposited C-T transition known to us, there is a $CaCO_3$ anomaly at or near the boundary (Fig. 4). A remarkable systematic trend was observed: the $CaCO_3$ content rapidly decreased from 39 percent at 116 centimeters to 32 percent at 109 cm to 19 percent at 108 cm of the same core and reached a minimum value of 2 percent for the C-T boundary clay (sample 20/3/104–105 cm). A mineralogic study (by A.M.K.) of the 2-micrometer fraction of the boundary clay (sample 20/3/105–106 cm) indicates that it is composed of 90 percent well-crystallized, iron-smectite clays, such as beidellite, and is identical in mineralogic composition to the bulk sample. This duplication strongly suggests that the boundary clay is a pelagic sediment that has experienced extensive dissolution of its biogenic-carbonate components. The $CaCO_3$ content increases to 10 to 25 percent in the transitional sediments, but again decreases dramatically to about 1 percent at 2.5 m above the C-T boundary. It returns to normal values within nannofossil zone NP-2, some 350,000 years after the beginning of the Tertiary (Fig. 3).

The decrease of $CaCO_3$ could be due to a greater influx of noncarbonate detritus, to reduced production of calcareous plankton, or to increased sea-bottom dissolution. Extensive dissolution of planktonic foraminifera in the uppermost Cretaceous sediments at site 524 and at many other localities throughout the world indicates that carbonate dissolution markedly increased at the end of the Cretaceous. The evidence favors the postulate that the calcite compensation depth (CCD) rapidly shallowed (*5*). However, the CCD may have soon deepened again during the earliest Tertiary, because tests (shells) of the earliest Tertiary foraminifera show little evidence of dissolution.

Six samples from near the C-T boundary were selected for trace-element analysis in Bern (by U.K.) with the neutron-activation method (Figs. 3 and 4). Accuracy, precision, and blank contribution were determined prior to analyzing the deep-sea sediments. The samples were dried at 105°C and no acid treatment was made before the neutron irradiation. Instrumental measurements of the activities were performed, as well as measurements after radiochemical separations. As expected, an iridium anomaly (3.3 ± 0.30 parts per billion) was found in the sample containing the C-T boundary (sample 20/3/103–105 cm) (Figs. 3 and 4). However, an anomalous iridium content was also detected in sample 20/3/107–109 cm just below the boundary. This is probably the result of contamination by bioturbation. Burrowing below the C-T boundary clay is quite visible (see Fig. 4) and the nannofossil assemblage of this same sample indicates the presence of downwardly reworked sediments.

Stable isotopic analysis of the $CaCO_3$ content in site 524 sediments was carried out in Zürich (mainly by Q.H. with assistance from J.A.M., H.W., and H.O.). Because the sample size is so small and foraminiferal tests so rare, general trends in the carbon and oxygen isotopic stratigraphy were established for the bulk samples. Since larger foraminiferal tests are rare in all samples, the bulk samples should give an approximation of the isotopic composition of the calcareous nannoplanktons and, hence, the near-surface waters. Whenever it was possible to separate size fractions, a fine fraction (< 28 μm) of the calcareous sediment was also measured. The finer fraction contains predominantly nannoplanktons and should be even more representative of surface-water conditions. The stable isotopic values in both the bulk and fine fraction are plotted together in Fig. 3, which shows that the data vary similarly with depth. Also plotted in Fig. 3 are the isotopic ratios for *Gavelinella beccariiformis* (picked by R.W.). This benthic species occurs on both sides of the C-T boundary and is sufficiently abundant to be picked and analyzed.

The isotopic results are expressed as per mil deviations from the PDB isotopic standard as $\delta = [(R_{sample}/R_{standard}) - 1] \times 10^3$, where R is the ratio of ^{13}C to ^{12}C or ^{18}O to ^{16}O. The precision of the measurements, as standard deviation of the mean calculated for replicate analyses, is $\pm$ 0.02 per mil for $\delta^{13}C$ and $\pm$ 0.04 per mil for $\delta^{18}O$. Samples chosen for stable isotopic analysis were taken from the pelagic sediments intercalated within the turbidite sequence. The isotope data are presented in Fig. 3 with sample depth plotted on a logarithmic scale in order to show the numerous datum points clustered near the C-T boundary. In Fig. 4, the isotopic data are plotted on a centimeter scale across the critical C-T boundary interval and can be compared with the exact position of each sample in the cored section. Examination of samples with a scanning electron microscope (by K.K.) indicated that the micro- and nannofossils have little or no overgrowth, which might have altered their isotopic compositions.

Two remarkable carbon-13 anomalies are seen in the data. The first occurs at the C-T boundary where only bulk analysis was performed because of the very low carbonate content (Fig. 4). Sample 20/3/104–105 cm, exactly at the boundary, has a $\delta^{13}C$ value of −0.6 per mil, which is significantly depleted in carbon-13 relative to an average Cretaceous value for bulk samples of +2.4 per mil. Sample 20/3/106–107 cm is also relatively depleted in carbon-13 (+0.8 per mil) but this may be due to bioturbation and the mixing of the isotopically light carbonate into the sediment underlying the boundary clay. The $\delta^{13}C$ value at 5 cm above the boundary is again more positive (+2.1 per mil). From this point, the $CaCO_3$ content of the sediments shows a steady, linear decrease in $\delta^{13}C$ in both the bulk and fine fractions, reaching a second minimum at about 1 m above the C-T boundary (Fig. 3). Afterward, the $\delta^{13}C$ ratio becomes gradually enriched in carbon-13 and approaches a Cretaceous-like value of +2.0 per mil at 11 m above the C-T boundary.

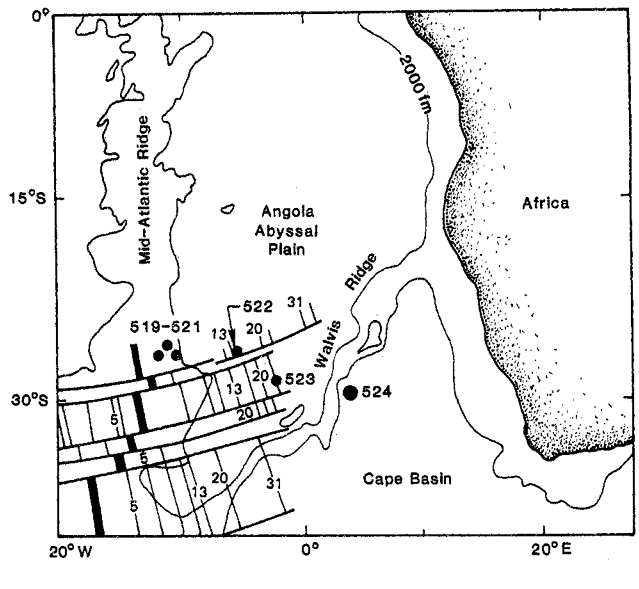

Fig. 1. Location of DSDP site 524. Numbers beside dots indicate drill sites and numbers between lines indicate sea-floor magnetic anomalies. The 2000-fathom bathymetric contour is also shown.

The $\delta^{13}C$ ratio of the *Gavelinella beccariiformis* remains basically constant throughout this period of carbon-13 oscillations. This indicates that the changes in the $^{13}C/^{12}C$ ratio were surface-water phenomena and were not felt in the deep bottom waters. Since the carbonate samples and especially their fine fraction consist almost exclusively of nannofossils, the signals represent changes in isotopic composition of nannoplankton skeletons and reflect a change of the isotopic composition of dissolved carbonate in the surface water of the ocean.

Among the planktonic tests of sample 20/3/98–100 cm, specimens from typically Cretaceous taxa, such as *Globotruncana* species, were analyzed separately from Tertiary (?) forms, such as the Globigerinide species. Our results give practically identical $\delta^{13}C$ values: +1.77 per mil for the Tertiary, and +1.75 per mil for the Cretaceous forms, and both values are about 1 per mil less than the $\delta^{13}C$ of the Cretaceous bulk samples. Since the oxygen-isotope values for the two are also similar, the results suggest that the "Cretaceous taxa" in this sample were largely survivors of the terminal Cretaceous event and lived in the same geochemical environment as Globigerinide in an early Tertiary ocean.

A decrease of about 3 per mil in the $\delta^{13}C$ ratio that is closely associated with the C-T boundary confirms earlier observations for other deep-sea drilling sites (*20*). Our data, however, show that this change was not instantaneous, but occurred over an interval of tens of thousands of years. The trend toward decreasing $\delta^{13}C$ values, which began just above the C-T boundary, continued for about 40,000 or 50,000 years. After the maximum decrease was attained, the carbon-isotope ratios gradually returned to Cretaceous-like values at about 300,000 or 400,000 years above the boundary.

The changes in the composition of oxygen isotopes across the C-T boundary are less systematic than the carbon oscillations, but nevertheless seem real (Figs. 3 and 4). Cretaceous bulk samples from cores 20 to 23 yielded $\delta^{18}O$ values ranging from −0.2 to −1.2 per mil. For the boundary clay (sample 20/3/104–105 cm), the $\delta^{18}O$ value is +0.4 per mil and represents, possibly, a temperature minimum at the C-T boundary. However, at 5 cm above the boundary, the $\delta^{18}O$ ratios return to Cretaceous values and afterward show a fluctuating but often decreasing value. A minimal $\delta^{18}O$ anomaly for a maximum temperature is registered by the value of −3.6 per mil in the fine fraction of sample 20/2/98–100 cm about 1.5 m above the boundary, or at about the same level as the most negative $\delta^{13}C$

value. The oscillating oxygen-18 values may signify varying degrees of contamination or isotopic disequilibrium, or they may be a true manifestation of temperature oscillations after the boundary event. The oxygen isotopic compositions of all samples, bulk and fine fraction and *Gavelinella beccariiformis*, show the same trend. The synchronous decrease in the $\delta^{18}O$ of the fine fraction and benthic foraminifera could signify that the early Tertiary oceans became temporarily warmer throughout, while, during the same period, only the surface waters showed a decrease in the $\delta^{13}C$ content of the dissolved bicarbonate.

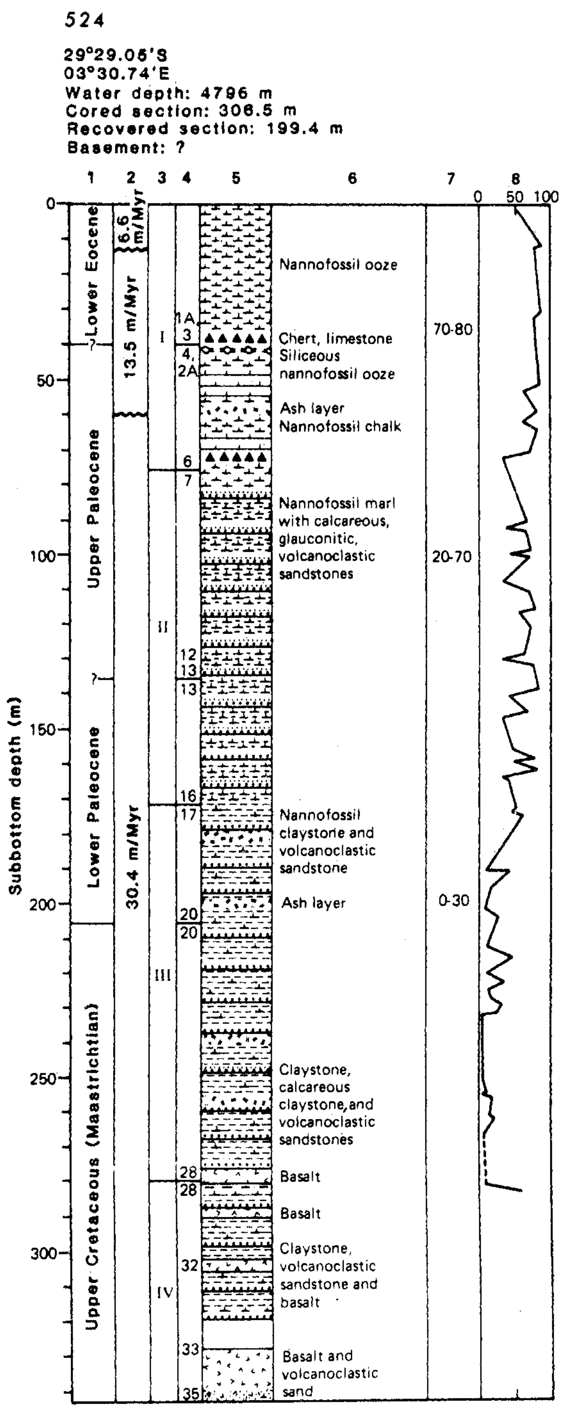

Fig. 2. Sedimentary sequence at DSDP site 524: 1, ages; 2, sedimentation rates; 3, lithologic units; 4, core numbers; 5 and 6, lithology; 7 and 8, $CaCO_3$ content and percentage variations by weight.

Discussion of Results

Nannofossil stratigraphy. The "Tertiary nannofossil taxa" in earliest Paleocene sediments have in fact all been recorded in late Cretaceous sediments in extremely low abundances, mainly at high-latitude sites (*21*). They were the species that flourished after the catastrophe. *Thorascophaera* species are considered to be calcified dinoflagellates (*22*), which may have formed in response to a stressed environment. *Braarudosphaera* species, another nannofossil commonly found in the transition interval elsewhere, is rare or absent at site 524.

The presence of the so-called Cretaceous taxa in the transition zone is a well-known problem and has been observed in almost every C-T transition (*21*). These taxa may represent Cretaceous nannofossil skeletons that have been mixed with truly Tertiary skeletons in the sediments by bioturbation, by resedimentation, or by mechanical disturbances during the coring operations (*21*). Or, they may have been remanent forms that survived and lived in the earliest Tertiary oceans before finally becoming extinct.

The core containing the transitional interval shows little to moderate amounts of bioturbation of the hemipelagic sediments, but evidence of resedimentation is obviously manifested by the common presence of turbidite beds (see, for example, Fig. 4). Coarse turbidites constitute about one-third of the section, and one cannot be certain if the marls or the marl oozes are entirely hemipelagic, or if they include considerable components of redeposited materials from the Cretaceous. A methodical examination of the entire transitional interval revealed the presence of rare individuals of Cretaceous taxa in all of the samples. It seems that, in this case, the presence of Cretaceous nannofossils does not give a clear-cut answer as to whether they are reworked or not.

If the Cretaceous taxa in the transitional interval are reworked, we have to adopt an ultracatastrophic view that all but a few of the Cretaceous species became extinct within a short time after the terminal Cretaceous event. The interval could be as short as 50 years, according to a study by Smit and Hertogen in Spain (*10*). If, however, the Cretaceous taxa are largely true survivors in the Tertiary ocean, the extinction of these survivors apparently required a few tens of thousands of years.

Perhaps the interpretation of the nannofossil sequence must take into consideration other data. If we assume that the Cretaceous taxa all became extinct at the C-T boundary, the tests of these taxa in the transitional sediments must have all been reworked. The isotopic data would thus be mixed signals given by a small percentage of Tertiary skeletons mixed with a much larger percentage of Cretaceous skeletons. For example, the fine fraction of sample 20/3/93–94 cm contains 90 percent Cretaceous species and has a $\delta^{13}C$ ratio of +1.5 per mil. If the average Cretaceous fine fraction has a $\delta^{13}C$ ratio of +2.5 per mil, the isotopic contribution of the Tertiary fraction must then have an extremely negative value of −7.5 per mil. It is perhaps more

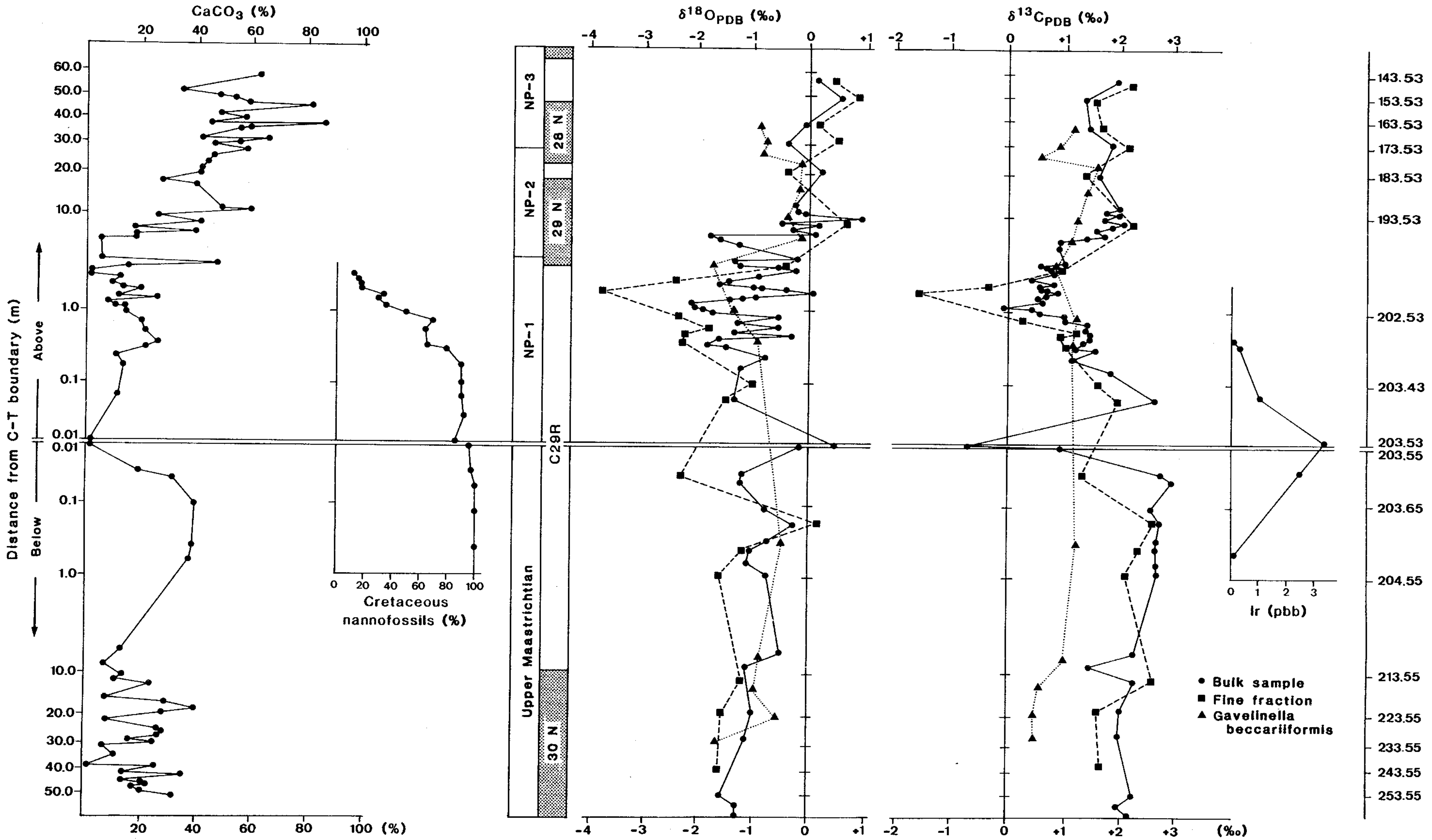

Fig. 3. Variations of $CaCO_3$ (percentage by weight); percentages of "Cretaceous taxa"; $\delta^{18}O$ and $\delta^{13}C$ in bulk samples, fine fractions, and *Gavelinella beccariiformis*; and iridium content across the C-T boundary section at DSDP site 524. Also shown are paleontological zonations (NP-1, for example) and magnetostratigraphic chrons (28, 29, for example). A logarithmic scale is used to amplify the details near the C-T boundary, with depth being plotted as meters above or below the contact on the left-hand ordinate and as meters below subbottom on the right-hand ordinate.

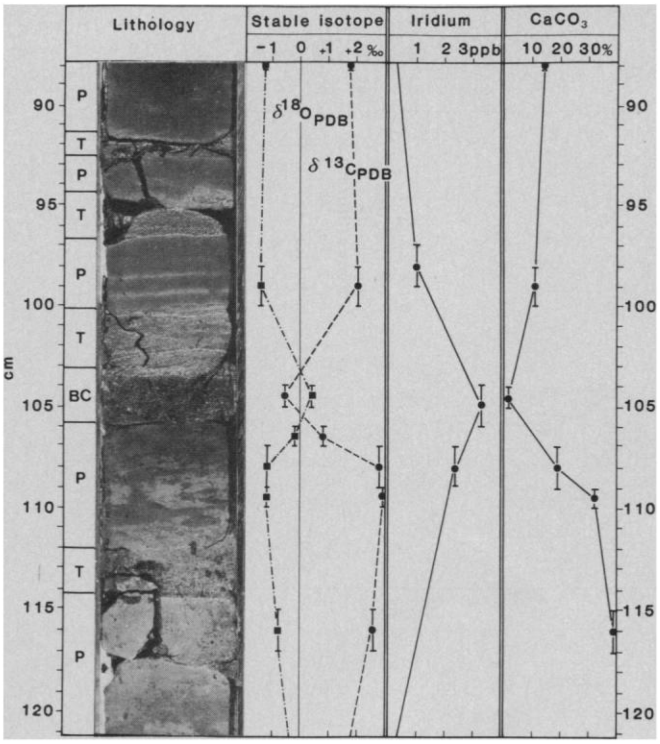

Fig. 4. Photograph of core 20, section 3, 88–120 cm (leg 73, site 524) showing the position of the C-T boundary clay and the location of the samples analyzed just above and below the boundary. Data for the corresponding stable isotope, iridium, and calcium carbonate (percentage by weight) are plotted alongside the core. Abbreviations: *T*, turbidite; *P*, pelagic sediment; *BC*, C-T boundary clay.

reasonable to assume that most of the Cretaceous species obtained their isotopic signals from the early Tertiary ocean which was beginning to show a depleted carbon-13 ratio resulting from decreased productivity.

Geochemistry of the oceans. The two carbon-isotopic anomalies recorded in both the fine and bulk fractions (Fig. 3) may, indeed, reflect one, if not two, drastic changes in the surface-water productivity. The existence of two carbon-13 anomalies, the first with a minimum at the C-T boundary and the second with a minimum at the beginning of the *G. pseudobulloides* zone, has been recorded in at least three other C-T boundary sections and will be discussed elsewhere (*23*). The isotopic data require a model that can explain: (i) the apparently sudden carbon isotope change in the C-T boundary clay, an expression of a temporary change in the carbon-isotope chemistry of the surface waters, and (ii) the more gradual, progressive change in the carbon-isotope chemistry occurring above the C-T boundary during an interval of 50,000 years or so.

The rapid decrease of $CaCO_3$ in the sediments immediately subjacent to the C-T boundary registers a sudden rise in lysocline and CCD at the end of the Cretaceous. This alone suggests a more acid ocean, or a drastic reduction in productivity, or both. By modeling the $CaCO_3$ sedimentation in lakes by photosynthetic plants, a good correlation between the chemistry of surface water and organic productivity has been obtained; the *p*H of lake water dropped sharply at night when photosynthesis was hindered or during the winter months or when the productivity was low (*24*). The $\delta^{13}C$ ratio of the dissolved bicarbonate in the surface water increased or decreased according to the magnitude of the productivity; this fluctuation results from the preferential utilization of CO_2 containing carbon-12 atoms during photosynthesis (*25*). At the end of the Cretaceous, a catastrophic reduction of the living planktonic biomass in the oceans and, hence, decreased productivity could account for a *p*H drop and a corresponding CCD rise and an alteration of the carbon isotopic composition of the total CO_2 in the surface waters.

The distribution of carbon-13 in the present Atlantic Ocean is well documented (*26–28*). In general, a depth profile of $\delta^{13}C$ shows that the surface waters are enriched in carbon-13 relative to the underlying waters at depths between 200 and 1000 m. These intermediate waters have relative $\delta^{13}C$ depletions of up to 2 per mil. The $\delta^{13}C$ profile usually parallels the distribution of dissolved O_2 leading to the interpretation that the $\delta^{13}C$ minimum is a result of oxidation of organic matter in situ. In fact, the $\delta^{13}C$ values of the intermediate waters can be accounted for by evaluating the combined input of carbon from the oxidation of organic matter (−23 per mil) and the dissolution of $CaCO_3$ (+2 per mil) (*27*).

Considering that the oxidation of organic matter in situ causes a $\delta^{13}C$ depletion of up to 2 per mil in intermediate waters, one could speculate on the consequence of oxidation of the organic material in the surface waters. A catastrophe, such as the near total mortality of all planktonic species, could produce a geologically short period of drastically reduced productivity accompanied by the oxidation of the organic matter in the surface water. In modern oceans, the $\delta^{13}C$ ratio of the total CO_2 in the surface water is controlled by an exchange with atmospheric CO_2 and by a balance between the amount of dissolved carbon removed from and returned to the system (*29*). If the rate of carbon removal approaches null, as proposed for the case of a catastrophic event, and all of the carbon fixed in the present biomass and the dissolved organic matter in the upper 100 m were oxidized, the $\delta^{13}C$ ratio of the dissolved inorganic carbon could decrease by as much as 1.8 per mil (*30*). With the restoration of normal rates of productivity, the combined factors controlling the $\delta^{13}C$ ratio of the surface water should allow the ratio to again return to the precatastrophic value.

Although the circulation patterns in the modern Atlantic Ocean are not comparable with those in the late Cretaceous ocean, the processes causing the fractionation of carbon isotopes should remain constant. On this actualistic basis, it is possible to interpret the significance of the two negative carbon-13 anomalies recorded in the isotopic stratigraphy of the C-T boundary section at site 524. In the 2 cm of red boundary clay, the first carbon-13 anomaly (−0.6 per mil) appears suddenly, but 5 cm above the $\delta^{13}C$ ratio returns to a positive value, which is slightly less than the pre-C-T boundary average (Figs. 3 and 4). In an expanded or more complete C-T boundary section from North Africa (*23*), this return to a positive $\delta^{13}C$ ratio is seen to be the end result of a series of transitional values. In the C-T boundary clay at site 524, this isotopic transition is obscured or lost because of the highly condensed nature of the sediment, whose 2 cm thickness could represent thousands of years. During this period, we propose that there was a rapid increase in the carbon-12 content of the surface waters, a consequence of the mass mortality which resulted in an imbalance in the quasi–steady state rate of carbon removed by photosynthesis compared to the rate returned by oxidation. After the first shock of the catastrophic event passed, the photosynthetic activity of the Cretaceous species partially recovered and the $\delta^{13}C$ value of the surface waters gradually increased as the rate of carbon removal compared to its rate of return approached a preboundary value. The recovery was short-lived and, at 0.1 m above the C-T boundary, the $\delta^{13}C$ ratio began steadily to decrease, reaching a minimum value at +1.5 m (Fig. 3). The region of declining $\delta^{13}C$ coincides exactly with the sediments of the transitional interval, where the percentage of Cretaceous nannofossils gradually diminishes and there is a second dramatic decrease in the percentage of $CaCO_3$. We propose that this second carbon-13 anomaly is, likewise, due to decreased surface water productivity. It was not a sudden change but occurred over a period of about 50,000 years and corresponded to the gradual extinction of the Cretaceous planktonic taxa. Later, as the new Tertiary species evolved and gained firm control of their environment, surface-water productivity increased, as shown by the steady increase in the $\delta^{13}C$ values and $CaCO_3$ contents. The nearly constant $\delta^{13}C$ value of *Gavelinella beccariiformis* throughout this period of carbon-13 oscillations indicates that the carbon-13 anomalies were surface-water phenomena not affecting the bottom waters. A return to late Cretaceous $\delta^{13}C$ values occurred about 350,000 years later than the C-T boundary and ostensibly denotes a return to late Cretaceous productivity rates.

Temperature variations. A long-term imbalance in the quasi–steady state removal and return of carbon to the surface waters not only affects the $\delta^{13}C$ contents of the total CO_2 but also its magnitude. The excess CO_2 in the surface waters that is not fixed during the period of reduced photosynthesis must eventually be transferred to the atmosphere. Modeling has indicated that a doubling of the CO_2 concentration in the atmosphere could have enough of a greenhouse effect to cause a global temperature increase of between 1.5° and 4°C (*31*).

Trends in the $\delta^{18}O$ data from site 524 are not as systematic as the changes in $\delta^{13}C$, but, on the average, the $\delta^{18}O$ in both the bulk and fine fractions is more negative above the C-T boundary than below. Considering the fine fraction carbonate as being more representative of surface water material, we calculate an average $\delta^{18}O$ difference between pre- and postboundary samples of 0.4 per mil, with a difference of 2.0 per mil between the extremes of the standard deviation. Assuming that a 0.2 per mil decrease in $\delta^{18}O$ represents a 1°C temperature increase, the data indicate at least a 2°C, possibly up to 10°C, warming of the surface water. However, if the $\delta^{18}O$ changes do, indeed, represent temperature variations, the isotope record indicates a possible cooling of about 8°C during the thousand years represented by the C-T boundary clay.

"Flash-heating" through atmospheric resistance to cometary fall has been postulated as a possible cause of a sudden temperature increase at the end of the Cretaceous (*15, 32, 33*). Instantaneous flash-heading may indeed have taken place, causing a mass mortality of living organisms in "disaster regions," but it could not have left a record. The warming trend shown by our isotope record could indicate a doubling to quadrupling of the atmospheric CO_2 in the earlier Tertiary atmosphere. We propose that temperature increases during the transitional interval above the C-T boundary resulted from a global warming caused by the greenhouse effect.

Mass Mortality and Its Environmental and Evolutionary Consequences

Our interpretations of catastrophic extinctions portray geologically instantaneous mass mortality and much reduced productivity causing immediate changes of the *p*H of the surface waters of the oceans. The more acid ocean waters caused a catastrophic rise of CCD, which led to widespread deposition of clays at the C-T boundary. The pelagic environments of the oceans were stressed so that the productivity of calcareous planktons remained low for many years and may have returned to normal only after some 50,000 years or so. Many species of calcareous planktons (greater than 90 percent) became extinct during this transitional period of environmental stress, but we do not rule out the possibility that the Cretaceous taxa in the lowermost Tertiary sediments include not only the last skeletons of the "endangered species" heading toward extinction, but also some skeletons of truly Cretaceous individuals reworked into the younger sediments.

The catastrophe seemed to have hit hardest the organisms living in equatorial surface currents of the Tethyan realm, as indicated by the pattern of selective extinction. The pelagic organisms became mostly extinct, whereas the benthic invertebrates which became extinct also seemed to have a pelagic larvae stage (*34*). The mass extinction of the tropical species created ecological niches, which were invaded by surviving species that had been more cosmopolitan or that had lived in high latitudes (*21*), such as the typically "Tertiary" species found in nannofossil zone NP-1. Tertiary planktonic foraminifera, *Globigerina eugubina*, had small tests, reduced to about one-tenth the size of the last Cretaceous species. Later Tertiary foraminiferal lineages have been traced to this primitive stock.

The reduction of productivity in the oceans led to an increase of CO_2 in the atmosphere, and the greenhouse effect resulted in a temperature increase in ocean waters. Presumably, the atmospheric temperatures must also have risen. The dinosaurs were vulnerable to thermal stress (*35*), and should have all perished if atmospheric temperature was increased by as much as 10°C (*36*). Although the dinosaurs may or may not have suffered mass mortality on land when the catastrophe occurred, the effect of a progressive global temperature increase, as suggested by our isotope record, should have led to the extinction of dinosaurs within 50,000 years of the terminal Cretaceous event. According to this interpretation, the last dinosaur may indeed have lived until the magnetostratigraphy chron C29N, as some vertebrate paleontologists believe (*37, 38*).

Cause of Mass Mortality

Our data suggest to us that the catastrophic environmental changes at the beginning of the Tertiary were the consequences of mass mortality in the oceans, not the causes. The finding of anomalous iridium contents at the C-T boundary in various regions, including areas of continental sedimentation (*39*), is good evidence that the mass mortality was related to the impact of a large extraterrestrial body from the solar system. Ratios of the various platinum-group metals in the boundary clay in Denmark further indicate the similarity of this body to carbonaceous chondrites (*40, 41*).

Various possibilities of mass mortality in connection with the impact of a large meteorite have been suggested. The dust from the ejecta may have prevented photosynthesis of plants, leading to starvation of animals all the way up the food chain (*9*). The meteorite may have been a comet containing cyanide which poisoned the marine planktons (*15*). Finally, the flash-heating of the atmosphere during the entry of a meteorite may have caused catastrophic extinctions (*11, 15, 32*). The second scenario for the initial mass mortality was preferred by K.J.H. because of the patterns of selective extinction. During a recent conference it was further pointed out (*42*) that heavy metals in the ejecta dust, such as osmium and arsenic, which have been found in anomalously high concentration in some boundary clays, may have been the chemical poison; such heavy metals are quickly precipitated in continental environments but may stay in ocean currents as chloride complexes to cause widespread damage (*42*). However, dust and heat are certainly contributing factors, if not alternative scenarios, which must be further explored.

Whether the fallen body was a meteorite or comet cannot be ascertained. The comet has been considered a heavenly broom collecting cosmic dust to form the nucleus of a "dirty snowball" or an "icy conglomerate" with a tail (*43*). The composition of such dust is very similar to that of carbonaceous chondrites (*44*). The boundary event may have been a super Tunguska event (*12, 15, 32*), as this event has been related to the fall of cometary materials (*45*). The comet scenario was previously preferred by K.J.H. because cyanide could be brought in by a comet to pollute the surface currents of the oceans. However, a heavy-metal poisoning could have been caused by the ejecta from an asteroid as well as from a comet.

Skeptics have objected to the hypothesis of meteorite impact with the argument that no terminal Cretaceous craters are known. In fact, two impact craters of such age have been found in southern Russia (48°N, 40°E). The Kamensk crater has a diameter of 25 kilometers and the Gusev a little to the northeast has a diameter of 3 km. Both have impact breccias including fragments of fossiliferous Cretaceous sediments, and both are overlain by lowermost Tertiary marine sediments (*46*). More recently, a large crater 60 km in diameter was found at Karsk in Siberia, 69°N, 65°E, and the age was given as 60 ± 5 million years (*47*). Future investigations may yield clues if these craters were indeed produced by a terminal Cretaceous event.

Our scenario postulates that the catastrophic near-extinction of the marine planktons was the consequence of the mass mortality in the surface waters of the oceans, and the dinosaurs became distinct because of thermal stress after a terminal Cretaceous catastrophe. The extinction took place within a few tens of thousands of years after the event. The Darwinian evolution mechanism of survival of the fittest in a stressed environment may well have been operating. However, the critical environmental changes that necessitated the struggle for existence were, in our opinion, caused by a chance collision. At another time, another chance collision may have led to a different set of environmental changes such as the drastic decrease of temperature after a terminal Eocene event (*15*) and a different kind of evolutionary response. Has chance, then, played a more important role in evolution than commonly envisioned?

References and Notes

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30. If we assume that the average depth of the world's oceans is 4 km and the surface waters comprise the upper 0.1 km, we are discussing 2.5 percent of the ocean water. The carbon content of the following reservoirs are: marine biosphere, 7×10^{15} g; dead marine organic matter, 3000×10^{15} g; and dissolved in seawater, $40,000 \times 10^{15}$ g. If for a geologic instant surface water productivity stopped and we proceeded to oxidize all of the organic matter in the surface water, which is taken to be equal to all of the marine biosphere plus 2.5 percent of the dead marine organic matter, we add about 82×10^{15} g of carbon to the dissolved carbon already in the surface waters ($0.025 \times 40,000 \times 10^{15}$ g = 1000×10^{15} g). This rough estimation increases the amount of dissolved carbon in the surface waters by 8 percent. If the newly dissolved carbon has a $\delta^{13}C$ ratio of −23 per mil, the surface waters would have a $\delta^{13}C$ ratio depleted by −1.8 per mil. The data pertaining to the carbon reservoirs are taken from table 6–7 in H. D. Holland, *The Chemistry of the Atmosphere and Oceans* (Wiley, New York, 1978).
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