# Impact dust not the cause of the Cretaceous-Tertiary mass extinction

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## ABSTRACT

**Most of the 3-mm-thick globally distributed Chicxulub ejecta layer found at the Cretaceous-Tertiary (K-T) boundary was deposited as condensation droplets from the impact vapor plume. A small fraction of this layer ($<1\%$) is clastic debris. Theoretical calculations, coupled with observations of the coarse dust fraction, indicate that very little ($<10^{14}$ g) was submicrometer-size dust. The global mass and grain-size distribution of the clastic debris indicate that stratospheric winds spread the debris from North America, over the Pacific Ocean, to Europe, and little debris reached high southern latitudes. These findings indicate that the original K-T impact extinction hypothesis—the shutdown of photosynthesis by submicrometer-size dust—is not valid, because it requires more than two orders of magnitude more fine dust than is estimated here. Furthermore, estimates of future impact hazards, which rely upon inaccurate impact-dust loadings, are greatly overstated.**

**Keywords:** Cretaceous-Tertiary boundary, mass extinctions, Chicxulub crater, impact crater, ejecta.

## INTRODUCTION

Two decades of research have clearly linked the Cretaceous-Tertiary (K-T) mass extinction to the catastrophic meteorite impact that formed the Chicxulub crater in Yucatan, Mexico. Nevertheless, causal factors in this link remain uncertain, and research continues on the mechanisms by which large impacts disrupt the biosphere. This paper examines the evidence for the impact extinction mechanism originally proposed by Alvarez et al. (1980): photosynthesis shutdown by a global cloud of fine dust. Although several other impact extinction mechanisms have been proposed for the K-T boundary, the dust hypothesis is perhaps the most widely recognized. Furthermore, impact dust is one of the key environmental perturbations used to estimate future hazards from more modest-sized impacts (Chapman and Morrison, 1994).

## ALVAREZ DUST EXTINCTION HYPOTHESIS

The original K-T impact extinction hypothesis of Alvarez et al. (1980) stated that there was a collapse of the global food chain due to the shutdown of photosynthesis by sun-blocking silicate dust injected into the stratosphere. The dust-loading threshold for photosynthesis is $\sim 10^{16}$ g of submicrometer-size dust (Gerstl and Zardecki, 1982; Toon et al., 1982). Below this mass, light levels remain sufficient for photosynthesis. Thus, the major challenge in evaluating the Alvarez dust hypothesis is estimating the mass of globally distributed submicrometer-size dust.

## THEORY AND EXPERIMENT

### Silicate Dust

Toon et al. (1997) used theoretical calculations coupled with energy scaling of experimental and atomic bomb data, adapted from O'Keefe and Ahrens (1982), to estimate that $\sim 3 \times 10^{17}$ g of submicrometer-size dust was lofted into the stratosphere by the K-T impact. Nevertheless, the data on particle-size distributions for impacts and atomic blasts used by O'Keefe and Ahrens (1982) do not cover size ranges below 50 μm. Below 100 μm, these same data show a sharp drop-off in cumulative mass, suggesting that the target rocks resist fragmentation below the crystal domain size of 100 μm (e.g., Melosh, 1989). O'Keefe and Ahrens (1982) assumed a simple exponential decrease in cumulative mass from 50 cm to 0.5 μm, which indicated that $\sim 0.1\%$ of impact debris would be $<1$ μm. Given the evidence for a drop-off in the $<100$ μm size fraction, a better estimate of the submicrometer-size dust is $<0.1\%$, perhaps much less.

### Vapor Condensation

Most of the mass in the fireball of an impact is vapor. Theoretical studies of a Chicxulub-size asteroid impact indicate that the vapor plume contained $1–3 \times 10^{18}$ g of silicate vapor from the target rocks (Toon et al., 1997; Pierazzo et al., 1998). The plume also contained vapor from the carbonates and sulfates in the target rock (e.g., Pope et al., 1997). Most of the Ca and Mg in the carbonates and sulfates probably condensed with the silicate vapors. Given the $CO_2$ and $SO_2$ mass estimated by Pope et al. (1997), the mass of vaporized Ca and Mg added an additional $\sim 5 \times 10^{17}$ g to the plume. Finally, the contribution of the impactor must be considered, which would add $\sim 1–3 \times 10^{17}$ g to the plume, or perhaps twice this amount if the impact velocity was $>20$ km/s (Pierazzo and Melosh, 2000). The total mass of the vapor plume was therefore $\sim 2–4 \times 10^{18}$ g. These vapors, which spread globally and condensed (e.g., Zahnle, 1990), are the primary source of the global ejecta layer.

O'Keefe and Ahrens (1982) calculated that vapor condensation droplets from a Chicxulub-size impact would be in the size range of hundreds of micrometers. Ablation of these spherules upon atmospheric reentry could produce smaller particles (Melosh and Vickery, 1991), although Zahnle (1990) calculated that the velocity of most condensates would be too low for significant ablation. Furthermore, the size of the droplets is close to the 100 μm size limit, below which little ablation occurs (Melosh, 1989). Therefore, the vapor condensates from a Chicxulub-size impact probably produce minimal amounts of submicrometer-size particles.

## GEOLOGIC STUDIES

### K-T Fireball Condensates

The thickness of the global ejecta layer is $\sim 3$ mm (e.g., Smit, 1999). The term ''fireball layer'' (Hildebrand and Boynton, 1990) is used here for this global layer. The fireball layer, which contains shocked quartz, spherules, and an Ir anomaly, is the only globally distributed K-T ejecta (other ejecta layers have a limited distribution). Mineralogical studies indicate that the bulk of the fireball layer is altered glass (Pollastro and Bohor, 1993). Well-preserved examples of the fireball layer are composed almost entirely of spherules with relict crystalline textures indicative of quenched melt, and are interpreted to be condensation droplets from the vapor plume (Montanari et al., 1983; Montanari, 1991; Smit et al., 1992a; Pollastro and Bohor, 1993; Bohor and Glass, 1995; Kyte and Bohor, 1995). Spherule diameters range from $\sim 20$ to 800 μm (Doehne and Margolis, 1990; Montanari, 1991; Kyte et al., 1996); a mean of 250 μm was reported from sites in Europe (Smit, 1999).

The 3-mm-thick fireball layer represents a global mass of $\sim 3.8 \times 10^{18}$ g (assuming a mean density of 2.5 g/cm$^3$), which matches the estimates of the vapor-plume mass noted here. Likewise, the composition of the fireball layer is consistent with most of the mass being derived from vapor condensation droplets $\sim 200$ μm in diameter. Nev-

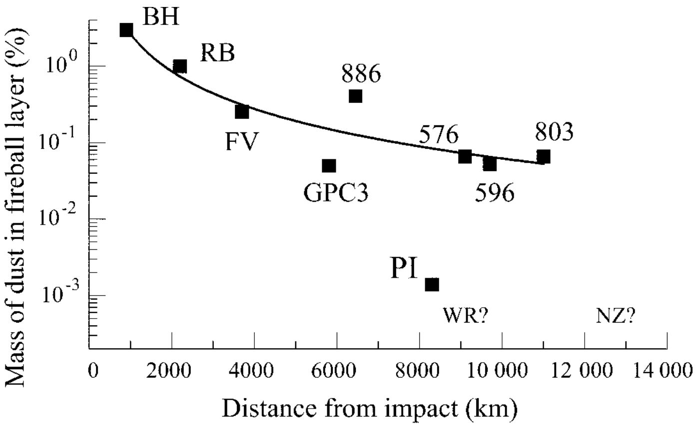

**Figure 1. Estimates of mass percent of clastic debris (dust) in the Cretaceous-Tertiary fireball layer as function of distance from Chicxulub crater. BH—Beloc, Haiti; RB—Raton basin; FV—Frenchman Valley; 886—Pacific core, ODP (Ocean Drilling Program) Site 886; GPC3—Pacific core, GPC (giant piston core) 3; 576—Pacific core, Deep Sea Drilling Project (DSDP) Site 576; 596—Pacific core, DSDP Site 596; 803—Pacific core, ODP Site 803; PI—Petriccio, Italy; WR—Walvis Ridge; NZ—New Zealand. Solid line is a power-law regression, excluding PI, WR, and NZ. See text for discussion of regression and source of estimates.**

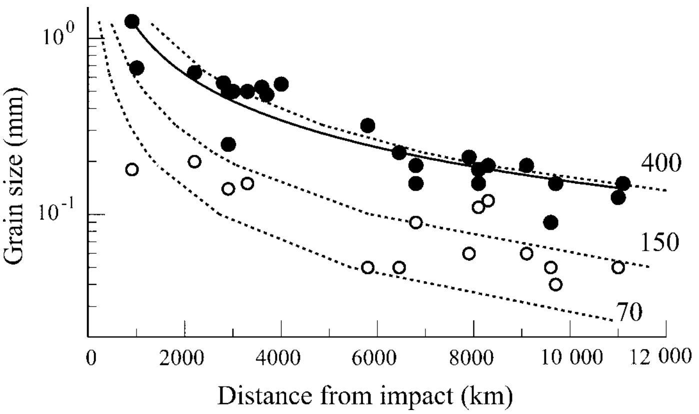

**Figure 2. Relationship between maximum (solid circles) and mean (open circles) shocked-quartz grain sizes in Cretaceous-Tertiary fireball layer and distance from Chicxulub crater. Data are from Bostwick and Kyte (1996), Izett (1990), Kring et al. (1994), Leroux et al. (1995), and Smit et al. (1992b). Solid line is power-law regression of maximum-grain-size data. Dashed lines represent theoretical distributions of grain sizes with distance from impact based on gravitational settling and dispersal of grains by stratospheric winds with speeds of 70, 150, and 400 km/h. Grains are modeled as spheres with densities of 2 g/cm$^3$ initially deposited at an altitude of 70 km over center of crater (cf. Toon et al., 1997).**

ertheless, these analyses do not prove that there is not a fraction of a percent of submicrometer-size dust in the fireball layer.

### Clastic Debris (“Dust”) in the Fireball Layer

The most complete analysis of clastic (pulverized rock) debris in the fireball layer comes from the Pacific Ocean (Bostwick and Kyte, 1996). Of the quartz grains examined, ~65% show evidence of impact shock, and these grains have a mean size ($d$) of 50 μm. The mass percentage of impact clastic debris in the Pacific K-T fireball layer can be estimated by assuming (1) all of the clastic quartz grains were originally deposited in the 3-mm-thick fireball layer; (2) the average mass of quartz grains = ¼ $d^3 \times 2.5$ g/cm$^3$, based on the ~1:2 aspect ratio reported by Izett (1990) and the density of quartz; and (3) the total mass of clastic debris in the fireball layer is equal to two times the mass of quartz, based on the data in Izett (1990) and the complex lithology of the target site (Sharpton et al., 1990). Given these assumptions, and the data reported by Bostwick and Kyte (1996), the mass percentage of clastic debris in five Pacific sites averages ~0.1% (Fig. 1). The same approach can be used to estimate the mass of clastic debris from Beloc in Haiti and Frenchman Valley in Saskatchewan, Canada, based on data reported by Leroux et al. (1995), and from Petriccio, Italy, based on data reported by Montanari (1991). Haiti has nearly 3% clastic debris in the fireball layer, Frenchman Valley ~0.3%, and Italy only 0.001% (Fig. 1).

Izett (1990) found 0.02%–0.7% clastic grains (by weight) in the fireball layer from sites in the Raton basin of Colorado and New Mexico. About half of the clastic grains are quartz, of which ~50% show impact-shock deformation (Izett, 1990). Sharpton et al. (1990) found 1% clastic grains in a 2–5-mm-thick fireball layer from the Raton basin. A clastic mass of 0.5% for the Raton basin is derived by using the methods outlined here and data reported by Leroux et al. (1995). Taking into account that the lower percentages probably represent incomplete recovery, the total amount of clastic debris in the Raton basin fireball layers is estimated to be ~1%.

Izett (1990) found no shocked quartz in an analysis of 15 000 quartz grains from three sites in New Zealand, although a few grains were found in later analyses. Analyses of a core from Deep Sea Drilling Project (DSDP) Site 527 (Walvis Ridge) in the South Atlantic produced only a few shocked-quartz grains, composing ~2% of the quartz grains in the K-T boundary samples (Huffman et al., 1990). These data are insufficient to make estimates of the clastic-debris mass in these two Southern Hemisphere sites, but given the paucity of shocked quartz, the mass is probably less than that found in Italy.

The mass of clastic debris in the fireball layer follows an inverse power-law relationship with distance from Chicxulub (Fig. 1), with the notable exception of Italy (and perhaps Walvis Ridge and New Zealand). With Italy omitted, a power-law regression of the mass ($y$ in %) with distance ($x$ in km) gives the function $y = 208\,012.3 \pm 2.5x^{-1.63 \pm 0.30}$; $r = 0.91$ (95% confidence interval). Another well-known aspect of the shocked quartz in the fireball layer is that the grains become smaller with distance from North America (e.g., Bohor, 1990; Izett, 1990). A compilation of data on maximum (24 sites) and mean (14 sites) shocked-quartz grain sizes is shown in Figure 2. Similar to the mass, there is a clear pattern of decreasing size with distance from the Chicxulub crater (Fig. 2). A power-law regression of the maximum size ($y$ in mm) with distance ($x$ in km) gives the function $y = 482.30 \pm 0.70x^{-0.87 \pm 0.08}$; $r = 0.91$ (95% confidence interval).

## GLOBAL PATTERNS AND PROCESS

The characteristics of the clastic debris in the fireball layer show clear geographic patterns that are not readily explained by ballistic transport. Alvarez et al. (1995) noted that the launch velocity required for ballistic transport of shocked quartz to distal K-T boundary sites can only be achieved by ejecta that is subjected to shock pressures that would have annealed or melted the quartz. They explained this apparent anomaly with a velocity boost imparted to moderately shocked ejecta by the vapor plume. Nevertheless, models of Chicxulub ballistic ejecta dispersal, with a velocity assist from the vapor plume (Durda et al., 1998), do not reproduce the mass distributions of clastic debris shown in Figure 1. Durda et al.’s (1998) model predicts that impacts produce a distribution of ballistic ejecta that is largely symmetrical around the crater. The model does not explain why Italy has more than an order of magnitude less debris than Pacific DSDP Site 576, which is at about the same radial distance from Chicxulub as Italy. Likewise, ballistic transport of clastic ejecta cannot explain the size sorting shown in Figure 2. Ballistic transport to distal sites occurs mostly outside the atmosphere, where no sorting would occur. Once in the atmosphere,

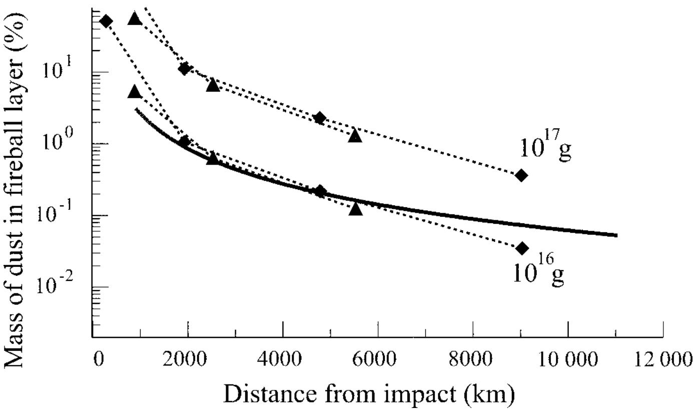

**Figure 3. Model (dashed lines) of clastic-ejecta (dust) mass dispersal compared to observed mass (solid line, from regression line in Fig. 1) in Cretaceous-Tertiary fireball layer. Model results for initial masses of $10^{16}$ g and $10^{17}$ g and wind speeds of 150 km/s (diamonds) and 400 km/s (triangles) are shown. Data points on dashed lines are center points in mass distribution for particles >1000 μm, 1000–500 μm, and 500–200 μm for 400 km/s case; and >1000 μm, 1000–200 μm, 200–100 μm, and 100–50 μm for 150 km/s case. Masses are given as percentages of fireball layer.**

drag would preferentially reduce the trajectory of smaller particles, producing patterns inverse to what is observed.

The mass and grain-size distributions of clastic debris in the fireball layer are better explained by (1) ballistic deposition of moderately shocked ejecta on top of the atmosphere near the crater; (2) subsequent spread of the debris by stratospheric winds; and (3) gravitational settling of debris as the cloud spreads. Such a process was proposed by Toon et al. (1997) and Covey et al. (1990). Covey et al. (1990) modeled the wind dispersal of a cloud of impact dust with an initial loading of $5 \times 10^{15}$ g centered (1000 km radius) on the Manson crater in Iowa. After five days, dense clouds of debris continued to rain down over North America, the northern Atlantic, and the Pacific; moderate dust loading had spread to central and western Europe; and very little dust had spread to the southern high latitudes. The speed of westward spread of the cloud was ~150 km/h. This pattern of dispersal is similar to the spread of the volcanic plume of the 1982 eruption of El Chichon, located just southwest of the Chicxulub crater, which spread westward at ~70 km/h and encircled the globe with a narrow band of debris (Rampino and Self, 1984).

To examine the wind dispersal of ejecta, grain-size distributions were modeled for three potential dispersal wind speeds: 70, 150, and 400 km/h (Fig. 2), based on the velocities of the Chichon plume, the Covey et al. (1990) impact simulation, and the jet stream, respectively. Note that the particle-size distributions found in the K-T fireball layer follow a power-law relationship similar to the model distributions, and that these distributions are mostly within the range expected for particles dispersed by winds with speeds of between 70 and 400 km/h.

The information on ejecta mass in Figure 1 and ejecta size in Figure 2 can be combined by assuming an initial particle-size distribution. The distribution assumed here is that measured in pyroclastic deposits (Sheridan, 1979). Pyroclastic deposits are a reasonable analogue for clastic ejecta and have been well studied down to the micrometer size range. Figure 3 presents a series of calculations of ejecta dispersion beginning with an initial mass ($10^{16}$ g and $10^{17}$ g) centered on the crater with the size distribution noted. Two models of stratospheric wind dispersion of ejecta (150 km/h and 400 km/h) were then applied. The calculations assumed that the clastic ejecta were dispersed in a radial fashion, which the data and Covey et al.'s (1990) model suggest is not the true case. This simplification will underestimate the true clastic ejecta mass in the fireball layer, given that the latitudinal dispersal of ejecta was probably more limited than the radial dispersal used in the calculations. Calculations were based on the distance particles of a given size range would travel before settling (Fig. 2); then the mass represented by that size range (taken from the size distribution) was distributed over the radial distance covered.

There are two conclusions to be drawn from Figure 3. (1) The distribution of mass is not highly sensitive to the wind speed, because the 150 km/s and 400 km/s calculations produced similar results. This insensitivity is because most of the mass is concentrated in the larger size fraction, so that the different wind speeds only greatly affect sedimentation near the crater. (2) The mass distribution is highly sensitive to the initial mass. The pattern of modeled mass dispersal for an initial loading of $10^{16}$ g compares well with the measured mass in the fireball layer (Fig. 3). Because this simplified model tends to underestimate the mass, the conclusion to be drawn is that the observed mass in the fireball layer is consistent with an initial mass of $<10^{16}$ g. If the initial mass was $10^{17}$ g, much more clastic debris would be expected than is observed. Note that the mass loading in this model is that part of the ejecta that was dispersed by winds and does not equate with the total mass ejected into the atmosphere.

Returning to the issue of the distribution of clastic debris in the K-T fireball layer, the anomalous small mass of debris in Italy, and perhaps Walvis Ridge and New Zealand, can be explained by the asymmetrical dispersal patterns of stratospheric winds. If the impact occurred during summer in the Northern Hemisphere, debris would be transported mostly westward; thus debris must travel three times further to Italy than to the western Pacific. Similarly, stratospheric winds are much less effective in transporting debris latitudinally; hence little debris may have reached New Zealand.

## DISCUSSION

### Implications for the K-T Mass Extinction

Although the submicrometer-size component of the fireball layer cannot be directly examined, it must be very small. Assuming a grain-size distribution typical for distal volcanic-ash deposits (e.g., Carey and Sigurdsson, 1982), the submicrometer-size component of the clastic debris in the fireball layer is probably <1%. The total mass of clastic debris in the fireball layer estimated here is $<10^{16}$ g. Therefore, the mass of submicrometer-size dust in the fireball layer is $<10^{14}$ g, and is perhaps as little as $10^{13}$ g. This mass is two to three orders of magnitude less than that needed to shut down photosynthesis.

These results shed doubt on the importance of impact dust in the mass extinction that marks the K-T boundary. A global atmospheric loading of $<10^{14}$ g of submicrometer-size dust would not cause the catastrophic impact winter often proposed (e.g., Covey et al., 1994). There are, of course, impact hazards other than dust clouds. For the K-T event, the shutdown of photosynthesis and global cooling are more likely to have been caused by the impact production of sulfate aerosols from the target rock (e.g., Pope et al., 1997), and by soot from global wildfires (e.g., Wolbach et al., 1990).

### Implications for Impact Hazards

Dust clouds have also been used to estimate the effects of small impacts (Toon et al., 1997). Given that a Chicxulub-size asteroid (10 km diameter) generates only modest amounts of fine dust, the dust effects from smaller impacts are probably negligible. This conclusion has major ramifications for assessments of future impact hazards. Chapman and Morrison (1994) assumed that the impact of an asteroid between 0.6 and 5 km in diameter would produce enough dust to cause global crop failures leading to the death of 25% or more of the world's population. The lower and nominal (0.6–1.5 km) asteroid sizes used in their calculations are much too small to have global consequences from the dust. Other factors such as sulfate aerosols from the asteroid (Kring et al., 1996) and soot from fires set by ejecta reentry (Toon et al.,

1997) only become important globally for asteroids ≥3 km in diameter. Therefore, the often cited 1:20 000 risk of death by impact (Chapman and Morrison, 1994), which assumes mass mortality during relatively small (1.5 km asteroid) impacts, is greatly overstated.

## ACKNOWLEDGMENTS

This research was funded by the National Aeronautics and Space Administration Exobiology Program contract NASW-96030.

## REFERENCES CITED

Alvarez, L.W., Alvarez, W., Asaro, F., and Michel, H.V., 1980, Extraterrestrial cause for the Cretaceous-Tertiary extinction: Science, v. 208, p. 1095–1108.

Alvarez, W., Claeys, P., and Kieffer, S., 1995, Emplacement of Cretaceous-Tertiary boundary shocked quartz from Chicxulub crater: Science, v. 269, p. 930–935.

Bohor, B.F., 1990, Shocked quartz and more: Impact signatures in the Cretaceous/Tertiary boundary clays, *in* Sharpton, V.L., and Ward, P.D., eds., Global catastrophes in Earth history: Geological of Society America Special Paper 247, p. 335–342.

Bohor, B.F., and Glass, B.P., 1995, Origin and diagenesis of K/T impact spherules—From Haiti to Wyoming and beyond: Meteoritics, v. 30, p. 182–198.

Bostwick, J.A., and Kyte, F.T., 1996, The size and abundance of shocked quartz in Cretaceous-Tertiary boundary sediments from the Pacific Basin, *in* Ryder, G., et al., eds., The Cretaceous-Tertiary event and other catastrophes in Earth history: Geological Society of America Special Paper 307, p. 403–415.

Carey, S.N., and Sigurdsson, H., 1982, Influence of particle aggregation on deposition of distal tephra from the May 18, 1980 Mount St. Helens volcano: Journal of Geophysical Research, v. 87, p. 7061–7072.

Chapman, C.R., and Morrison, D., 1994, Impacts on Earth by asteroids and comets: Assessing the hazard: Nature, v. 367, p. 33–40.

Covey, C., Ghan, S.J., Walton, J.J., and Weissman, P.R., 1990, Global environmental effects of impact-generated aerosols: Results from a general circulation model, *in* Sharpton, V.L., and Ward, P.D., eds., Global catastrophes in Earth history: Geological Society of America Special Paper 247, p. 263–270.

Covey, C., Thompson, S.L., Weissman, P.R., and MacCracken, M.C., 1994, Global climatic effects of atmospheric dust from an asteroid or comet impact on Earth: Global Planetary Change, v. 9, p. 263–273.

Doehne, E., and Margolis, S.V., 1990, Trace-element geochemistry and mineralogy of the Cretaceous/Tertiary boundary: Identification of extraterrestrial components, *in* Sharpton, V.L., and Ward, P.D., eds., Global catastrophes in Earth history: Geological Society of America Special Paper 247, p. 367–382.

Durda, D.D., Kring, D.A., Pierazzo, E., and Melosh, H.J., 1998, Model calculations of the proximal and globally distributed distal ejecta from the Chicxulub impact crater: Lunar and Planetary Science, v. 29, CD abstract 1252.

Gerstl, S.A.W., and Zardecki, A., 1982, Reduction of photosynthetically active radiation under extreme stratospheric aerosol loads, *in* Silver, L.T., and Schultz, P.H., eds., Geological implications of impacts of large asteroids and comets on Earth: Geological Society of America Special Paper 190, p. 201–210.

Hildebrand, A.R., and Boynton, W.V., 1990, Proximal Cretaceous-Tertiary boundary impact deposits in the Caribbean: Science, v. 248, p. 843–847.

Huffman, A.R., Crocket, J.H., Carter, N.L., Borella, P.E., and Officer, C.B., 1990, Chemistry and mineralogy across the Cretaceous/Tertiary boundary at DSDP Site 527, Walvis Ridge, south Atlantic Ocean, *in* Sharpton, V.L., and Ward, P.D., eds., Global catastrophes in Earth history: Geological Society of America Special Paper 247, p. 319–334.

Izett, G.A., 1990, The Cretaceous/Tertiary boundary interval, Raton basin, Colorado and New Mexico, and its content of shock metamorphosed minerals: Evidence relevant to the K/T boundary impact-extinction theory: Geological Society of America Special Paper 249, 100 p.

Kring, D.A., Hildebrand, A.R., and Boynton, W.V., 1994, Provenance of mineral phases in the Cretaceous-Tertiary boundary sediments exposed on the southern peninsula of Haiti: Earth and Planetary Science Letters, v. 128, p. 629–641.

Kring, D.A., Melosh, H.J., and Hunten, D.M., 1996, Impact-induced perturbations of atmospheric sulfur: Earth and Planetary Science Letters, v. 140, p. 201–212.

Kyte, F.T., and Bohor, B.F., 1995, Nickel-rich magnesiowüstite in Cretaceous/Tertiary boundary spherules crystallized from ultramafic, refractory silicate liquids: Geochimica et Cosmochimica Acta, v. 59, p. 4967–4974.

Kyte, F.T., Bostwick, J.A., and Zhou, L., 1996, The Cretaceous/Tertiary boundary on the Pacific plate: Composition and distribution of impact debris, *in* Ryder, G., et al., eds., The Cretaceous-Tertiary event and other catastrophes in Earth history: Geological Society of America Special Paper 307, p. 389–402.

Leroux, H., Rocchia, R., Forget, L., Orue-Etxebarria, X., Doukhan, J.-C., and Robin, E., 1995, The K/T boundary at Beloc (Haiti): Compared stratigraphic distributions of the boundary markers: Earth and Planetary Science Letters, v. 131, p. 255–268.

Melosh, H.J., 1989, Impact cratering: A geologic process: New York, Oxford University Press, 245 p.

Melosh, H.J., and Vickery, A.M., 1991, Melt droplet formation in energetic impact events: Science, v. 350, p. 494–497.

Montanari, A., 1991, Authigenesis of impact spheroids in the K/T boundary clay from Italy: New constraints for high-resolution stratigraphy of terminal Cretaceous events: Journal of Sedimentary Petrology, v. 61, p. 315–339.

Montanari, A., Hay, R.L., Alvarez, W., Asaro, F., Michel, H.V., and Alvarez, L.W., 1983, Spheroids at the Cretaceous/Tertiary boundary are altered droplets of basaltic composition: Geology, v. 11, p. 668–671.

O'Keefe, J.D., and Ahrens, T.J., 1982, Interaction of the Cretaceous/Tertiary bolide with the atmosphere, ocean, and solid Earth, *in* Silver, L.T., and Schultz, P.H., eds., Geological implications of impacts of large asteroids and comets on Earth: Geological Society of America Special Paper 190, p. 103–120.

Pierazzo, E., and Melosh, H.J., 2000, Hydrocode modeling of oblique impacts: The fate of the projectile: Meteoritics and Planetary Science, v. 35, p. 117–130.

Pierazzo, E., Kring, D.A., and Melosh, H.J., 1998, Hydrocode simulation of the Chicxulub impact event and the production of climatically active gases: Journal of Geophysical Research, v. 103, p. 28 607–28 625.

Pollastro, R.M., and Bohor, B.F., 1993, Origin and clay-mineral genesis of the Cretaceous/Tertiary boundary unit, western interior of North America: Clays and Clay Minerals, v. 41, p. 7–25.

Pope, K.O., Baines, K.H., Ocampo, A.C., and Ivanov, B.A., 1997, Energy, volatile production, and climatic effects of the Chicxulub Cretaceous/Tertiary impact: Journal of Geophysical Research, v. 102, p. 21 645–21 664.

Rampino, M.R., and Self, S., 1984, The atmospheric effects of El Chichon: Scientific American, v. 250, p. 48–57.

Sharpton, V.L., Schuraytz, B.C., Burke, K., Murali, A.V., and Ryder, G., 1990, Detritus in K/T boundary clays of western North America: Evidence against a single oceanic impact, *in* Sharpton, V.L., and Ward, P.D., eds., Global catastrophes in Earth history: Geological Society of America Special Paper 247, p. 349–357.

Sheridan, M.F., 1979, Emplacement of pyroclastic flows: A review, *in* Chapin, C.E., and Elston, W.E., eds., Ash-flow tuffs: Geological Society of America Special Paper 180, p. 125–136.

Smit, J., 1999, The global stratigraphy of the Cretaceous-Tertiary boundary impact ejecta: Annual Review of Earth and Planetary Sciences, v. 27, p. 75–113.

Smit, J., Alvarez, W., Montanari, A., Swinburne, N., Kempen, T.M., Klaver, G.T., and Lustenhouwer, W.J., 1992a, ''Tektites'' and microkrystites at the Cretaceous/Tertiary boundary: Two strewn fields, one crater?: Lunar and Planetary Science Conference Proceedings, v. 22, p. 87–100.

Smit, J., Montanari, A., Swinburne, N., Alvarez, W., Hildebrand, A.R., Margolis, S.V., Claeys, P., Lowrie, W., and Asaro, F., 1992b, Tektite-bearing, deep-water clastic unit at the Cretaceous-Tertiary boundary in northeastern Mexico: Geology, v. 20, p. 93–103.

Toon, O.B., Pollack, J.B., Ackerman, T.P., Turco, R.P., McKay, C.P., and Liu, M.S., 1982, Evolution of an impact-generated dust cloud and its effects on the atmosphere, *in* Silver, L.T., and Schultz, P.H., eds., Geological implications of impacts of large asteroids and comets on Earth: Geological Society of America Special Paper 190, p. 187–200.

Toon, O.B., Zahnle, K., Morrison, D., Turco, R.P., and Covey, C., 1997, Environmental perturbations caused by the impacts of asteroids and comets: Reviews of Geophysics, v. 35, p. 41–78.

Wolbach, W.S., Gilmore, I., and Anders, E., 1990, Major wildfires at the K-T boundary, *in* Sharpton, V.L., and Ward, P.D., eds., Global catastrophes in Earth history: Geological Society of America Special Paper 247, p. 391–400.

Zahnle, K.J., 1990, Atmospheric chemistry by large impacts, *in* Sharpton, V.L., and Ward, P.D., eds., Global catastrophes in Earth history: Geological Society of America Special Paper 247, p. 271–288.

Manuscript received May 11, 2001
Revised manuscript received September 10, 2001
Manuscript accepted October 2, 2001

Printed in USA

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## Impact dust not the cause of the Cretaceous-Tertiary mass extinction

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*Geology* 2002;30;99-102
doi: 10.1130/0091-7613(2002)030<0099:IDNTCO>2.0.CO;2

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