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Sudden death at the end of the Mesozoic

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A paleoecological analysis of the fossil record before and after the Cretaceous/Tertiary boundary indicates that the widespread extinctions and biological stresses around the boundary are best explained in terms of a sudden, significant, but short temperature rise. L. Alvarez and co-authors, having found an enrichment in iridium at the same boundary, postulated that it was associated with the impact of an extraterrestrial body. If this body struck the ocean, the water injected into the atmosphere may have led to a transient increase in the global surface temperature. This temperature pulse may have been primarily responsible for the effects observed in the biosphere. The pattern of extinction of higher plant species suggests that splash down occurred in the northern Pacific–Bering Sea area.

1. Introduction

Hallam [1] has recently summarized some of the facts known about the mass extinctions at the end of the Mesozoic and some of the theories proposed to explain them. To these we must now add the reports of Thierstein and Okada, Boersma et al., and Tucholke and Vogt [2] on Site 384 of the Deep Sea Drilling Project; the report of Alvarez et al. [3] on the discovery of a manyfold enrichment in iridium at the Cretaceous/Tertiary boundary in the sections at Gubbio, Italy, Stevns Klint, Denmark, and New Zealand, and of Smit and Hertogen [4] on iridium enrichment at the same stratigraphic level in the Barranco del Gredero section in Spain; the study by Ganapathy [5] showing that Ir, Pt, Os, Ru, Pd, Ni, and Co in the Stevns Klint

section are in cosmic proportions; the contribution of Napier and Clube [6] on asteroidal and cometary impacts; the work of Kyte et al. [7] on DSDP core 3, hole 456A, Leg 62 extending to the Central Pacific (33°49.23'N, 178°55.14'E) the geographic range of the observed Ir enrichment in sediments; and the brief analyses by Hsü [8] and Emiliani [9].

Alvarez and co-authors have suggested that the enrichment in iridium was probably due to the capture by the earth of an Apollo asteroid about 10 km in diameter: the impact would form a large crater and would throw into the atmosphere a very large amount of dust that would dim the sun and suppress photosynthesis. They visualize that the food chain would be nipped at the root and the extinctions would follow [3]. Both Hsü [8] and Emiliani [9] accept the impact event but suggest

that the bolide may have targeted the ocean rather than land; Hsü notes the possible contamination of the environment by the constituents of a comet and Emiliani draws attention to the injection of an amount of energy sufficient to raise the Earth's surface temperature to levels lethal to many taxa. A totally different theory was advanced by Gartner and Keany and by Gartner and McGuirk [10] who suggested that the observed extinctions were due to a fresh water flood from the Arctic following the opening of a rift between Greenland and Norway.

In the Umbria-Marche Apennine sections of central Italy, apparently deposited in sedimentary continuity, Maestrichtian (latest Cretaceous) pink-to-white pelagic limestones with abundant globotruncanids are abruptly replaced by a 1- to 2-cm clay layer which grades in color from greenish-gray below to dark red above and contains abundant benthic arenaceous foraminifers and fish teeth. The layers immediately following are reddish limestones containing abundant, very small (average diameter less than 0.10 mm) globigerinids of earliest Paleocene age. This layer is followed by more pelagic limestones with an orderly sequence of progressively younger Tertiary foraminiferal assemblages [11]. The anomalous quantities of iridium and certain other metals were discovered by Alvarez et al. [3] in the boundary clay layer.

This discovery is of momentous significance, for it may open the way to an understanding of what really happened. We believe that the observed extinctions can be explained much more readily by a temperature rise than by a temperature decrease or some other cause. This is so because not only the Mesozoic reptiles, but much of the tropical, subtropical and temperate biosphere, at least during the summer, has been and is close to the upper limit of temperature tolerance. This idea was proposed by Cowles [12] in 1939 for the dinosaurs. Today, however, it is possible to bring together many more data than available in 1939 to test the theory that heat was the primary cause of the extinctions at the end of the Mesozoic.

2. The paleontological record

Writing in *Science* in 1939, Cowles observed that even the most heat-tolerant reptiles, the diurnal lizards of the deserts of southern California, are adjusted to optimum temperatures of 37–38°C but cannot survive temperatures only 2°C higher. On the other hand, temperatures 10° or 20°C lower may be tolerated. Cowles hypothesized that heat, rather than cold, may have been responsible for the disappearance of the Mesozoic reptiles, Cowles [13], Coll [14], and Colbert et al. [15] gathered additional data, both in the field and in the laboratory, about heat tolerance of reptiles. The conclusion of these studies, which focussed on desert lizards [13,14] and on the American alligator (*Alligator mississippiensis* [15]), was that a modest increase in ambient temperature at the end of the Cretaceous was the probable cause for the extinction of the dinosaurs [16].

If it was heat that killed the dinosaurs, it must have had a visible effect on other taxa as well. A direct test of this hypothesis would be the tracing of the different taxa across the Cretaceous/Tertiary boundary. Unfortunately, in most cases, this is not possible. The end of the Cretaceous was a time of strong marine regression. As a result, there are virtually no continuous sections ranging into the earliest Tertiary for the environment most rich in diversified taxa, namely the shallow-water marine environment. The only sections for which continuity is practically certain are of deep-sea facies (see below). The best we can do, therefore, is to evaluate the taxa that are known to have lived in the late Cretaceous, even though we do not know if they were still living at the very end of this period, and see how they are represented in the early Tertiary. Table 1 summarizes data on heat tolerance of at least some groups *within* the different taxa listed. In spite of the fact that the data are incomplete and of varying quality, some important conclusions may be drawn. We notice, in particular, that plants have a generally higher temperature tolerance than animals and that among the land animals, the more advanced classes, the mammals and birds, have a higher tolerance than the lower classes, fish, amphibians, and reptiles.

Russell [17,18] has tabulated generic diversities

TABLE 1

Maximum temperatures tolerated for short periods of time by at least some common genera within the major taxa of animals and plants (from Bramlette and Martini [50])

	Maximum temperature (°C)
<i>Animals</i>	
Mammals	42– 50
Birds	42– 50
Reptiles (exc. Iguanidae)	38– 40
Iguanidae	46– 48
Amphibians	38– 40
Fish	35– 38
Insects	40– 48
Crustaceans (exc. <i>Artemia</i>)	38– 42
Cephalopods	36
Pelecypods	36– 38
Gastropods	36– 38
<i>Coelenterates</i>	
Anthozoa: Porites	36.4 (mean lethal temperature)
<i>Plants</i>	
<i>Algae</i>	
fresh water	30– 84
marine, tropical, intertidal	35– 40
Lichens	70–100
Mosses	35– 50
Ferns	42– 50
Gymnospermae	40–150
Angiospermae	40– 50

of various groups of organisms known to have lived during the last 20 Ma of the Late Cretaceous and the first 10 Ma of the Cenozoic. If this criterion were used as an index, it would appear that some groups (dinoflagellates, diatoms, radiolarians, higher plants, mammals) suffered little from the “terminal Cretaceous event” while others (coccolithophorids, planktonic foraminifers, ammonites, belemnites, marine reptiles, and dinosaurs) suffered total or near-total extinction. Table 2 repackages table 1 of Russell [18] in terms of the ratio Early Cenozoic/Late Cretaceous generic diversity. The higher the number, the lesser (presumably) was the group affected.

Selecting groups of organisms particularly significant in terms of the dynamics of the terminal Cretaceous event, we have determined from the literature the percentage of genera that successfully crossed the Cretaceous/Tertiary boundary. As mentioned earlier, this approach is full of pitfalls: in most cases it is not possible to determine from the literature if a given genus, listed as living during the Late Cretaceous, was in fact still living at the very end of the Cretaceous and had not disappeared some time before. Further-

TABLE 2

Number of genera known to have existed during the first 10 Ma of Early Cenozoic time in different environments vs. the number of genera known to have existed during the last 20 Ma of Late Cretaceous time in the same environments (from Russell [18])

Environment	Number of genera Early Cenozoic/Late Cretaceous ($\times 100$)			
	0–	30–	60–	90–
Terrestrial (incl. fresh water)		cartil. fishes	pelecypods bony fishes reptiles	gastropods amphibians mammals higher plants
Neritic		sponges corals gastropods pelecypods crinoids echinoids	asteroids bryozoans brachiopods barnacles malacostracans	calc. algae foraminifers
Nektonic	ammonites belemnites bony fishes reptiles		nautiloids cartil. fishes	
Pelagic	coccolithophorids foraminifers	acritarchs ostracods	dinoflagellates	diatoms radiolarians

more, the concept of "genus" varies tremendously from group to group, being much more restrictive for birds than, for instance, for foraminifers. The Radiolaria present a particularly vexing case, for many genera are reported as having tremendous range (some even Cambrian/Recent). It is really doubtful if any genetic matrix has the capacity to remain stable for such an enormous length of time. The extreme success of the Radiolaria in crossing the Cretaceous/Tertiary boundary may thus be more apparent than real, and may in fact be due, at least in part, to poor taxonomic resolution for this group. In spite of these difficulties, the data (Table 3), even though limited to the generic level, appear to be supportive of the conclusion that heat was in fact the probable cause of the observed extinctions. Let us now examine each environment separately.

2.1. Pelagic environment

The predominantly low-latitude, shallow pelagic coccolithophorids and foraminifers are decimated (13% survival each), while the predominantly high-latitude diatoms and dinoflagellates fare much better (31 and 78% survival, respectively). This is to be expected because rising temperature will reach lethal levels much sooner at lower than at higher latitudes, even though high latitude temperatures were much higher at the end of the Cretaceous than today (cf. [19]). In addition, diatoms and dinoflagellates commonly form resting cells when the environmental conditions become unfavorable. The radiolarian percentage, if real, could be explained by the observation that radiolarians are common at high latitudes and also at lower latitudes in deeper water, so that they would be in a much better position than the shallower plankton to survive a high-temperature episode.

2.2. Nektonic environment

Of particular interest here are the nautiloids, ammonoids, and belemnoids. The nautiloids crossed the boundary quite successfully. Of the twelve genera present in the Upper Cretaceous, six crossed into the Tertiary (50% survival). On the other hand, ammonoids and belemnoids became

TABLE 3

Percentage of Late Cretaceous genera that survived the terminal Cretaceous event

Group	Percentage survival	Source
<i>Planktonic</i>		
Coccolithophoridae	13	[50]
Foraminifera	13	[51]
Diatoms	31	[52]
Dinoflagellates	78	[53]
Radiolaria	93	[54]
<i>Nektonic</i>		
Ammonoids	0	[54]
Belemnoids	0	[54]
Nautiloids	50	[54]
Elasmobranchii	67	[55]
Osteichthyes	4	[55]
Ichthyosauria	0	[55]
Plesiosaurs	0	[55]
<i>Benthic (bathyal-abyssal)</i>		
Foraminifera	75-85	[21,55]
<i>Benthic (neritic)</i>		
Corals (hermal)	20	[25]
Foraminifera (Orbitoidia)	0	[21,56]
Pelecypods (excl. Ostracea and Hippuritacea)	43	[54]
Ostracea	32	[54]
Hippuritacea	0	
<i>Terrestrial</i>		
Amphibia	100? *	[55,57]
Reptilia		[55,57]
Chelonia	23	[55]
Sauroptrygia	0	[55]
Squamata		
Lacertilia	27	[55,57]
Serpentes	0? *	
Crocodylia	12	[55]
Saurischia	0	[55]
Ornithischia	0	[55]
Pterosauria	0	[55]
Aves	0? *	[55]
Mammalia	52	[26]
Higher plants	69	[58]

* Insufficient data.

entirely extinct. The only modern genus of nautiloid is *Nautilus*. It occurs in the tropical Indo-Pacific at depths greater than 100 m (maximum abundance at 300-500 m). Reproduction is internal, as in all cephalopods. The eggs are enormous (45 mm across) and are fastened to bedrock, again at depths greater than 100 m [60]. The mor-

phology of the early stages of the *Nautilus* shell indicates that what emerges from the egg is a 25-mm shelled embryo already prepared for life at depth. There is no shallow larval stage. Similar studies on the early stages of ammonoid shells indicate that the ammonoid eggs were miniscule, and that an epipelagic larval stage must have followed [60]. As to the belemnoids, their closest living relative, *Loligo*, inhabits shallow waters and fastens its eggs on shallow (10–30 m) bottoms [61]. A sudden temperature rise, therefore, would have affected adversely the ammonoids and belemnoids while leaving untouched the deeper-living nautiloids, as the record indicates. It should be noted that ammonite juveniles occur in considerable number at the Cretaceous/Tertiary boundary at Stevns Klint, Denmark [20], suggesting an unusual stress for this population.

Elasmobranchii, with internal fertilization, exhibit a high survival rate (65%). By comparison, the Osteichthyes, whose eggs in most cases freely float at or near the surface or are dropped on shallow bottoms, become almost extinct (4% survival).

2.3. Benthic environment: bathyal-abyssal

One would expect that benthic life in the bathyal-abyssal environment would suffer little direct effects from the postulated surface temperature rise. The bathyal-abyssal benthic metazoan record is poor, but that of Foraminifera is good largely because of the abundant material recovered by the Deep Sea Drilling Program. The record shows that 75–85% of the genera that were living in the Late Cretaceous survived the terminal Cretaceous event [21]. Nearly all bathyal genera also live in the neritic environment, at depths as shallow as 50 m or even less. Populations living in such shallow bottoms may have suffered but most genera had no problem in surviving because of their considerable depth ranges.

2.4. Benthic environment: neritic

The neritic environment, as generally defined, extends from the intertidal zone to 200 m of depth (see, e.g., Gross [22, p. 314]). The neritic zone most

affected by a sudden temperature rise would be the shallowest one, from 0 to 10 m. Unfortunately, under the strongly regressive conditions prevailing toward the end of the Cretaceous [23, fig. 11], there is no certain record across the Cretaceous/Tertiary boundary of sediments deposited in marine water less than 10 m deep [24]. It appears, nevertheless, that only 20% of the hermal coral genera living during the Late Cretaceous survived into the Tertiary [25], while none of the rudistid genera did. It should be noticed that both groups were well diversified and vigorous in Middle Maestrichtian time. The decline or extinctions of these taxa may have been due in major part to the substantial areal reduction of the shallow-water environment, with the postulated temperature rise only providing the *coup de grace*. In any case, there seem to be no coral reefs in Early Paleocene time. Late Cretaceous benthic foraminifers associated with the shallow carbonate environment (the orbitoids) also became extinct. A significant observation is that modern benthic foraminiferal faunas characteristic of the shallow water (0–10 m), tropical-subtropical marine environment, as exemplified by Florida Bay, contain less than 50% of pre-Cenozoic genera, as compared to 70–85% for the bathyal-abyssal faunas mentioned above.

2.5. Terrestrial

One genus of Anura and five of Urodela are reported from the Late Cretaceous. All survived into the Cenozoic. Among the reptiles, survival is about 23% for turtles, 27% for the lizards, and 12% for the crocodylians. Mass extinction affected the ornithischian and saurischian dinosaurs, the pterosaurs, and the sauropterygians. Not enough data exist for the snakes and the birds. The mammals did very well, exhibiting a 52% survival at the generic level [26]. Even better did the higher plants, with 69% of the genera surviving the boundary. Altogether, it would seem that the smaller amphibians and reptiles managed to cross into the Cenozoic (again at the generic level!) while none of the larger ones (e.g., the dinosaurs) did. Survival rates were even better for the heat resistant mammals and higher plants. The higher plants, of course, produce seeds, which is a means

by which they survive periods of unfavorable ecological conditions. Seeds may generally last a few years but would generally die if adverse conditions were to last much longer. Survival of higher plant genera in good number (see, however, below) provides one of the constraints about the duration of the high temperature episode. Altogether, the evidence again appears to support the idea that a short, intense pulse of higher temperatures may have been the primary cause of the disturbances observed in the biosphere at the end of the Cretaceous.

3. Physical effects of impact of a large extraterrestrial body in the ocean

An adequate mechanism for raising the temperature of the troposphere and oceanic thermosphere appears to be provided by impact of an extraterrestrial body approximately of the dimensions suggested by Alvarez et al. [3]. The heating occurs primarily as a result of the addition of material to the atmosphere, specifically a large quantity of water, if the impact occurs in the ocean. Here we will review the sizes and characteristics of bodies colliding with the Earth. Then we will follow, in some detail, the consequences of impact in the ocean of what is likely to have been the largest body to strike the Earth during the Neozoic.

3.1. Plausible size and other characteristics of impacting body

Shoemaker et al. [27] have estimated that the present population of earth-crossing asteroids equal to, or brighter than, absolute visual magnitude 18 is approximately 1.3×10^3 . This estimate is based on the rate of discovery of asteroids near the Earth in systematic surveys of the sky by wide field telescopes. An asteroidal object of absolute visual magnitude 18 has a surface area equivalent to a sphere 0.89 km in diameter, if the visual geometric albedo is 0.14 (equal to the mean for S-type asteroids), and a sphere 1.73 km in diameter if the visual geometric albedo is 0.037 (equal to the mean for C-type asteroids). Recent physical studies of earth-crossing asteroids show that they

include both S-type and C-type objects; the majority of objects observed have relatively high albedo (comparable to S-type asteroids), but the largest objects are dark (C-type). Probably the bulk of the mass is in the dark, C-type or related bodies. Assuming that half the earth-crossing asteroids are bright (S-type) and half are dark (C-type), Shoemaker et al. [27] found that their estimate of the population is consistent with the observed Phanerozoic record of impact cratering in North America, if densities are assigned to the bright and dark asteroids on the basis of presumed meteorite analogues.

About 40 earth-crossing asteroids have been discovered to date. The number is too small to determine with useful accuracy the magnitude distribution or size distribution of the population directly from the discovered objects. However, the size distribution of post-mare impact craters on the Moon is fairly accurately known. For craters larger than a few kilometers, but less than 120 km diameter, this distribution closely follows a simple power function:

$$N_D = KD^{-1.7}$$

where N_D is the cumulative frequency of craters equal to or larger than diameter D , and K is a constant [28]. From empirical scaling relations for craters it is easy to show that the crater size distribution implies a magnitude distribution for impacting bodies of the form:

$$N_m = k e^{\gamma m}$$

where N_m is the cumulative frequency of bodies equal to or brighter than absolute magnitude m , and k and γ are constants. Using a scaling relationship introduced below, and appropriate corrections for the enlargement of diameters by collapse for lunar craters larger than 20 km, the value of γ that corresponds to the observed lunar crater size distribution is close to 0.8. A slightly higher value, $\gamma = 0.9$, was found by Shoemaker and Wolfe [29] for the absolute nuclear magnitude distribution of short-period comets.

Assuming that $\gamma = 0.8$, we can estimate the magnitude and size of the largest asteroid expected to collide with the earth in any given interval of time, for example, 65 Ma (which is the approxi-

mate time since the end of the Cretaceous). An estimated collision rate of ~ 3.3 per million years for objects equal to or brighter than magnitude 18 was obtained by Shoemaker et al. [27]; this gives a total of ~ 215 objects in 65 Ma. Half of these are assumed to be dark objects, which will include the largest body. For dark objects in this time period, $k = N_m/e^{\gamma m} = 107/\exp(0.8 \times 18) = 6.0 \times 10^{-5}$. To obtain the magnitude of the largest of the 110 dark bodies, we solve for $N_m = 1$, which yields $m = 12.2$. At the mean visual geometric albedo of 0.037 for C-type asteroids, a visual magnitude of 12.2 is equivalent to a sphere whose diameter, d , is given by:

$$\log d = 3.122 - 0.2m - 0.5 \log 0.037$$

and $d = 25$ km. A mean bulk density of 1700 kg/m^3 was derived by Shoemaker et al. [27] for the dark, C-type asteroids. At this density, a 25-km-diameter asteroid would have a mass of 1.4×10^{16} kg. Of course, a large statistical fluctuation is to be expected in the size and mass of the single largest body.

It is of interest that, even though the discovery of earth-crossing asteroids is far from complete (about 3% complete at absolute visual magnitude 18), two earth-crossing asteroids have been discovered with absolute visual magnitudes near 14 and estimated diameters of about 10 km [27]. Two other known earth-approaching asteroids that can be perturbed into earth-crossing orbits by close encounters with Mars, 433 Eros and 1036 Ganymed, have equivalent diameters in the range of 20–40 km [30]. On the other hand, the distribution of the largest post-mare craters on the Moon indicates that the frequency of post-mare craters drops below the frequency given by a simple power law for craters larger than ~ 120 km diameter. This suggests that, at magnitudes below about 14 or diameters greater than about 6 km, the number of earth-crossing asteroids is less than indicated by the simple exponential law for magnitudes. A likely diameter for the largest asteroid impacting the Earth in the last 65 Ma is about 15 km and the probable mass is about 2.5×10^{15} kg.

The derived mass of 2.5×10^{15} kg may be compared with the surface density of iridium found by Alvarez et al. [3] at Gubbio, Italy and Stevns

Klint, Denmark, by Smit and Hertogen [4] at Barranco del Gredero, Spain, and by Kyte et al. [7] in the deep Pacific sediments. As calculated by Alvarez et al., the measured surface density of Ir at Gubbio leads to an estimate of 4×10^7 kg of Ir spread over the earth and to an asteroid mass of 3.4×10^{14} kg, if 22% of the asteroid is taken to be dispersed world wide and an Ir mass fraction of 0.5×10^{-6} is adopted for the asteroid. At Stevns Klint, however, the surface density is about one order of magnitude greater than at Gubbio; a similar calculation would lead to a mass of 3×10^{15} kg for the asteroid. A slightly higher mass would be obtained from the Ir analyses reported for the Pacific sediments and an intermediate mass for the section in Spain. Clearly it is crucial to understand what fraction of the impacting body may have been dispersed from the impact site and how this material is distributed over the Earth. It is also important to determine the nature of the impacting body.

Various authors [7,8,31] have discussed the possibility that comets have collided with the Earth. Many long-period comets, in fact, are on orbits that overlap the orbit of the Earth. Some must occasionally collide. The collision of comets is probably responsible for nearly all the young craters (ray centers) observed on the icy Galilean satellites of Jupiter [29]. Because the gaseous coma tends to conceal the nucleus as a comet approaches perihelion, there is a common misconception that a comet is simply a diffuse very low-density object. Nearly all comets, if observed at large solar distances, however, are found to have a nucleus of essentially stellar appearance [32]. The observed characteristics of comets indicate that the nucleus is a rotating solid body composed of various kinds of ice and embedded non-volatile material [33]. As shown by the form of the ray craters on Ganymede, the largest satellite of Jupiter, collision of comet nuclei produces impact craters that are basically similar to impact craters on the Earth and Moon [34]. From considerations of composition of the early solar nebula and the mineral phases expected to condense from the nebula at low temperature, Delsemme [35] has deduced that fresh comet nuclei are composed about half by weight of ice (chiefly H_2O) and half

of rocky (chiefly silicate) constituents. This proportion appears to be borne out by the amounts of gas and dust lost to the tails of well observed long-period comets [36].

From detailed considerations of published nuclear magnitudes of comets, the orbits and the circumstances of discovery of about 600 comets, and the cratering record of Earth, Moon, and the Galilean satellites, Shoemaker and Wolfe [29] concluded that comet impact currently produces about one third of the impact craters on Earth larger than 10 km diameter. About 95% of the cratering by comet impact is attributable to long-period comets. If the body that produced the Ir anomaly at the Cretaceous/Tertiary boundary was a comet nucleus, then perhaps twice as massive a body might be associated with the observed anomaly as would be calculated for a stony earth-crossing asteroid.

The high abundance of Ir and other noble metals observed at Stevns Klint and elsewhere provides possible clues about the impacting body. A concentration of 65 ppb Ir was reported by Alvarez et al. [3] for the acid-insoluble fraction of the calcareous boundary claystone; concentrations of up to 69 ppb Ir were found by Ganapathy [5] for the whole rock. Up to 15 ppb was found by Kyte et al. [7] for the non-carbonate fraction of the Pacific sediment. These abundances are roughly one order of magnitude lower than the Ir abundance found in most stony meteorites (including carbonaceous chondrites). But the constituents of the impacting body may be expected to be diluted by a factor of ~ 50 – 100 with terrestrial rock material in the relatively high-velocity plume of ejecta expelled from a typical impact crater. The impacting body may have been unusually rich in Ir and other noble metals [7]. On the other hand, it may have partly disintegrated in the atmosphere and thereby left local deposits richer in extraterrestrial material than would be expected for crater ejecta. In either case, it appears unlikely that the boundary claystone at Stevns Klint can be much diluted with ordinary terrigenous sediments. The abundance of Ir found in the claystone and the high surface density at Stevns Klint suggest that the collision occurred at a relatively high northern latitude.

3.2. Penetration of atmosphere and ocean and formation of crater in sea floor

The physical phenomena associated with an asteroid or comet nucleus hitting an oceanic area are exceedingly complex. The problems involved cannot be fully analyzed—least of all in a paper of the present limited scope. However, it is possible to make order of magnitude estimates, on the basis of some simple physical arguments and extensive observations of the phenomenology of explosions and craters [37].

The preceding arguments suggest that the mass of the body which presumably hit the Earth 65 Ma ago was of the order $M = 2.5 \times 10^{15}$ kg and its radius was of the order $r_b = 7 \times 10^3$ m. The weighted mean impact velocity of earth-crossing asteroids [27] is given by $v = 2 \times 10^4$ m/s. A likely kinetic energy of the bolide therefore is $W \approx 5 \times 10^{23}$ J. A body of this type probably will survive passage through the atmosphere more or less intact. For an entry angle ϕ , the ratio ϵ of the intercepted atmospheric mass to the mass of the (spherical) bolide is:

$$\epsilon = \frac{3}{4} \frac{\rho_a}{\sin \phi} \frac{h_*}{\rho_b r_b} = \frac{3}{4} \frac{\rho_a}{\sin \phi} \frac{c_s^2}{\rho_b g r_b}$$

where $h_* \approx 11$ km is the atmospheric scale height, $c_s \approx 3.3 \times 10^2$ m/s is the sound velocity and ρ_a is the mean air density. Assuming $\phi \approx 45^\circ$ one gets then $\epsilon \approx 9 \times 10^{-4}$. This is also the approximate fraction of momentum which is lost from the bolide during atmospheric entry. The resulting velocity decrease is negligible. A moderate shock is propagated during the atmospheric passage from the leading face back into the solid body of the bolide, but the shock probably cannot reach the bulk of the mass of the bolide before impact with the ocean. Assuming the bolide is roughly equant in shape, only a very small fraction of the mass of bolide can be deflected or significantly separated from the main body by interaction with the atmosphere in the short time available. If the high surface density of iridium at Stevns Klint is representative of a broad swath of the Earth's surface near the latitude of Denmark and is to be explained by separation and stopping of a significant fraction (10^{-2} to 10^{-1}) of the bolide in the atmo-

sphere, then it appears necessary to suppose either that the elevation angle of entry was unusually low or that the body was initially extremely irregular in shape or consisted of multiple objects prior to encounter. (We reject the suggestion of O'Keefe and Ahrens [38] that the object had extremely low density, i.e. $\sim 10 \text{ kg/m}^3$, as there is no evidence for such low-density projectiles having formed any of the very numerous post-mare craters on the Moon.)

Passage of the bolide opens a rapidly expanding hole in the atmosphere. If all the air escapes sideways, the initial radial flux of momentum is given by:

$$\pi r_b^2 h_* \rho_a U_0^2 = 2\epsilon W \approx 10^{21} \text{ J}$$

which implies an initial radial velocity U_0 which is of the same order or slightly larger than v . In reality this is an upper bound, as some of the atmosphere will be unable to escape laterally and will be smashed into the material below. The mass of air behind the expanding shock wave increases with the square of the distance r^2 and the radial velocity decreases therefore with the inverse of r . At a critical distance:

$$r_c = r_b v / c_s \approx 420 \text{ km}$$

the Mach number drops to unity. Beyond that distance, the outward flow becomes subsonic and is rapidly decelerated by an adverse pressure gradient. The shock wave reaches the critical distance r_c within a time:

$$t_c \approx 1/2 r_b v c_s^{-2} \approx 640 \text{ s}$$

The same order of magnitude numbers are obtained from comparison with large nuclear explosions in the atmosphere, such as the 25- and 58-megaton tests at Novaya Zemlya [39]. On the basis of that experience it is estimated that the period of initial expansion of the hole behind a $\sim 10^{21} \text{ J}$ shock is about:

$$\frac{1}{2} (10^{21} \text{ J} / 4 \times 10^9 \text{ J/s}^3)^{1/3} \approx 3 \times 10^3 \text{ s}$$

Neglecting the complications that will arise from high-velocity ejecta from the ocean and ocean floor, the hole in the atmosphere opened by the bow shock would expand to several hundred kilometers radius before the return flow begins to

fill it in. Again scaling from nuclear explosions (and the 1908 Tunguska fireball), an extraordinarily powerful wind, capable of flattening forests out to a distance of 500–1000 km, would blow outward for about an hour. This would be followed by a very strong return wind. If the bolide entered the atmosphere at an unusually low angle, a somewhat larger region may have been scoured by very high-velocity winds.

When the 2.5×10^{15} -kg body strikes the ocean, the layer of ocean water responds chiefly like a thin incompressible skin which is punctured by the impact. The diameter of the body is significantly larger than the ocean depth, here assumed to be 5 km, but small compared to the oceanic scale depth. The water in the immediate target area will be strongly compressed by shock and then vaporized upon decompression, as it is sprayed out of an expanding transient cavity. A large additional volume of weakly shocked water is sprayed upward and another large volume is pushed radially outward.

For convenience in applying an empirical scaling formula for craters, we will treat the ocean layer relatively close to the path of penetration of the bolide simply as part of the target material in which a crater is formed. The diameter of the transient crater formed in the ocean and rocks of the ocean floor can be estimated by the formula [29]:

$$D = K(sW)^\alpha$$

where $\alpha = 1/3.4$ and the crater scaling constant for impact craters on Earth $K = 0.074 \text{ km}/(\text{kt TNT equivalent})^\alpha = 1.4 \times 10^{-2} \text{ m/J}^\alpha$. The scaling factor s is simply the ratio of the density $\rho_a = 1800 \text{ kg/m}^3$ of the alluvium at Jangle U crater, Yucca Flat—which formed the basis for the derivation of the empirical formula—to the mean density (water and rock) of the excavated material. By iteration, the latter is found to be about 2400 kg/m^3 , which makes $s \approx 0.75$, with $W = 5 \times 10^{23} \text{ J}$. The transient crater diameter at the sea surface is computed to be $D \approx 1.4 \times 10^5 \text{ m}$. In fact, the seawater will probably be swept back farther from the impact center than the indicated 70 km, and an initial removal of the water layer from a circle of at least 100 km radius seems not implausible. For simplic-

ity of calculation, the shape of the transient cavity can be approximated by a cone with a nominal depth of order $h \approx D/4 \approx 35/\text{km}$. Assuming an ocean depth of 5 km and an oceanic crust also of 5 km thickness, one can then calculate that roughly about 35% of the volume of the nominal transient cavity would be excavated in water, about 25% in the oceanic crust, and the remaining 40% in the mantle.

The initial rise of the water level in the area around the impact area must have been of the same order as the depth of the ocean itself. The resulting, monstrous gravity waves would still have heights of several hundred meters, even on deep water many thousands of kilometers away. If the impact occurred in the Pacific these super tsunamis would penetrate deeply into the surrounding continents with enormously destructive effects. This catastrophe by itself may have been sufficient to exterminate species whose habitat was restricted to the low lands around the northern Pacific. It may explain, in part, the particularly high rate of extinction which has been reported from that area (see below).

The growing transient cavity in the ocean and ocean floor reaches a maximum size in a matter of minutes. As the ocean layer is swept back farther than the crater in the rocky floor, material ejected at low velocity during the late stages of opening of the transient cavity falls near the transient cavity rim, forming a concentric deposit that may extend to a radius of about 100 km or more on the exposed sea bed. About half of the strongly shocked rock remains in or falls back into the transient cavity.

The sea near the open hole in the ocean then stops flowing out and starts to flow back as a gigantic bore, filling the hole. Almost certainly, the returning bore would entrain much ejecta deposited outside the cavity and transport them back toward the center. This material, plus much hot debris left in the cavity, might become intimately mixed with seawater. On a longer time scale, the asthenosphere also flows toward the transient cavity, pushing up the floor of the cavity and greatly flattening the initial crater. As the floor rises, the rim subsides, and a series of one or more scarps are formed surrounding the crater of excavation in

the sea floor. Depending on the thickness of the lithosphere, the outermost scarps would define a multi-ring basin with a diameter ~ 1.3 to ~ 2 times the transient cavity diameter [40].

3.3. The release of ambient heat from the lithosphere

As the transient cavity penetrates deeply into the oceanic mantle, rocks excavated from near the base of this cavity are hot prior to receiving any increment of heat from the shock that produced the crater. Hence, it is of interest to estimate the initial heat content of the excavated rock that might later contribute to the heating of the ocean and atmosphere.

We assume an average density of the lithosphere of $\rho_r \approx 3200 \text{ kg/m}^3$ and an average specific heat $C_r \approx 1000 \text{ J/kg K}$. The depth z is measured downward from the ocean floor and the temperature gradient in the crust and mantle below is assumed constant and equal to:

$$dT/dz = 0.03^\circ \text{ K/m}$$

Using the mean ocean temperature ($T_0 = 277^\circ$) as a reference, the specific enthalpy of the rocks is then given by:

$$\eta = A_r^2 \text{ J/m}^3$$

where $A_r = 9.6 \times 10^4 \text{ J/m}^4$. measured from the sea floor, the approximately conical transient cavity has a maximum depth h and a constant diameter depth ratio $\beta = D/(h - z)$. The total initial heat content H of the excavated rocks is specified therefore by the integral:

$$\begin{aligned} H &= \frac{\pi\beta^2}{4} \int_0^h (h - z)_\eta^2 dz \\ &= \frac{1}{4} \pi\beta^2 A_r \int_0^h (h - z)^2 z dz = \frac{1}{48} \pi\beta^2 A_r h^4 \end{aligned}$$

Substituting $h = 3.0 \times 10^4 \text{ m}$, $\beta = 4$ and the listed value for A_r , the last equation yields $H \approx 0.82 \times 10^{23} \text{ J}$.

Instead of expressing H in terms of the maximum depth h , one can also express it in terms of W :

$$H = \pi A_1 \beta^2 [K(sW)^\alpha - \beta h']^4 / 48$$

where h' represents the depth of the sea. As $h' \ll h + h'$:

$$H/W \approx NW^{4\alpha-1} = NW^{0.18}$$

where N is a constant. Hence, the ratio H/W increases with W , but only slowly. With the parameters and approximate geometry we have adopted, H will exceed W when the impact energy is nearly 3 orders of magnitude greater and the crater is about 5 times larger than the case we have considered here. However, with a more realistic bowl-shaped transient cavity and with a steeper thermal gradient than that assumed (under a mid-ocean ridge, for example), the initial enthalpy of the rocks excavated by impact of a 2.5×10^{15} -kg body could become comparable to the energy of the bolide.

With the conditions considered here, the initial thermal energy available in the rocks excavated from the impact crater is about 20% of the kinetic energy of the bolide. This means that a total of about 6×10^{23} J would become available locally. The oceans today cover an area of 3.61×10^{14} m². The available energy would be sufficient therefore, in principle, to raise the temperature of the top 30 m of all the oceans by about 13°C.

In reality, only a fraction of the total energy becomes available to the ocean. The actual temperature rise depends not on the amount of energy, but on the power, that is the rate at which heat is being supplied and the rate at which it is lost by atmosphere-ocean interactions and by radiational cooling of the sea surface. The following argument suggests that the power supply is probably insufficient for the direct large-scale heating of the ocean.

If the initial crater collapses promptly, the returning sea may recover the temporarily exposed ocean floor within a matter of hours. For considerable time, however, a hot spot with a diameter approximately equal to that of the transient cavity (~ 130 km) would be left on the ocean floor. In the center of this hot spot, shock-heated debris would rest directly on upwelled mantle over a diameter of ~ 120 km. It is possible that the sudden decompression of the mantle in the center of the basin would trigger secondary basaltic volcanism. Depending on the initial thickness of

the lithosphere, great quantities of basaltic melt might be formed and convected to the ocean floor, or, more likely, intruded beneath the comparatively low-density shocked debris. Precisely such an event apparently occurred at the Precambrian impact crater at Sudbury, Ontario [41].

Modern ocean bottom lava flows have not been observed to produce any signature on the ocean surface. It is thought that this is due primarily to a layer of superheated steam and to the rapid formation of a thin skin of solidified rock. Either or both together effectively insulate the molten rock from the overlying water. The phenomenon is scale dependent and it seems improbable that a disturbance of the indicated magnitude and area would not affect the whole depth of the water column particularly as the water may be able to circulate through the shocked debris. However, even if a significant local oceanic temperature anomaly is maintained, it is unlikely to have significant large-scale effects for the following reasons.

Assume that water is heated over the hot spot sufficiently to rise to the surface and to spread out there. Rotational constraints will cause then a cyclonic circulation near the bottom and an anti-cyclonic circulation in the upper ocean. These rotating eddies will effectively contain most of the heat anomaly within a diameter which depends on the latitude, but which cannot be larger than a few hundred kilometers except on the equator. If the impact was directly on the equator, its effect could be spread by the ocean around the globe within a few months, but this would be confined again to an equatorial wave guide with a width of only a few hundred kilometers. The escape of water and heat from these eddies—or from the equatorial wave guide—and their large-scale diffusion is a slow baroclinic process with a time scale which can be measured in decades. During such a time, the temperature anomaly of the surface waters would have been dissipated by air-sea interactions. This brings us to the consideration of atmospheric effects.

3.4. *The high-velocity plume*

As the impacting body penetrates the ocean and the ocean floor, a plume of shock-heated

steam and volatilized, melted and solid rock is sprayed at high velocity out of the expanding cavity. About half of the bolide becomes part of this high-velocity plume. The entrainment of mass into the plume is associated with a lateral deflection of mass near the collision surface and an associated rarefaction that propagates from the free surfaces of the ocean and the bolide into the rear of the shock. The plume expands initially through the hole punched in the atmosphere by the bolide at highly supersonic speeds. It therefore catches up with the atmospheric bow shock wave and provides additional power to it.

The material of the high-velocity plume is derived from an approximately conical region with an axis along the path of penetration of the bolide and an apical angle of about 90° . For a penetration depth $h + h' = 35$ km, this indicates an original volume of $\pi(h + h')^3/3 = 4.5 \times 10^{13}$ m³. Assuming as above that 37% of this volume was filled initially by liquid water and 63% by crustal and mantle rock with a mean density of 3200 kg/m³, one readily estimates the mean mass of the plume as equal to about 10.8×10^{16} kg. About 16% of this mass— 1.8×10^{16} kg—will consist of steam and the remainder of vaporized, melted and fragmented rock.

The earlier argument suggested that the mean initial heat content of the material in the stipulated plume was 0.2×10^{23} J. Adding this amount to half the kinetic energy of the bolide we find that 2.7×10^{23} J are carried in the high-velocity plume. This may be an overestimate and, therefore, the immediately following computations are in the nature of an upper bound.

With a plume mass of 1.1×10^{17} kg and an energy of 2.7×10^{23} J, the energy per unit mass is $e_p \approx 2.5 \times 10^6$ J/kg. About half of this energy is internal and half kinetic. The kinetic energy, in turn, can be partitioned into vertical and horizontal components of the velocity. The average elevation angle of ejection of the plume is 45° and the mean kinetic energy of the vertical motion $K_v = 6.3 \times 10^5$ J/kg. A mass hurled upward with this initial energy can reach a maximum height of:

$$Z_m = K_v/g = 6.4 \times 10^4 \text{ m}$$

The leading edge of the rising plume will have

much greater initial vertical specific kinetic energy. On the other hand, a large fraction of the remainder of the mass of the plume will have less than the average kinetic energy and is unlikely to rise much above the $5 \frac{9}{10}$ km level.

From the preceding argument it would appear that most of the ejected high-velocity material will remain trapped in the stratosphere. This applies particularly to all the coarse solid and liquid debris. Whether the fine aerosols can be carried higher by the volatile part of the plume, depends on the rate of expansion and on the internal energy.

Any silicate vapor in the plume soon condenses to liquid droplets or solid grains. The mixture of silicate melt droplets, solid particles and shock-heated water vapor tends to approach local internal thermal equilibrium in all but the most energetic parts of the plume. To estimate the equilibrium temperature of this mixture, we equate the specific internal energy $e_p/2$ to the difference between the enthalpy of the plume mixture, immediately after impact, when it had a characteristic mean temperature $T = T_0 + T'$, and a reference state which was characterized by the mean ambient ocean temperature $T_0 = 277^\circ$. Approximately:

$$e_p/2 = (\delta_r C_r + \delta_w C_{pv})T' + \delta_v L(T_0)$$

where $\delta_r = 0.84$ is the mass fraction of rocky material, $\delta_v = 0.16$ is the mass fraction of water vapor, $C_r \approx 1000$ J/kg is the approximate specific heat of the rocks, $C_{pv} = 1867$ J/kg K is the specific heat of water vapor at constant pressure and $L(T_0) = 2.51 \times 10^6$ J/kg is the latent heat of evaporation at the temperature T_0 . Substitution of 3×10^6 J/kg for e_p yields, after introduction of the quoted numbers, $T' = 965^\circ$ K and therefore $T = T_0 + T' \approx 1240^\circ$.

The potential temperature of the water vapor is considerably lower than T because of the high initial pressure. To obtain a very crude estimate of this pressure, we consider that 16% of the plume kinetic energy will have been contained in 37% of the initial volume. Equating the kinetic energy per unit volume with the initial pressure, one might estimate the latter to have been of order:

$$\begin{aligned} p &= 1.4 \times 10^9 \text{ J/m}^3 = 1.4 \times 10^7 \text{ mbar} \\ &= 1.4 \times 10^4 \text{ atm} \end{aligned}$$

The potential temperature can then be computed from:

$$\theta = T \left(\frac{P_0}{p} \right)^{R_v / C_{pr}} = 120^\circ \text{K}$$

This is almost certainly a gross underestimate. The potential temperature in the plume will be increased by condensation once the temperature and pressure have dropped below their critical values ($T = 637^\circ \text{K}$, $p = 195 \text{ atm}$), when the plume assumes the character of a rising steam cloud. The potential temperature remains, however, below 1000°K , that is below the approximate potential temperature of the ambient air at the 80-km level at the top of the stratosphere. Most of the ejected water vapor is therefore expected to find its ultimate equilibrium level below the mesopause and within the stratosphere. The global distribution of cloud droplets and solid material—including iridium—would then be chiefly an airborne transport process.

The existence of a stratospheric equilibrium level does not imply that there will be no overshooting. During an early stage of the evolution, part of the water vapor in the plume is likely to expand well into the ionosphere. Solar radiation there would dissociate the water causing an increase of the atomic oxygen mixing ratio. In fact repeated events of this type may have contributed to the oxygen content of the atmosphere. The importance of this effect depends on the relative rates of photo dissociation and of fall back into the stratosphere. We have not attempted to model this here.

It is interesting to note that the ultimate conditions are not very sensitive to the amount of impact energy W . If W increases, the total amount of energy is larger but the amount of ejected material is also larger. The change in the plume specific energy is therefore relatively small. Substantially different specific energies can be expected if either W is much smaller or if it is large enough for the enthalpy of the excavated rocks to become comparable to the energy of the bolide.

3.5. The surface temperature change

What will be the effect of stipulated events upon the global surface temperature? In the first

instance, we are adding locally a mass $M_p = 1.1 \times 10^{17} \text{ kg}$ to the mass of the atmosphere. The resulting initially localized pressure excess will be spread around the globe in less than 18 hours by pressure waves. It will then produce a mean pressure increase of:

$$\frac{gM_r}{4\pi r^2} = 23 \text{ mbar}$$

The associated adiabatic compression of the surface air layer would cause an immediate global surface temperature increase of about 2°C . Much of this will be transient, as the larger solid component of the plume will fall back quickly. If one assumes that only the vaporized mass of ocean water remains airborne for some time, the global pressure increase would be about 4.4 mbar with a corresponding long term surface temperature rise of only about 0.35° . The continued suspension of other aerosols may increase this to perhaps 0.5° .

By itself, a global increase of surface temperature by about one half degree would not be very dramatic. The effect is amplified, however, by the subsequent increase in tropospheric humidity and the resulting change in the surface radiation balance. Convective processes tend to keep the mean relative humidity of the atmosphere approximately constant. The troposphere adjusts itself to any forced increase of its temperature and of the surface temperature by an increase of its absolute water content. As water vapor is a most effective absorber of infrared radiation, but is transparent to visible radiation, any increase enhances the greenhouse effect on the Earth's surface. This is the reason why modellers have found that a forced increase in the surface temperature actually decreases the radiation balance—that is the net outgoing radiation near the Earth's surface [42]. As a result, the forced increase of the surface temperature by 0.5° could result in a new equilibrium surface temperature which is more than one degree warmer than the original state.

The new higher equilibrium temperature would require a few months to establish itself. During this period, atmospheric diffusion will have produced a change in the composition of stratospheric air all over the globe which could cause a surface temperature change of very much larger ampli-

tude. The gas and aerosols of the original plume can be diffused globally by large-scale turbulence in the atmosphere within a relatively short time. As in the ocean, one should expect the spreading of the initial disturbance to give rise to an anticyclonic circulation. The diameter of this anticyclone, however, will be one or two orders of magnitude larger in the atmosphere than in the ocean. In most latitude belts, the plume material will be carried zonally around the globe in the stratosphere within a period of a few weeks. Meridional diffusion is somewhat slower. Studies of bomb tritium and of transient CO_2 suggest that it takes about one year for material from northern hemisphere sources to reach the South Pole (Claes Rooth, personal communication).

The plume will inject a relatively very large amount of water and water vapor into the stratosphere. Normally, the turbulent vertical diffusion of water vapor into the upper atmosphere is inhibited by the low temperature of the upper tropical troposphere, which sets an upper bound on the mixing ratio of air which is entrained into the stratosphere. As a result, it is thought that the mean amount of water vapor above the 100-mbar level amounts at present to less than 4×10^{-3} kg/m^2 which is equivalent to a depth of 0.004 cm of precipitable water.

The impact plume carries 2.2×10^{16} kg of water substance. Spread out over the globe this is equivalent to 43 kg/m^2 or more than 4 cm of precipitable water. Most of this will rain out rather quickly and incidentally carry almost all the ejected dust back to the surface. The remainder should remain airborne for some considerable time—until photochemical processes re-establish the initial state. Until then, one would have to expect an upper stratosphere made up predominantly, if not entirely, of water vapor and suspended ice crystals. The temperature distribution in such a water vapor stratosphere cannot be expected to be the same as today's U.S. Standard Atmosphere. However, if, as a first approximation, one takes the latter as a guide, one finds that about 0.2 cm of precipitable water would suffice to saturate the mean annual standard atmosphere at 15°N throughout the layer from 100 mbar at about 16 km to 2 mbar level at about 44 km height. Between 44 km and 66 km the

atmosphere at 15°N could not be saturated with present-day temperatures because the static pressure there is smaller than the vapor saturation pressure. Saturation could occur again between 66 km and the lower ionosphere—the region of noctilucent clouds.

For the present purpose, we note that a high-level injection of about 2 cm of precipitable water would suffice to replace all the present constituents of the upper stratosphere above 45 km by pure water vapor and to saturate all the lower stratosphere below. A very much smaller change would be amply sufficient however to produce very large climatic effects.

The increase of the equilibrium temperature at the Earth's surface which is produced by a change in the stratospheric water content—in terms of precipitable water above the 100-mbar level—is shown in Table 4. The first line of this table is said to be reasonably representative of today's stratospheric water content. It can be seen that an injection of less than 0.01 cm of precipitable water would be sufficient—within the terms of the model—to produce a surface temperature increase of about 8°C . The preceding arguments suggest that a very much larger amount of water was injected into the stratosphere. Furthermore, if a hot spot remained at the ocean surface, the charging of the lower stratosphere with water vapor may have continued for a rather long time.

The last aspect to be considered is the effect of aerosols. These can either cool or heat the Earth's surface depending largely on their size. A good review of this subject has been published recently [43]. Stratospheric aerosols can have a marked cooling effect if they are made up of particles below a critical size, which varies with the material.

TABLE 4

The variation of the equilibrium temperature at the earth's surface T_s with the depth D of precipitable water above the 100-mbar level (after Manabe and Wetherald [42])

D (cm)	T_s
3×10^{-4}	288.4
1.5×10^{-3}	290.4
7.5×10^{-3}	296.4

Larger particles tend to warm the surface. In the present case, with a large amount of water vapor available, practically all the small, solid particles will act as condensation or freezing nuclei. As a result, there will be some further precipitation of suspended matter. Much of the remainder is likely to remain suspended as droplets or crystals which are above the critical size and which will form extensive layers of stratospheric cirrus clouds. This will tend to cool the stratosphere [44]. On the other hand, Manabe's model shows that it would tend to produce an additional, rather dramatic temperature increase on the ground.

In summary, the following scenario may describe the postulated sequence of climatic effects after impact of an asteroid or comet nucleus in the ocean. An increase in atmospheric pressure would raise the mean global surface air temperature by about 1°C. The increase would occur within hours. It would be largest in the vicinity of the impact. A spreading dust cloud would subsequently intercept a substantial fraction of solar radiation. This would tend to produce cooling over an extensive area. It would also reduce the sun light available for photosynthesis. However, because of the very large amount of moisture, most of the dust would be washed out within a few weeks or months. After that, the remaining water vapor and clouds in the stratosphere would cause a substantial global temperature increase at the surface which could have exceeded 10°C. The anomaly would persist until diffusion and photochemical processes in the upper stratosphere had reestablished the planetary equilibrium (months to years).

4. Conclusions

It appears that an oceanic impact would inject enough water substance into the stratosphere to raise the surface temperature (ocean and land) by an amount sufficient to produce the selective extinctions observed at the Cretaceous/Tertiary boundary.

If, as suggested, heat was the principal cause of the extinctions, at least some of the vacated niches should have been repopulated from colder environments, the higher latitudes and/or, in the

case of marine organisms, deeper water. The generally "cold" character of the early Paleocene faunas and floras supports this contention.

It should be noticed that the last twenty million years of the Cretaceous were a period of transition, a period of accelerating marine regression and environmental change [45]. Conspicuous faunal and floral changes were in progress, including the reduction of such groups as the ammonites in both diversity and number [46]. Asteroid or comet impact, therefore, should be viewed as a catastrophe for the flourishing groups affected and as a *coup de grace* for the dwindling groups that were brought to an end.

It has been shown that for some groups, such as the mammals, diversity at the generic level was actually *greater* shortly after the boundary than before [17]. This has been taken to indicate that mammals were little affected by the boundary event. Actually, it appears that half of the genera did not cross the boundary (Table 3). The remarkable diversity observed after the boundary is better interpreted as demonstrating that radiation can be explosive *when a number of attractive ecological niches becomes suddenly available*. In fact, abrupt environmental changes produced by major impact events and other causes may well be means by which nature prods the biosphere into periods of explosive evolution and adaptive radiation. The rapidity of these phenomena (as exemplified by the terminal Cretaceous event) may explain the continued absence of "missing links" from the paleontological record and the apparent sudden "creation" of new species and higher taxa (*macroevolution*) at critical times during the long history of life on Earth.

The selected extinctions and declines, and, more importantly, the selected survivals at the Cretaceous/Tertiary boundary would seem to be best explained in terms of a catastrophic but very short ecological jolt, such as the one produced by the postulated impact. A corollary is that extinctions must have been simultaneous for the groups listed in Table 3. Although this has not yet been proven to be the general case [47], synchronism between the most conspicuous extinctions, those of the phyto- and zoo-plankton is a proven fact.

Survival of the higher plants at the generic level

was 69% (Table 3), but at the specific level it was of course much lower. It appears that extinction of higher plant species was not uniformly distributed throughout the globe but was restricted mainly to the Aquilapollinites province [48] which extends from the Urals eastward through Siberia and western North America to the Rockies. The southern border corresponds roughly to the southern border of Siberia and the border between the United States and Mexico. This province, in other words, surrounds the northern North Pacific. Hickey's [48] data indicate that the "pole of destruction" is in the northern North Pacific-Bering Sea area. This is *not* a latitudinal effect because no appreciable amount of species extinction is exhibited by either the adjacent Normapolles province (which ranges from the Rockies eastward across eastern North American and Northern Europe to the Urals), nor by the high southern paleolatitudes (e.g., Australia). We venture the suggestion that the "pole of destruction" mentioned above locates, in effect, the point of impact.

Although the object proposed by Alvarez and co-authors may well have been the largest to strike the earth since the beginning of the Cambrian, at least several others not much smaller should have encountered the earth and produced similar effects. The discovery of their geochemical signatures and their effects on the biosphere may well prove to be a fruitful field of research for years to come.

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