36. A SCENARIO FOR THE TERMINAL CRETACEOUS EVENT[1]

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ABSTRACT

Geochemical anomalies near the Cretaceous/Tertiary boundary in sediments from Site 524 include (1) a decrease in carbonate content from 40% in the upper Maestrichtian to ~2% in the earliest Tertiary boundary clay, (2) an anomalous concentration of iridium in the boundary clay (maximum: 3.3 ppb), (3) an anomalous drop of about −3‰ in the $\delta^{13}C$ values for the boundary clay and a subsequent anomalous peak in a sediment some 40,000 yr. younger, (4) oxygen-isotope shifts indicative of an immediate (10^2 yr.) cooling and a subsequent (10^4 yr.) warming trend. A nannoplankton extinction seems to have taken place during the 40,000 yr. of rapid environmental change.

If a large extraterrestrial body hit the Earth, the immediate consequences should be to cause (1) high-temperature shock waves in the atmosphere, (2) ground disturbances, (3) oxidation of the nitrogen in the Earth's atmosphere, (4) ozone depletion, (5) chemical pollution, and (6) the ejection of dust into the stratosphere. The data from Site 524 are consistent with the postulate of a mass mortality of plankton in the oceans, of large reptiles on land, and widespread deforestation. The long-term (10^4 yr.) environmental consequences should include changes in the CO_2 content of the oceans and warming due to increased CO_2 in the atmosphere and the greenhouse effect. The data from Site 524 suggest that those kinds of environmental stresses were the cause of the mass extinction during the first 30,000 or 50,000 yr. of the Tertiary.

INTRODUCTION

The rapidly deposited sediments at Site 524 provide an amplified record of the environmental and biostratigraphic changes that took place at the beginning of the Cenozoic. As discussed in Hsü et al. (1982), many of the Cretaceous pelagic organisms do not appear to have become extinct instantly; instead, they seem to have died out over a period of 10^4 yr. Geochemical anomalies in the earliest Tertiary sediments deposited at this site indicate that significant changes took place in the chemistry and temperature of the oceans. The impact of a comet at the end of the Cretaceous may have caused a mass mortality, but it was environmental stress that led to the mass extinction of plankton in the oceans and large animals on land during the first few tens of thousands of years of the Tertiary.

These data and conclusions are already published (Hsü et al., 1982), and it is superfluous to write another article covering the same ground. However, the article published, which was co-authored by the Shipboard Scientific Staff and a team of my associates in Switzerland, necessarily represented the consensus of 20 people. Writing a chapter in this volume offers the opportunity to air more provocative views without the need to compromise or to seek consensus. In this article I shall use deductive reasoning or an approach called modeling, a methodology often attempted in the physical sciences but usually neglected by geologists. I shall start with the premise that there was a large-body impact at the end of Cretaceous and that the bolide probably fell in southern Russia. I shall then determine whether our findings at Site 524, which are summarized graphically in Figures 1 and 2, are consistent with this hypothesis.

[1] Hsü, K. J., LaBrecque, J. L., et al., *Init. Repts. DSDP*, 73: Washington (U.S. Govt. Printing Office). Contribution No. 215 of the Laboratory of Experimental Geology.

DIRECT CONSEQUENCES

Three types of evidence support the hypothesis that a large comet or asteroid hit the Earth at the end of the Cretaceous, namely:

1) The presence of an anomalous concentration of iridium, osmium, and other siderophile elements, in proportions similar to those in chondritic meteorites, in a Cretaceous/Tertiary (C/T) boundary clay (Alvarez et al., 1980; Smit and Hertogen, 1980; Kyte et al., 1980; Ganapathy, 1980; Orth et al., 1981; Hsü et al., 1982).

2) The presence of geochemical or sedimentological anomalies in the earliest Tertiary sediments that are indicative of environmental changes too sudden to be accounted for by normally operating terrestrial processes (e.g., Hsü, 1980 and 1981; Hsü et al., 1982).

3) A record of biological extinction that shows a rate much faster than that in normal evolutionary development (Smit and Hertogen, 1980; Emiliani et al., 1981; Russell, 1979; Russell and Rice, 1981).

In a conference held in 1981 at Snowbird, Utah, physicists and space scientists evaluated the probability of the impact of a large (10^{17}–10^{18} g) body, and they suggested a number of the direct and indirect consequences for the oceans and atmosphere (after the impact). These subjects are discussed in the following sections.

Probability of Large-Body Impacts and Possible Terminal Cretaceous Impact Sites

The characteristics of impact craters on Earth indicate that the frequency of meteor impact is inversely proportional to the size of the crater, which in turn is related to the size of the bolide. An empirical relationship suggests that the probability that a bolide with a mass of 10^{18} g will hit the Earth is about 10^{-8} per year (Hsü, 1980; Emiliani et al., 1981). Given enough time, however, a rare event is bound to happen. Gretener (1967)

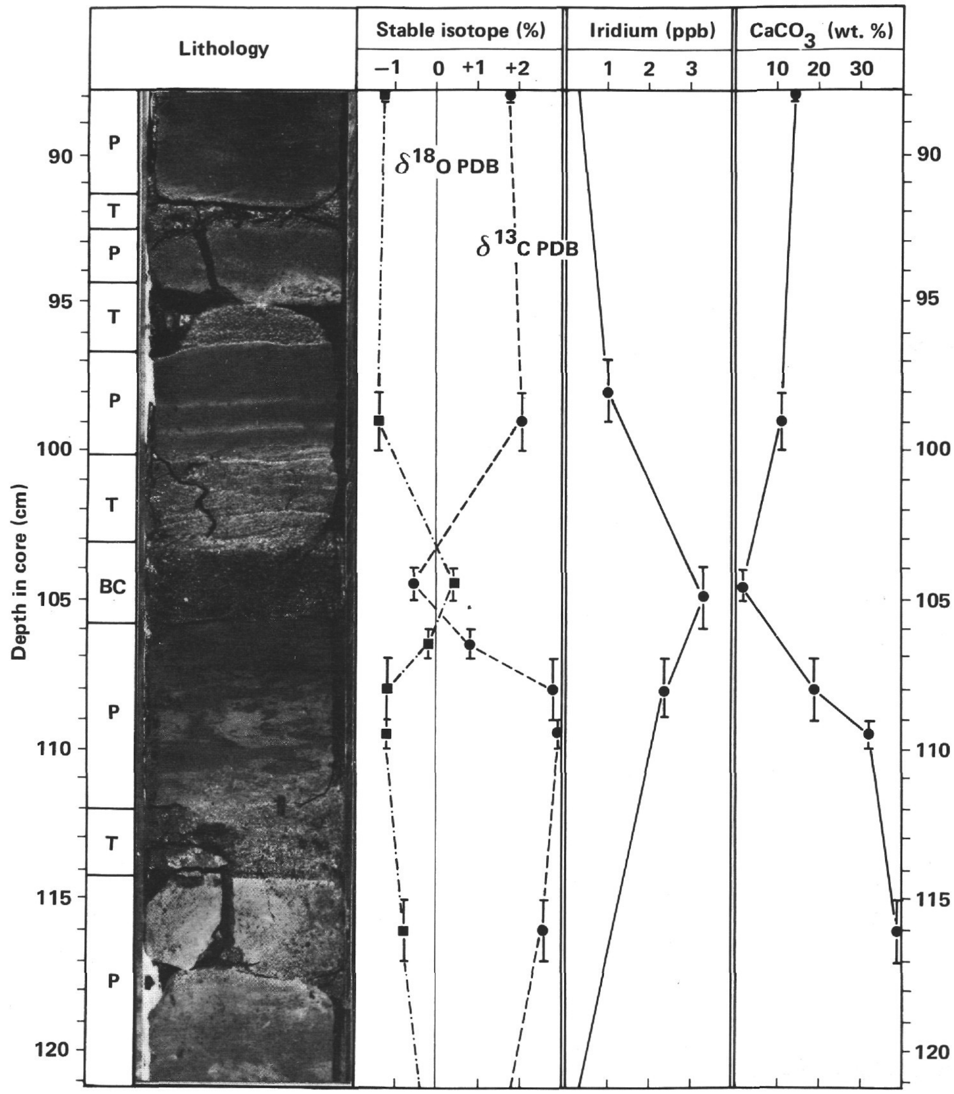

Figure 1. Photograph of 524-20-3, 88–120 cm showing the position of the C/T boundary clay and the location of the samples analyzed just above and below the boundary. The corresponding stable-isotope, iridium, and calcium carbonate data are graphed alongside the core. T denotes turbidite, P pelagic sediment, BC Cretaceous/Tertiary boundary clay.

showed that an event with an yearly occurrence probability of 10^{-8} has a statistical probability of happening at least once in 300 m.y. In other words, we are almost certain that a body with a mass of 10^{18} g has hit the Earth once or twice during the 600 m.y. since the beginning of the Phanerozoic. For convenience, we follow O'Keefe and Ahrens' (1982) usage and call such a large extraterrestrial body an extinction bolide because of the evolutionary consequences of its impact on Earth.

An extinction bolide should excavate a crater 100 to 200 km in diameter. We know of no crater of that size of terminal Cretaceous age. Five impact craters have ages that are close enough to be considered terminal Cretaceous (Grieve, 1981). The largest, at Karsk in northern Siberia, is 60 km across, but it seems too young in age (60 ± 5 m.y.). Two smaller craters in southern Russia, at Kamensk (25 km) and at Gusev (3 km) are more likely candidates: the impact breccias include fragments bearing fossils of Late Cretaceous age, and the breccias are overlain by early Danian marine sediments. Masaytis (1976) gives the terminal Cretaceous age of 65 m.y. to both craters. Their sizes are much smaller than predicted (one and two orders of magnitude respectively), but we should probably not rule out these two impact sites, because the size of an impact crater depends upon the amount of kinetic energy coupled to cratering. If the bolide was cometary with a small bulk density, less than 10% of the kinetic energy of this low-density projectile would be expended on cratering; most of the energy should be transported upward into the atmosphere by a plume of ejecta (Orphal et al., 1981). Furthermore, a cometary body may disintegrate upon atmospheric entry, and the multiple craters created by its broken fragments would be much smaller than the single crater excavated by a solid asteroid. This line of reasoning led me to adopt a working hypothesis that the twin craters in

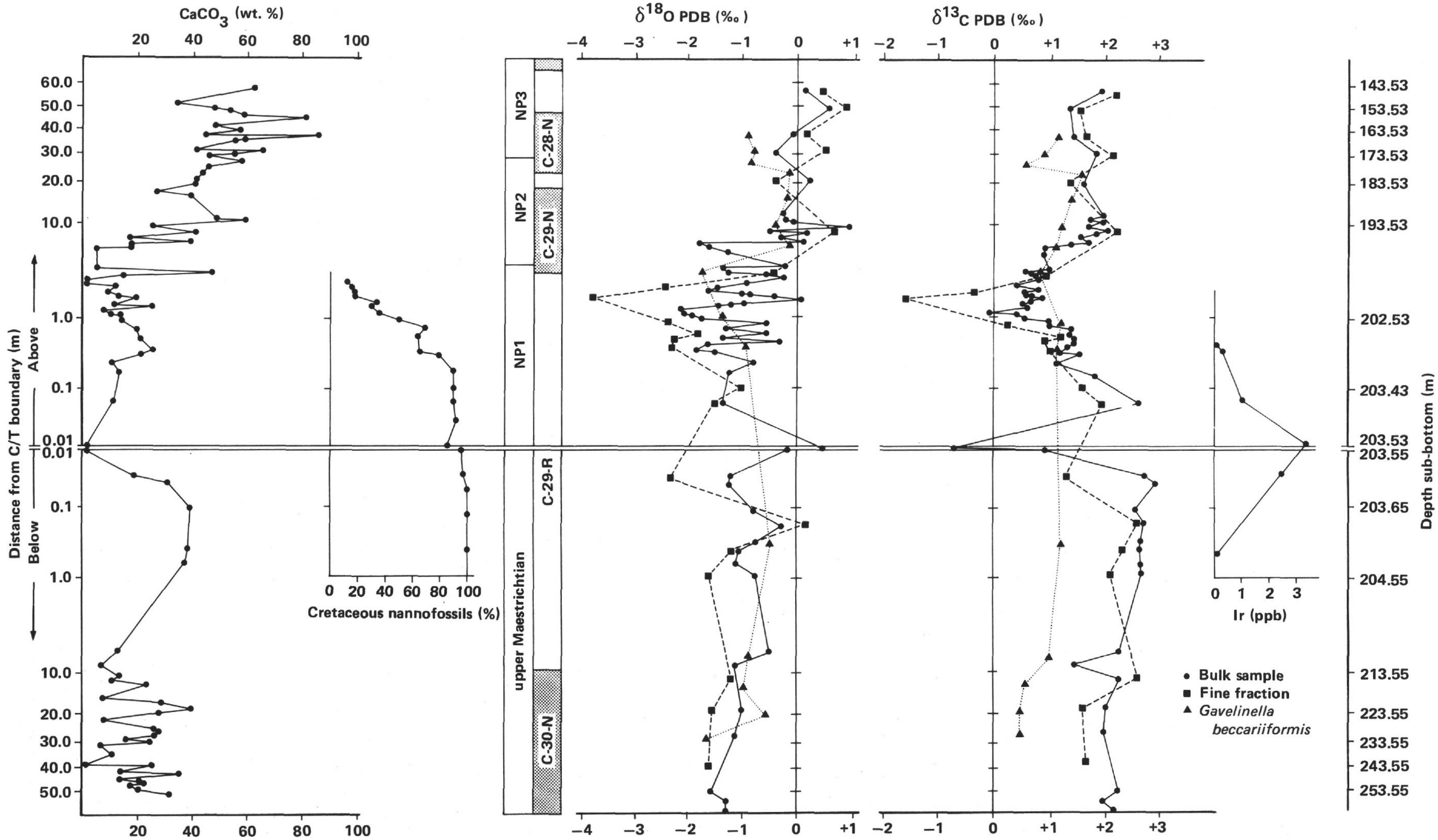

Figure 2. Variations in $CaCO_3$; percentages of Cretaceous taxa; $\delta^{18}O$ and $\delta^{13}C$ in bulk samples, fine fractions and *Gavelinella beccariiformis;* and iridium content across the Cretaceous/Tertiary boundary at DSDP Site 524. Also shown are paleontological zonations (NP1, etc.) and magnetostratigraphic chrons (C-28, C-29, etc.). A logarithmic scale is used to amplify the details near the C/T boundary.

southern Russia mark the impact of two fragments of the terminal Cretaceous extinction bolide. Such a hypothesis is, as will be shown later, consistent with many of the facts known about the terminal Cretaceous event. Whether the larger crater at Karsk represents still another fragment of the same fallen comet is questionable, because the parts of a disintegrated bolide should not become very widely dispersed (W. Melosh, pers. comm., 1981).

Impact Ejecta Fallout

The boundary clay at Stevns Klint in Denmark and at DSDP Site 456 in the North Pacific probably consists mostly of ejecta fallout. The anomalous iridium concentration (up to 30 ppb) suggests that the extraterrestrial component (ETC) in the fallout may be as high as 20% (Kyte et al., 1980). Fallout much enriched in ETC should represent the prompt ejecta that circulated latitudinally (O'Keefe and Ahrens, 1982). The boundary clay at those localities consists of pure clay minerals devoid of other detrital components; Kästner (pers. comm., 1982) concluded that the clays are devitrified glass, which may have derived from the cooling of vaporized ejecta. Smit and Klauer (1981) found millimeter-sized chondrule-like spherules in the boundary clay of Caravacas, Spain; they consist of a high-temperature sanidine, which may have crystallized rapidly from vaporized ejecta. Similar spherules have been found in the C/T boundary clay of northern Italy (Castellarin et al., 1974) and Tunesia (Perch-Nielsen, pers. comm., 1982). The size of the spherules is of the order of 10^2 μm, or about the maximum stable diameter of a vaporized ejecta droplet (see O'Keefe and Ahrens, 1982). Such spherules are too large to stay in the stratosphere long enough for global distribution.

An iridium concentration of 3.3 ppb, about an order of magnitude less than the maximum observed in the Northern Hemisphere, was found in the terminal Cretaceous boundary clay at Site 524 (Krähenbühl, in Hsü et al., 1982). In addition, our boundary layer clay sample consists of a mixture of detrital clay minerals not significantly different from the clays immediately above and below (Karpov, in Hsü et al., 1982). Apparently the component of ejecta fallout has been much diluted by detrital clays at this Southern Hemisphere site. The low percentages of ETC are consistent with an assumption of an impact in southern Russia: the ETC-enriched fallout has been distributed latitudinally to sites at high northern latitudes only, and neither a rich iridium anomaly nor sanidine spherules have been reported from any Southern Hemisphere site except one in New Zealand (Alvarez et al., 1980).

Ground Disturbance after Impact

Much publicity has been given to the idea that tidal waves up to 8 km high would have formed if the extinction bolide had fallen into the ocean. Hard grounds, representing slow or nondeposition, are common at numerous localities on land (Novbakht, 1973). They indicate erosion and diagenesis by bottom currents, but such minor disconformities are hardly evidence for 8-km tidal waves. The absence of large tsunami effects argues against an oceanic impact but does not contradict my hypothesis of impact on land in Russia.

The kinetic energy of a 1-trillion-ton comet hitting the Earth at 45 km/s should be 10^{31} ergs. Even if only 10% were coupled to the target, the impact energy would be equivalent to an earthquake of magnitude 12.4. The shaking of the ground should induce large-scale slumping and resedimentation. Submarine slumping deposits are generally absent directly above the C/T contact but have been reported at the base of the Paleocene in northern Italy (Novbakht, 1973). At Site 524, however, the sediment immediately above the contact is a pelagic red clay; the first Paleocene turbidite is present some 2 cm above the contact and was laid down about 1000 yr. after the boundary event. Our South Atlantic site may have been too far away from the postulated impact site in Russia for the effects of ground shaking to be recorded.

Temperature and Pressure Effects of the Blast

Friction upon atmospheric entry could dissipate little of the kinetic energy of an extinction bolide. The energy transfer would take place upon impact with the Earth. The plume of ejecta would rise as a mushroom cloud above the impact site; the temperature inside the plume could be as high as 10^5 degrees (Jones et al., 1981). If the energy were then distributed globally, the atmospheric temperatures would rise 20°C for several days (O'Keefe and Ahrens, 1982).

The blast should ravage the flora and fauna near the impact site. Trees around the site of the 1908 Tunguska Event were uprooted and partly burned by the blast. The damage due to the postulated terminal Cretaceous impact should have been far greater, inasmuch as the bolide should have had a mass 1 million times as large as the meteor at Tunguska. However, the destruction of all life in a single geographic region would only cause the extinction of species confined to the affected region. The biogeographical distribution of the modern world, for example, is such that the extinction rate for terrestrial families and marine genera would be only about 2%, even if the lethal radius were as large as 5,000 km (Raup, 1981). A giant blast would undoubtedly have killed many living organisms, but the direct consequences for biologic extinction should have been negligible.

Effects of Impact on Atmospheric Mass and Composition

An impact with energy on the order of 10^{28} to 10^{32} ergs will remove part of the Earth's atmosphere (Lewis et al., 1982). A more serious effect of the blast is, however, to produce NO_x from a combination of atmospheric nitrogen and oxygen. Turco et al. (1981) estimated that up to 45% of the ozone in the Northern Hemisphere may have been depleted by a nitric oxide cloud after the giant meteor fall of 1908 at Tunguska. The much larger terminal Cretaceous impact could have destroyed the global ozone layer completely for a decade or so (O'Keefe and Ahrens, 1982). The immediate effect of a manifold increase in ultraviolet radiation (UV-B) after such a catastrophe would be to destroy plants and microorganisms sensitive to such radiation (Nier et al., 1975), and the long-term effect would be to induce genetic mutations.

We are uncertain whether an overdose of UV-B was the primary cause of the mass mortality manifested by the large carbon-isotope anomaly in the boundary clay at Site 524. We do, however, have good evidence of mass extinction and of rapidly evolving new species during the first million years of the Tertiary (Perch-Nielsen et al., 1982); the accelerated rate of evolution could well be related to a higher mutation rate due to the exposure of terrestrial organisms to intense UV-B radiation.

The N_2O formed by high-temperature shock waves after impact is an effective defoliant (Lewis et al., 1982). I believe that the production of this toxic substance may have been responsible for the destruction of the Cretaceous *Aquilapollenites* flora of Siberia and western North America; if carried downwind from the impact site in Russia, the chemical pollution should have seriously affected the forest in those northern provinces. The trees may have recovered eventually because of the long dormancy period of their seeds, but the *Aquilapollenites* spp., which are believed to be parasitic (Russell and Rice, 1981, p. 108), became extinct; they, like most parasites, would cease to reproduce if they could not find the host needed for their survival.

Pirozynski (in Russell and Rice, 1981) suggested that chemical pollutants may also have reduced the population of insects at the beginning of the Tertiary. Pollinating insects would be unable to survive if flower production halted for 2 years after the catastrophe. If insects became scarce or extinct, wind would become the dominant pollinating mechanism. Jarzen (in Russell and Rice, 1981, p. 120) found indeed a general trend toward more wind-pollinated and fewer insect-pollinated plants across the C/T boundary.

The tree-pollen/fern-spore ratio in the sediments of the southwestern United States decreased suddenly at the C/T boundary (Fassett, 1981). We may extrapolate from this evidence of local forest devastation a global reduction of the terrestrial biomass. The consequent increase of particulate carbon in the influx into the oceans should have changed the carbon-isotope composition of the carbonates dissolved in the ocean waters, and this change may account, in part, for the large negative $\delta^{13}C$ anomaly in the C/T boundary sediments (see Herman, 1981).

Chemical Pollution of the Oceans

Spectral analyses have shown that the nucleus of a comet is an icy solid containing CN, CO, CH, NH, OH, and other radicals (see Hsü, 1980). Cyanide is a powerful poison that arrests cellular respiration by inactivating metalloenzymes in the respiratory process (De Brune, 1976). Inasmuch as this process is fundamental to all living beings, cyanide poisoning could kill all kinds of organisms. However, O'Keefe and Ahrens (1982) believed that the shock pressure and the internal energy densities in a cometary bolide should decompose and detoxify cometary cyanides.

Heavy metals constitute another source of chemical pollutants. Osmium, ruthenium, arsenic, and nickel are all toxic and have been found in unusual abundance in the C/T boundary clay (Smit, in Russell and Rice, 1981). In ocean waters osmium and ruthenium form soluble compounds, such as chlorides or aminochlorides, and these highly toxic substances can elicit physiological responses at concentrations as low as 10^{-9} g/ml (Feldman, in Russell and Rice, 1981). If the osmium was evenly distributed in the ocean waters, the toxins may have been harmless, because the chemistry of the C/T boundary clay indicates a dissolved osmium content about four orders of magnitude less than the critical concentration. However, the soluble toxins may have been concentrated locally in the uppermost part of some surface currents, where they could have been toxic enough to be lethal to marine plankton. The poisonous heavy metals could then be recycled up the food chain and have done widespread damage before they were finally diluted or precipitated. In continental environments, the toxic heavy metals should have been quickly precipitated as carbonates or other insoluble compounds, so their toxicity may have been buried in soil before much damage was done (Feldman, pers. comm., 1981). Differences in the chemistry and distribution of the toxins may thus provide an explanation for the selective destruction at the end of Cretaceous. Marine plankton of Tethyan equatorial waters were almost all destroyed, whereas land invertebrates largely escaped.

The immediate effect of chemical pollution was mass mortality, but the decimation of marine plankton and the subsequent suppression of its reproduction may have resulted in significant changes in ocean chemistry, resulting in the enhanced dissolution of calcareous skeletons and in a large carbon-isotope shift. Both of these effects are recorded in the boundary clay at Site 524 (Hsü et al., 1982). The catastrophic mortality and the resulting mass of organic debris may also have seriously depleted the oxygen dissolved in the intermediate waters, causing an expansion of the minimum-oxygen zone. Where the terminal Cretaceous seafloor was hundreds of meters deep, as it was at some localities on land and at DSDP Site 465, the boundary shales are dark gray or black and are finely laminated, characteristics indicative of deposition under anoxic conditions. At Site 524 and several other deep-sea sites, however, no anoxic sediment is present across the C/T boundary; the oxygenated condition at our site is indicated by the dark reddish brown color of the boundary clay there.

Ejecta Dust Cloud

The flow fields induced by the impact of comets or asteroids on the Earth can inject matter of about 10 to 10^2 times the bolide mass into the atmosphere. In the case of the ocean impact, water masses of from 10 to 10^2 times the bolide mass are also injected. The initial high-speed ejecta are enriched in ETC in concentration ranges similar to those measured in C/T boundary clay (see Alvarez et al., 1980; Kyte et al., 1980; O'Keefe and Ahrens, 1982). The ejected materials, consisting of condensed vapor, melt, and fine materials, should have been lofted up to heights of more than 10 km. Stratospheric aerosol with a mass of 10^{16} would reduce terrestrial photosynthesis by a factor of 10^{-3} to 10^{-6}.

Phytoplankton cease to reproduce at the depth in the sea where sunlight is 10^{-2} that at surface levels. The postulated mass of dust, if airborne long enough, could kill off the phytoplankton and cause the food chain to collapse. Milne and McKay (1981) estimated that a 1-mo. blackout could initiate a collapse of the food chain in the tropics and that a year-long blackout could exterminate marine life totally.

Since marine life was not totally exterminated, it is safe to assume that the global blackout, if there was one, did not last for several years, as Alvarez et al. (1980) first proposed. Toon et al. (1981) suggested that the ejecta dust probably remained in the atmosphere only 3 to 5 mo., because physical processes of coagulation would cause micrometer-sized particles to form and to settle from the atmosphere. In fact our record at Site 524 indicated that most nannoplankton did not become extinct immediately after the postulated impact event (Perch-Nielsen in Hsü et al., 1982). Obviously, if there was a blackout, it was neither long enough nor global enough to cause the immediate extermination of all marine plankton.

It is questionable whether a global blackout existed at all, because the necessary residence time for the ejecta in the upper atmosphere is incompatible with the size of the particles and the physical processes of coagulation. For the ejecta to become globally distributed, they would have to remain in the upper atmosphere more than several months. To remain that long the particles would have to be 1 μm or less in size (O'Keefe and Ahrens, 1982). However, coagulation processes should have eliminated much of such fine dust during a few months. Therefore, the amount of fine dust in the upper atmosphere may never have been sufficient to cause a total global blackout. A partial blackout could not have led to total extinction, but it could have contributed to a mass mortality and to low fertility in photosynthetic organisms. The carbon-isotope anomaly of $-3‰$ in the skeletons in the boundary clay records the scarcity of marine plankton in the oceans immediately after the postulated impact event, although we cannot be certain whether a blackout or chemical pollution was the primary cause.

A latitudinally confined partial blackout may explain the pattern of plant extinction noted by Hickey (1981), who found generally high levels of floral survival from high-southern to mid-northern paleolatitudes; those regions should have lain outside the belt of latitudinally distributed ejecta dust, if the target site was indeed in southern Russia.

Since a total blackout, even if there was one, cannot have lasted longer than 1 yr., it cannot have been the primary cause of those geochemical anomalies, nor of those biological extinctions, that took place long after the first year of the bolide fall. Thus, the mass extinction of the Cretaceous nannoplankton and the oxygen- and the carbon-isotope anomalies in the sediments above the boundary clay have to be explained in terms of more long-lasting environmental changes during the subsequent 10^4 yr., as proposed in Hsü et al. (1982).

INDIRECT CONSEQUENCES

The impact energy of 10^{31} ergs is equivalent to 250 million megatons, or 0.5 megaton per square kilometer if the energy were evenly distributed over the surface of the globe. One could well imagine the devastated land- and seascape after the impact of such a large body. If the extinction bolide fell at high latitudes during the winter period of dormancy, the damage to vegetation could be less than catastrophic, and the recovery might begin the following spring, when the sky had cleared up. If the bolide came on a spring or summer day, the damage resulting from a partial blackout would have been far more extensive and the recovery more delayed. In either case, the living biomass should have been much reduced for years after the extinction bolide hit. The changes in climate due to the ejecta and the changes in environment due to the mass mortality and low fertility should have been directly responsible for the accelerated extinction rate during the earliest Tertiary.

Reduced Fertility and Carbon-Isotope Fractionation

A sharp perturbation of $-3‰$ in $\delta^{13}C$, as recorded by the boundary clay, is an indication of the immediate mass mortality of marine plankton (Hsü et al., 1982); the enrichment of $\delta^{13}C$ in surface waters stopped when organisms were no longer there to preferentially utilize the light carbon.

A long-term (10^{-4}-yr.) effect on the carbon-isotope budget was produced because of changes in CO_2 fluxes. A simplification of the CO_2-flux model suggested by Pytkowicz (1973) is shown in Figure 3. In this model, the total number of carbon atoms in the oceans and in the atmosphere remain constant. The land loses carbon to the sea and gains carbon from the air; the ocean bottom receives carbon through sedimentation. The land delivers light carbon (atoms enriched in ^{12}C) to the sea and gains light carbon from the atmosphere. The excess light carbon received by the ocean is largely returned to

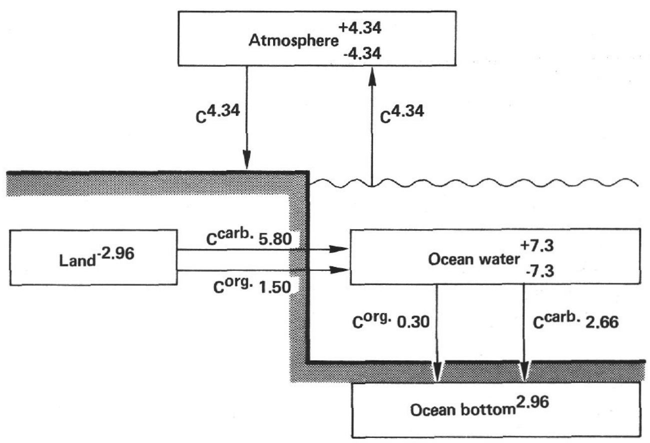

Figure 3. Carbon flux cycles. Numbers indicate 10^{14} grams carbon atoms (simplified after Pytkowicz, 1973).

the atmosphere, because the amount of excess ^{13}C atoms deposited in calcareous skeletons is about the same as that of deficient ^{13}C atoms in the organic carbon of the sediments (see Table 1).

The steady-state carbon flux must have been completely interrupted by the postulated impact event. Reduced photosynthesis on land and in the oceans required less input of light carbon atoms from the atmosphere, but a river flux depleted in organic material would also deliver fewer light carbon atoms. We have no way to estimate the path of fractionation in the land–ocean–atmosphere carbon cycle, but an excess of ^{13}C atoms in ocean waters may have resulted because of the unusual ocean–sediment exchange. The expansion of the minimum-oxygen zone prolongs the preservation of organic matter with an excess of ^{12}C, and a more acid ocean favors the dissolution of calcareous skeletons, releasing more than usual ^{13}C. We noted a sharp increase of ^{13}C in the sediment deposited a few thousand years after the beginning of the Tertiary. The shift of more than +2‰ that occured after the initial shift of −3‰ during the deposition of the boundary clay probably resulted from the intense ocean bottom dissolution of calcareous skeletons.

If the reduction of ocean fertility continued, and if the oxidation of organic carbon in seawater should become the dominant process, the carbon-isotope fractionation path should then reverse itself and the seawater should again become enriched in ^{12}C. McKenzie (in Hsü et al., 1982) estimated that an 1.8‰ decrease of $\delta^{13}C$ could result if the biomass and the dissolved organic matter in 100 m of seawater were all oxidized. We believe this mechanism explains the systematic negative shift of $\delta^{13}C$ in the sequence deposited during the time interval in which the Cretaceous nannoplankton died out. This second negative anomaly reached a maximum of −2 to −3‰ some 40,000 yr. after the boundary event. As a new Tertiary microfauna and nannoflora evolved, the fertility of the ocean returned gradually to normal; the sediments deposited a few hundred thousand years after the end of the Cretaceous again have isotope signals and carbonate contents similar to those that prevailed during the Late Cretaceous.

Climatic Changes

The envelope of ejecta around the Earth after an impact should intercept solar radiation and could result in a considerable cooling of the troposphere and of the oceans (O'Keefe and Ahrens, 1982). On the other hand, if the impact was oceanic, the large amount of water injected into the stratosphere would wash out the dust in a few weeks or months. The remaining vapor would then create a greenhouse effect and raise global surface temperatures for several years (Emiliani et al., 1981).

A longer term (10^3–10^4 yr.) greenhouse effect could have resulted from an increase in atmospheric CO_2. The present ocean surface water, with which the atmosphere is equilibrated, has a p_{CO_2}, or CO_2 content, of 300×10^{-6} atm. This is, however, only a third as much as would be attained if deep water were brought to the surface and warmed isochemically to 20°C, releasing CO_2 into the atmosphere (see Broecker, 1982). The discrepancy is a consequence of the steady-state p_{CO_2} reduction that results from photosynthesis by marine plankton. We explain the negative carbon-isotope shift in the earliest Tertiary by postulating a reduction of ocean fertility and the oxidation of dissolved organic matter in the upper water column. A corollary of these circumstancs is a substantial increase of dissolved CO_2 in ocean surface waters. Equilibrium exchanges between the oceans and the atmosphere would lead to a corresponding increase of the CO_2 content of the atmosphere. Studies of ice cores have found a correlation between global temperatures and atmospheric CO_2 content (Delmas et al., 1980; Berner et al., 1980). Modeling studies predict a temperature rise of 2 to 3° if the level of atmospheric CO_2 is doubled (Wigley and Jones, 1981) and a temperature rise of 5 to 10° if the level of atmospheric CO_2 is tripled.

The temperature recorded by the skeletons of marine plankton in the boundary clay at Site 524 did indicate a cooling of 8°C as the "short-term" (10^0–10^2 yr.) response to the impact; the flash heating immediately after the impact was too brief in duration to be recorded in the sediments. The cooling supports the idea of solar insulation by ejecta dust in the stratosphere after an impact on land; there was no evidence of immediate (10^0 yr.) warming by a greenhouse effect due to stratospheric water vapor, which Emiliani et al. (1981) suggested would take place after an ocean impact. The insulation by stratospheric dust could not have lasted very long, and the "long-term" effect (10^3–10^4 yr.) was a temperature rise. The sample from a sediment deposited 10^3 yr. after the event has an oxygen-isotope value about the same as that of the last Cretaceous sediment. Then the paleotemperatures oscillated, with an overall warming trend during the next 40,000 yr. The $\delta^{18}O$ anomalies correspond to temperatures 2° to 10°C higher than prevailed during the terminal Cretaceous. An increase of ocean bottom temperatures by a few degrees is indicated by the isotope values of benthic foraminifers at Site 524 (Hsü et al., 1982). Preliminary studies from several other DSDP sites have yielded oxygen-isotope shifts at rates and with magnitudes similar to those found here (e.g., Boersma et al., 1979). It seems safe to conclude that the warming of the ocean waters during the first 30 or 50 thousand years of the Tertiary was global in extent, as one might expect from an increase of atmospheric CO_2.

Table 1. Distribution of ^{13}C atoms in carbon cycles (units in 10^{17} g carbon atoms).

Total dissolved inorganic carbon in seawater	380
Total ^{13}C in dissolved inorganic carbon in seawater	+4.2
Excess ^{13}C deposited per yr. in calcareous sediment with $\delta^{13}C$ of +2 ‰	$+5.3 \times 10^{-6}$
Excess ^{13}C deposited per yr. in organic sediment with $\delta^{13}C$ of −25 ‰	-7.5×10^{-6}
Excess ^{13}C brought per yr. by river to oceans	-1.1×10^{-4}
Excess ^{13}C gain per yr. by terrestrial biomass	-1.1×10^{-4}

SUMMARY

Inductive reasoning was used to formulate the hypothesis of a terminal Cretaceous large-body impact (Alvarez et al., 1980; Hsü, 1980; Smit and Hertogen, 1980). Terminal Cretaceous craters, though smaller than predicted, are present in Russia (Masaytis, 1977). By using experimental and computer-modeling approaches, the direct consequences of such an impact for the physical world were formulated (see Emiliani et al., 1981; Lewis et al., 1981; and O'Keefe and Ahrens, 1982, among others). Our studies of Site 524 cores gave support to the impact hypothesis (Hsü et al., 1982). The purpose of this article is to use deductive reasoning to discuss the geological record that should be left behind by a large cometary impact and to determine whether the record at Site 524 and that at other localities on land and in the deep sea are in agreement with such a theoretically derived model.

The geochemical anomalies in the boundary clay at Site 524 indicate that mass mortality, global cooling, and ocean bottom dissolution were the more immediate consequences of a large-body impact. The isotope signals further indicate that reduced fertility and global warming were among the "long-term" (10^3–10^4 yr.) consequences. Finally, the stratigraphic records at Site 524 suggest that nannoplankton did not become extinct instantly (10^0 yr.); the marine plankton died off gradually during the first 30,000 or 50,000 yr. of the Tertiary because of environmental stress induced indirectly by the impact of an extinction bolide.

REFERENCES

[The Snowbird Conference refers to the Conference on Large Body Impacts and Terrestrial Evolution: Geological, Climatological and Biological Implications, which was held at Snowbird, Utah, Oct. 19–22, 1981. Abstracts of the papers presented were published by the Lunar and Planetary Institute, Houston, Texas.]

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Date of Initial Receipt: October 26, 1982