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K-Pg extinction: Reevaluation of the heat-fire hypothesis

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[1] The global debris layer created by the end-Cretaceous impact at Chicxulub contained enough soot to indicate that the entire terrestrial biosphere had burned. Preliminary modeling showed that the reentry of ejecta would have caused a global infrared (IR) pulse sufficient to ignite global fires within a few hours of the Chicxulub impact. This heat pulse and subsequent fires explain the terrestrial survival patterns in the earliest Paleocene, because all the surviving species were plausibly able to take shelter from heat and fire underground or in water. However, new models of the global IR heat pulse as well as the absence of charcoal and the presence of noncharred organic matter have been said to be inconsistent with the idea of global fires that could have caused the extinctions. It was suggested that the soot in the debris layer originated from the impact site itself because the morphology of the soot, the chain length of polycyclic aromatic hydrocarbons, and the presence of carbon cenospheres were said to be inconsistent with burning the terrestrial biosphere. These assertions either are incorrect or have alternate explanations that are consistent with global firestorms. We show that the apparent charcoal depletion in the Cretaceous-Paleogene layer has been misinterpreted due to the failure to correct properly for sediment deposition rates. We also show that the mass of soot potentially released from the impact site is far too low to supply the observed soot. However, global firestorms are consistent with both data and physical modeling.

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1. INTRODUCTION

[2] *Alvarez et al.* [1980] discovered the iridium anomaly at the Cretaceous-Paleogene (K-Pg) boundary and deduced from it that the K-Pg mass extinction had been triggered by an asteroid impact. Modern evidence supporting their hypothesis has been summarized by *Schulte et al.* [2010]. *Melosh et al.* [1990] showed that the kinetic energy of reentrant ejecta from this impact would have heated the upper atmosphere to incandescence and that the resulting infrared (IR) radiation would have ignited fires around the globe. *Robertson et al.* [2004a] proposed that the terrestrial survivors were sheltered from this heat and fire either underground or in water and then showed that this sheltering hypothesis explains the observed patterns of survival of terrestrial species in the earliest Paleocene. Recent modeling indicates a lower but still sufficient amount of radiation at the surface to ignite widespread fires [*Goldin and Melosh*, 2009].

[3] Evidence supporting global fires includes the results of physical modeling of the upper atmosphere obtained by *Melosh et al.* [1990], *Goldin and Melosh* [2009], and others; the presence of reentrant ejecta as a global layer of spherules near the iridium-containing layer [*Smit*, 1999]; soot in the iridium anomaly layer [*Wolbach et al.*, 1988]; a “fern spike” of spores with an absence of Cretaceous pollen types in sediments above the K-Pg boundary [*Tschudy et al.*, 1984; *Tschudy et al.*, 1984; *Tschudy and Tschudy*, 1986; *Vajda et al.*, 2001]; and a fungal spore spike in the same sediments [*Vajda and McLoughlin*, 2004]. These data imply the complete destruction of global terrestrial communities within days to months after the impact [*Schulte et al.*, 2010, p. 1218], to which *Robertson et al.* [2004a] added evidence from the observed terrestrial survival patterns: No non-aquatic vertebrate much larger than a squirrel survived. All known non-aquatic survivors in the lowest Paleocene, including birds, were plausible burrowers.

[4] The idea of global wildfires was challenged by *Belcher et al.* [2004, 2003, 2005, 2009], *Belcher* [2009], and *Harvey et al.* [2008] because of the absence of charcoal and the presence of noncharred organic matter in the K-Pg boundary sediments as well as by the results of the revised impact modeling by *Goldin and Melosh* [2009] and the lack of

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post-impact erosion at some terrestrial sites. In order to explain the observed soot in the thin layer marking the K-Pg boundary, these authors proposed that the impact itself produced the soot from organic carbon at the impact site. They further claimed that the morphology of the soot, the chain length of polycyclic aromatic hydrocarbons (PAHs) in the K-Pg boundary layer, and the presence of carbon cenospheres in the K-Pg boundary layer can only be explained by the burning of hydrocarbons, not by the burning of biomass. Table 1 summarizes these counterarguments and our alternate explanations, which are detailed below.

2. Computer Modeling of the IR Heat Pulse

[5] *Goldin and Melosh* [2009] reevaluated how much of the downward-directed component of the IR radiation from the reentrant ejecta would reach the surface of the Earth (Table 1, line 1). The mass density of the ejecta spherules is about 10 kg/m^2 over the Earth, and the spherules would have had a velocity only slightly below the escape velocity. Their kinetic energy was converted upon reentry to IR radiation [*Melosh et al*., 1990]. This energy would have been approximately equal to 1 Mt hydrogen bomb explosions at 6 km spacing around the entire planet. However, as *Goldin and Melosh* [2009] pointed out, the impact ejecta would have transferred their heat to the atmosphere and then would have fallen below the emitting layer, effectively blocking some of the IR radiation from reaching the ground. Complete quantification of this effect is not yet available. *Goldin and Melosh* [2009] listed several mechanisms that are not included in their modeling, all of which would tend to increase the radiation intensity at the Earth's surface. These mechanisms include scattering caused by the falling particles (i.e., the particles do not absorb all of the incident radiation, as a gas might, but instead are translucent to some of it and reflect or scatter the rest) and reflection from a possible overlying layer of submicron dust that would redirect some of the outward escaping radiation back toward the Earth. *Johnson and Melosh* [2012] suggested that this submicron dust was largely the remains of the vaporized impactor. However, even the recent calculations of *Goldin and Melosh* [2009, p.1137] describe an IR pulse that is sufficient to ignite tinder, including dried leaves, pine needles, grass, and lichen. Most forest fires today are ignited in tinder, not by the direct ignition of trees, so the IR pulse would be expected to ignite fires across much of the Earth.

[6] Large terrestrial areas could have been sheltered from ignition either by smoke and clouds in the atmosphere or by precipitation, but fires that were ignited elsewhere in the region may have moved quickly into sheltered regions. Fires proximate to each other tend to spread together, which increases the fuel consumption rate, heat release, and flame height [*Finney and McAllister*, 2011]. Fires originating from many ignition points often become unusually intense [*Finney and McAllister*, 2011]; they generate strong local winds, which may inhibit fire spread (*e.g.*, *Eden*, 2004; *Glasstone and Dolan*, 1977). The work of *Goldin and Melosh* [2009] is consistent with the idea that countless individual mass fires were ignited by reentrant ejecta at the K-Pg boundary, but additional modeling may be useful to clarify the behavior of mass fires distributed over continental scales.

3. Charcoal Evidence

[7] *Belcher et al.* [2004, 2003, 2005, 2009], *Belcher* [2009], and *Harvey et al.* [2008] noted the absence or marked reduction of background charcoal in K-Pg boundary sediments (Table 1, line 2). Over six sites, charcoal comprised 1.75% of the K-Pg layer and 16.3% of surrounding rocks [*Belcher et al.* 2003]. *Belcher et al.* [2005] stated that charcoal is lower than local ambient concentrations by factors of 4–8 in the K-Pg layer, suggesting that less charcoal was produced when the K-Pg layer was created than over a similar time interval during the Cretaceous or Paleogene, which seems inconsistent with the large amounts of soot in the K-Pg layer. Several interpretations are consistent with these observations: (1) there could have been fewer fires than normal and therefore less charcoal formed during the K-Pg event, and the observed soot then had to come from sources other than global fires; (2) the time duration for the deposition of the K-Pg layer could have been less than that of adjacent layers of similar thickness; (3) the fires could have produced less charcoal than normal fires because they were hotter, which would have tended to consume charcoal but still produce soot (note that interpretations (2) and (3) are not mutually exclusive); and (4) the particular sites studied by *Belcher et al.* [2004, 2003, 2005, 2009]

Table 1. Arguments Made Against Extinction by Thermal Radiation and Continental-scale Firestorms at the K-Pg Boundary

Evidence	Argument	Our Explanation
Reduced thermal radiation in new models	Fires could not start	Incorrect: Current models predict enough radiation to start fires
Low charcoal in K-Pg boundary layer	Fires suppressed after impact	Data not corrected for sedimentation rate Charcoal destroyed by high-intensity fires
Noncharred organics in K-Pg boundary layer	No fires at sites with noncharred organics	Most surviving K-Pg boundary sediments were deposited under water that sheltered organics from charring
No anomalous post-impact erosion	No removal of vegetation by fires at sampling sites	Rainfall was suppressed; data are from depositional environments
Calculated in situ reduced carbon greater than the mass of the observed soot	Adequate carbon in crater	Assumed crater too large; in situ carbon from crater is inadequate to explain soot
Carbon cenospheres in boundary sediments	Formed only from burning hydrocarbon mists	Incorrect: Cenospheres can form from burning biomass oils
PAHs lack high-temperature forms	PAHs cannot be formed in global firestorms	Incorrect: PAHs easily formed in forest fires; not a unique identifier of burnt oil
Aciniform soot morphology	K-Pg soot looks like oil soot only	Incorrect: K-Pg soot also looks like wood soot

(interior North America) could have been moist with rain or snow. With regard to interpretation (4), it is not clear if moisture would stop a firestorm. For example, the World War II firestorm in Dresden occurred with snow on the ground, and several fires in Japan occurred with either snow on the ground or rainfall [*Eden*, 2004, pp. 90–91]. Due to the physical distances between the sites investigated by *Belcher et al.* [2004, 2003, 2005, 2009], the scenario of no local fires seems unlikely to have occurred, but charcoal data from other parts of the world would be useful.

[8] *Belcher et al.* [2004, 2003, 2005, 2009] followed interpretation (1) that the charcoal data are evidence against firestorms spreading across the globe, stating [2003, p. 1061]: "The K-Pg and lowermost Tertiary sedimentary rocks of six non-marine sequences (Colorado to Saskatchewan) contain no charcoal or below-background levels of charcoal and a significant quantity of noncharred organic materials, revealing that there was no distinctive wildfire across the North American continent related to the K-Pg event." *Harvey et al.* [2008, p. 355] repeated the claim: ". . .minimal amounts of charred plant remains and abundant noncharred material occur in various K-Pg boundary locations across North America. This refutes the inference that wildfires occurred on a global scale.. . ."

[9] This interpretation by *Belcher et al.* [2004, 2003, 2005, 2009], *Belcher* [2009], and *Harvey et al.* [2008] requires that the observed soot did not come from wildfires but did from another source. *Belcher et al.* [2003] suggested this other soot source is hydrocarbons at the impact site, which we will show (below) to be implausible. In addition, as pointed out by *Robertson et al.* [2004b], this interpretation also requires an explanation for why normal (non-impact) wildfires did not occur at this time. *Belcher et al.* [2003; 2005; 2005; 2009] did not attempt to explain why normal forest fires did not create charcoal in the K-Pg boundary sediments as they did in the adjacent sediments.

[10] The most likely explanation for this lack of normal charcoal deposition is interpretation (2), that the K-Pg layer was created within a short period compared with other layers of similar thickness, i.e., short compared to the time to deposit charcoal from fires. In analyzing their data on pPAH (discussed below), *Belcher et al.* [2009, p. 4113] recognized the need to correct for differing sedimentation rates between the K-Pg layer and the surrounding sediments. They used data on variations in organic carbon in the sediments to correct for the variations in sedimentation rate and thereby renormalize the abundance values of pPAH. The average values for these organic carbon sedimentation rate–renormalizing factors are larger by a factor of about 12 for the data in the boundary clay compared to those for the data in the adjacent sediments, substantially larger than the average charcoal depletion values of 4–8 reported by *Belcher et al.* [2005]. This renormalization therefore converts minimum values in pPAH in the K-Pg layers into maximum values, relative to the adjacent sediments, and these same sedimentation rate corrections that were used for the pPAH data should have been applied to the charcoal data as well. Had they been applied, the charcoal data would not show a minimum in the K-Pg layer and instead show a maximum, and the reported deficiency in charcoal in the boundary sediments would be seen as nothing more than an artifact of changing sedimentation rates. Our arguments below and the scaling applied by *Belcher et al.* [2009, p. 4113] for pPAH strongly suggest that the charcoal depletion discussed by *Belcher et al.* [2003, 2005; 2005; 2009] is simply an artifact of increased sedimentation rate in the K-Pg layer.

[11] It should be noted that if it required more than a day or two to burn the nearby forests, the spherule-containing parts of the K-Pg layers would have been depleted in charcoal even if the entire forest burned, because the spherules only took a few days to fall to the ground. Charcoal is generally transported by rain to areas where it is measured. If it took more than 1 year to transport the charcoal to the locations that were studied by *Belcher et al.* [2003; 2004; 2005; 2009], then the entire layer would seem depleted in charcoal because even fine particles in the post-impact atmosphere would settle out in a year or two. As noted below, rainfall in the several years after the impact was likely greatly suppressed. If rainfall was needed to transport the charcoal to the locations studied by *Belcher et al.* [2003; 2004; 2005; 2009], then the deposition of charcoal in the K-Pg layer would have been suppressed even though all the forests burned.

[12] Charcoal is formed during vegetation fires from charring woody fragments under reducing conditions as described by *Cofer et al.* [1997] and usually composed of large particles. Elemental carbon, often called soot, is usually micrometer sized or smaller. While elemental carbon can be easily dispersed over the globe by winds, charcoal is generally likely to be removed from the atmosphere near the source. Hence, the distribution of charcoal and its deposition in lake or peat bog sediments where it can be found later in sedimentary records depend on many local factors, such as wind speed and direction during the fire as well as rainfall during and after the fire that may wash debris into the lake or bog. While soot is an indication of global fire activity, charcoal is an indication of highly localized activity and therefore harder to interpret. Hence, it is possible, and in fact highly likely, that the charcoal data have no clear information content about the presence or absence of fires and to first order it reflects the time scales of deposition and/or the time scales between natural fires.

[13] Interpretation (3), as pointed out by *Robertson et al.* [2004b], suggests that the charcoal data constitute evidence supportive of K–Pg firestorms that spread over large areas with sufficient intensity to consume much charcoal. *Belcher et al.* [2005, p. 596] attempted to show that charcoal would be produced in such firestorms by soaking pieces of pine in distilled water for 5 days and then placing them in an oven for 2 h. The relevance of this experimental procedure to actual charcoal production in a firestorm is dubious at best. The issue to understand for quantifying charcoal production is the ratio of smoldering combustion to flaming combustion. The latter type produces soot and the former charcoal. This ratio varies considerably between different types of vegetation. For example, grass or savannah fires generally burn with little smoldering and therefore produce little charcoal, while boreal fires have significant smoldering phases [*Cofer et al.*, 1997; *Stocks and Kauffman*, 1997]. Mass fires grow from many ignition points and generate inflowing winds of high velocity. Because of these inflowing winds, combustion tends to be relatively complete, which suppresses the formation of charcoal.

[14] Unfortunately, there are very little data on firestorms because they are relatively rare in nature, and it is difficult to burn an area large enough to conduct experimental

studies. Historical fires include the Peshtigo (Chicago) fires of 1871 [*Haines and Kuehnast*, 1970] and the fires that resulted from the San Francisco earthquake in 1906 [*Lawson et al.*, 1908]. *Glasstone and Dolan* [1977, p. 299] stated that in the burned area of Hiroshima, "virtually everything combustible within the firestorm area was destroyed." Charcoal of course is a combustible material. Similar anecdotal data come from the Hamburg firestorm of July 1943. *Ebert* [1963] quoted an air temperature of about 800°C, apparently based on the fact that glass windows in cars and trams melted in the streets. According to *Lowe* [2007, p. 184], cutlery, glass, and bricks burned to ash inside buildings where it must have been even hotter than the outside air temperatures. There were only moderate winds about 4 mi outside the core of the firestorm rising from about 18 to 54 km/h as the storm grew [*Ebert*, 1963]. However, inside the firestorm, violent winds were estimated near 180 km/h. People were reported to have been blown into the fire or having to crawl to move against the winds [*Lowe*, 2007, pp. 190–202]. *Lowe* [2007, p. 206] stated that "[i]n many areas the house facades were the only things left standing. . .everything else—floors, ceilings, furniture, the stuff of people's everyday lives—all had been consumed. In some buildings, particularly those whose occupants had stocked up early on coke and coal for the winter, the fire would continue to burn. . .." Clearly, these observations suggest that charcoal, even when relatively protected in a basement, cannot survive a mass fire.

[15] It has been suggested that global firestorms would initiate convection and rainfall that would wash smoke and soot out of the atmosphere and inhibit global distribution of that soot that is observed in the K-Pg boundary sediments in Europe and New Zealand [*Wolbach et al.*, 1985, 1988]. *Toon et al.* [2007, p. 1994] and *Turco et al.* [1990] argued that in major fires the soot production is so great that it will overseed the resulting cumulus clouds, thereby severely inhibiting rainfall. Therefore, only about 20% of the total soot/smoke production can be expected to be washed out. These ideas are supported by direct measurements of particulates in deep convective clouds, as well as by direct observations of smoke being placed into the stratosphere from large forest fires [*Fromm et al.*, 2000; *Fromm et al.*, 2008; *Siddaway and Petalina*, 2011]. The injection of a large fraction of the soot into the stratosphere is consistent with the enormous total volume of soot reported by *Wolbach et al.* [1988], about 4% of the total biomass carbon, roughly the total that would be expected from complete combustion of the global biomass (much of the carbon goes into CO_2, not soot).

4. Noncharred Organic Material in the K-Pg Boundary Sediments

[16] The observed widespread presence of noncharred organic material in K-Pg boundary strata (Table 1, line 3) does not constitute evidence against a global firestorm, contrary to the claims of *Belcher* [2004, 2003, 2005, 2009], *Belcher* [2009], and *Harvey et al.* [2008]. Rather, this noncharred material is best explained by Kirk Johnson's observation (personal communication, 2005) that most terrestrial K-Pg boundary–layer sediments were deposited under water, in ponds and mires in poorly drained landscapes [see also *Fastovsky and Dott*, 1985*; Nichols and Johnson*, 2008]. *Belcher* [2009, p. 4113] stated that all of their sites were pond or swamp deposits. Only a few centimeters of water would have provided adequate shelter against charring of organic materials by the K-Pg firestorms. Standing water therefore adequately explains the observed survival of noncharred organic material through the heat and fire that followed the impact.

5. Estimates of Carbon in Situ

[17] *Harvey et al.* [2008] and *Belcher et al.* [2009] proposed that soot in situ in the K-Pg sediments was produced by combustion of carbon in the pre-impact strata at Chicxulub (Table 1). *Harvey et al.* [2008] calculated that 10^{18} g of reduced carbon was available in the pre-impact rock, which would have been more than enough to produce the 7 × 10^{16} g (~70 km^3) of soot observed by *Wolbach et al.* [1988].

[18] The calculations by *Harvey et al.* [2008] used 200 km, the approximate size of the outer crater wall, for the crater diameter, but the impact would have ignited carbon only within a much smaller region inside the so-called transient crater, the hole made during the initial impact, whose diameter has been estimated as 80–110 km [*Morgan et al.*, 2002]. The simulations by *Pierazzo and Melosh* [1998] showed that temperatures inside this transient crater would have reached the approximate ignition point of organic carbon compounds (~600 K) within a diameter of only about 70 km, which we used as a starting point for estimating the amount of organic carbon released from the rocks in the impact zone.

[19] The stratigraphy described by *Ward et al.* [1995] shows that Paleozoic sediments are completely absent at Chicxulub, as is coal. *Claeys et al.* [2003] stated that sediments under the Yucatan Peninsula of either the Triassic age or the Jurassic age to the Early Cretaceous age occur above the crystalline basement. In the stratigraphic columns shown by *Ward et al.* [1995], the pre-impact sediments at Chicxulub consist of approximately 3 km of Mesozoic carbonates and evaporites with about 3%–4% shale and sandstone. The global average limestone has 0.2% C; shale has 0.9% C [*Gehman*, 1962]. These values should be representative of the Chicxulub limestones except those for the Cretaceous Oceanic Anoxic Event 2 (Bonareli Event; *Ward et al.*, 1995) and possibly late Jurassic rocks where organic carbon concentrations might be as high as 5% for tens of meters (D.A. Budd, personal communication, 2011). These carbon-rich units would affect the calculated total carbon content in the entire stratigraphic column underlying Chicxulub by only about 10%–20%. Thus, the total reduced carbon within a radius of 35 km of the impact with a depth of 3 km is about 6 × 10^{16} g, which would produce *Wolbach's* [1988] estimate of soot only if all of the carbon were converted to soot. In combustion, however, much carbon is converted to carbon dioxide. Typical soot emission factors for burning hydrocarbons are about 3%–10% [*Turco et al.*, 1990]. Thus, the total carbon in the strata combusted by the Chicxulub impact is 1 or 2 orders of magnitude less than the amount that is needed to produce the soot observed by *Wolbach et al.* [1985, 1988]. The only plausible alternate source of the observed soot is combustion of biomass in global firestorms.

5.1. Carbon Cenospheres

[20] Cenospheres are hollow spheres of 10–500 μm diameter. One type is composed mainly of silica and alumina ("ceramic"); it is gray or white. An example is found in the by-product of coal combustion at thermal power plants. Carbon is a minor constituent. A second type of cenosphere is produced from the burning of oils in sprays or with bubbles. These are carbon cenospheres.

[21] *Harvey et al.* [2008] claimed that carbon cenospheres observed in K-Pg boundary sediments could have formed only from hydrocarbons in situ at Chicxulub (Table 1). *Harvey et al.* [2008] stated that carbon cenospheres require dispersion of organic matter as small droplets or particles prior to heating, which cannot occur by combustion of exposed fossil organic matter or wildfires. *Belcher et al.* [2009] also stated that carbon cenospheres can only be formed by combustion of hydrocarbons.

[22] The assertions that cenospheres are diagnostic of hydrocarbon combustion are not supported by *Lightman and Street* [1983] and are contradicted by *Wornat et al.* [1994], who reported that biomass oil combustion produces droplets that emit clouds of soot caused by gas-phase pyrolysis leading to the formation of carbonaceous cenospheres. *Hallett and Clark* [2006] reported similar conclusions. Heating the ashes of some plants (sugar cane, wheat, and rice) produces cenospheres [*LeBlond et al.*, 2008; *Thy et al.*, 2006]. These happen to be grasses; grasses are not generally thought to be found in the Cretaceous, but evidence for Cretaceous grasses has recently been discovered [*Prasad et al.*, 2005]. These plants are rich in silica, which can melt at high temperature, resulting in the formation of quasi-spherical particles similar to those produced from burning coal. According to *Novokov et al.* [1997], "Biomass burning particles include some hollow carbonaceous spheres with a mean diameter of 200 to 400 nm, similar in appearance to fly ash particles although much smaller." Therefore, the presence of cenospheres cannot be taken as evidence against global wildfires being a source of carbon in the K-Pg sediments.

[23] *Harvey et al.* [2008] estimated the mass of cenospheres in the K-Pg layer as 2×10^{12} g. The efficiency of cenosphere production from burning oil is relatively high. Data from *Bomo et al.* [1984] give cenosphere yields as high at 2×10^{-3} from burning oil at high temperature. If, as we suggest, 6×10^{16} g of organic C was available from the Chicxulub impact, about 1.2×10^{14} g of cenospheres could have been produced by the impact. Hence, it is possible the cenospheres came from the impact site. It is also possible they came from burning vegetation, but the types of vegetation at the various sites where cenospheres are observed are not known, apparently as is the cenosphere production efficiency from burning plants.

[24] The small mass of cenospheres [~2×10^{12} g; *Harvey et al.*, 2008] and their relatively large size (d, ~6 μm) account for their negligible optical depth: ~$3M/(Ad\rho) \sim 6 \times 10^{-3}$, where ρ is the particle density [~0.28 g cm^{-3}; *Harvey et al.*, 2008], M is the global mass, and A is the area of the Earth. Therefore, the cenospheres are of little relevance to changes in the post-impact climate. The carbon mass from the impact is not sufficient to produce more than a few percent of the soot in the K-Pg layer; the soot is relevant to climate, as discussed below, and it is evidence for global fires.

5.2. Polycyclic Aromatic Hydrocarbons

[25] PAHs are widespread complex organic ring compounds that can be produced in burning organic matter. Belcher *et al.* [2009] argued that the boundary impact rocks have a pPAH signature consistent with the combustion of hydrocarbons and not living plant biomass, but *Venkatesan and Dahl* [1989] argued that the PAH distributions at the K/T boundary from their study sites reflect combustion, which links them to global fires, as did *Arinobu et al.* [1999]. The origin of PAHs is unresolved, but their production by fire is a possibility.

[26] *Belcher et al.* [2009] argued that the PAH chain lengths in their samples are indicative of a low-temperature oil fire. Table 2 of their work shows, however, that only 50% of their samples are comparable to hydrocarbon combustion products. While some samples may not have elevated pPAH even after the corrections *Belcher et al.* [2009] applied for sedimentation rate, a substantial number of their samples do not resemble hydrocarbon combustion products.

[27] Moreover, an impact site, which is on average 600 m under the ocean surface [*Gulik et al.*, 2008], is not a likely spot for a low-temperature oil fire. The temperatures in the impact fireball were far higher than those in normal forest fires. Hence, it is implausible that an oil fire in the conventional sense could have occurred.

5.3. Soot Morphology

[28] *Belcher et al.* [2005] stated that the morphology of K-Pg soot as described by *Wolbach et al.* [1985] is inconsistent with soot derived from combustion of biomass but morphologically similar to soot produced by burning petroleum or coal. Note, however, that what is described as "[s] oot from the 2002 Hayman wildfire" [*Belcher et al.*, 2005, pp. 597–599] was in fact not obtained from a smoke plume but was collected from the floor of a burnt out forest, and at the magnification used by *Belcher et al.* [2005, p. 599], the electron microscope images primarily emphasize charcoal rather than soot. *Wolbach et al.* [1985] described the soot particles from the boundary sediments that they observed with a scanning electron microscope as showing the characteristic morphology of carbon deposited from flames, such as soot or carbon black: irregular, fluffy, and often chainlike clusters of spheroids (Figure 1). Comparison of the particles in Figure 1 with those from the forest fire smoke shown in Figure 2 [K. Adachi, Arizona State University] demonstrated that, contrary to the claims of *Belcher et al.* [2005], the soot from forest fires is morphologically identical to that in the K-Pg layer. Figure 2b in the study by *Novakov et al.* [1997] shows further examples of soot from both forest fires and diesel exhaust, which are morphologically identical to the particles in the K-Pg boundary layer. Despite the K-Pg soot having been buried for 65 million years, its grape-bunch morphology is still similar to that of the modern soot. Because soot consisting of clustered spheroids can be produced by burning either vegetation or hydrocarbons, its morphology cannot be used to determine the fuel source [*Harvey et al.*, 2008].

5.4. Post-impact Erosion

[29] *Belcher et al.* [2005, p. 596] stated that post-impact fires would have led to accelerated erosion and deposition, which are not shown by sedimentary records. McKenna (personal communication, 2004), however, noted that most

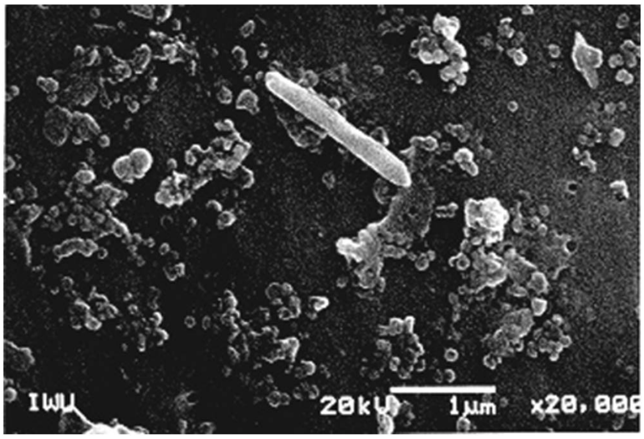

Figure 1. Soot (65 million years old) recovered from K-Pg boundary clay at Stevns Klint, Denmark. The large rod is a crystal of rutile. (Photo courtesy of W. Wolbach, DePaul University.)

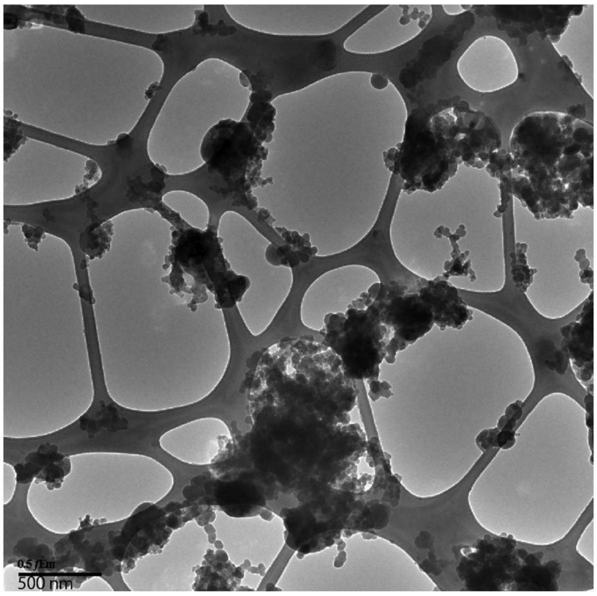

Figure 2. Modern soot collected from a forest fire in Mexico (shown on collection mesh; see the work of *Adachi and Buseck* [2011] for the sample). (Photo courtesy of K. Adachi and P.R. Buseck, Arizona State University.)

terrestrial K-Pg transitions are erosional unconformities that do not preserve an undisturbed impact deposit. Thus, the rare places where the terrestrial K-Pg boundary can be precisely identified by iridium, spherules, and other evidence are exactly the locations that were not affected by erosion but rather are depositional environments. Moreover, as discussed below, rainfall was likely strongly suppressed after the K-Pg impact, so if anything one would expect erosion and deposition to have been reduced.

5.5. The Post-Impact Environment

[30] Several issues concerning the preservation of material after the K-Pg impact are related to the nature of the environment after the impact. Infrared radiation from the ejecta that reentered the atmosphere would have ceased after a few hours. This radiation produced the first global insult to life on land. The size distribution of the spherules making up the resulting ejecta layer suggests that they would have fallen to the ground as fine solids over a few days. Fires would have burned globally for days to weeks, devastating most non-sheltered terrestrial life forms.

[31] The amount of soot in the boundary layer is equivalent to about $1.4 \times 10^{-2}\,\mathrm{g\,cm^{-2}}$ [*Wolbach et al.*, 1988]. The optical depth of this soot in the atmosphere depends on particle size. Monomers with a size near 0.1 µm would give an optical depth of several hundred. In addition to soot, there were sulfate aerosols and small particles of ejecta in the atmosphere, each with a significant optical depth. *Toon et al.* [1997] showed that such optical depths would have prevented virtually all sunlight from reaching the ground.

[32] No modern climate simulations predict the effect of post-impact particles on the Earth's climate, but *Robock et al.* [2007] used a modern climate model to estimate the effect of an atmospheric load equal to 0.2% of the amount of soot found in the K-Pg layer. As expected from early climate models (see the work of *Toon et al.* [1997] for a review), surface temperatures are predicted to reflect ice age conditions quickly after the soot injection and to remain low for more than a decade. Precipitation is significantly suppressed in *Robock et al.*'s [2007] calculations because of ocean surface cooling (50% general decline and 90% or more in the middle of North America and Europe). Such large declines in precipitation could significantly reduce aqueous erosion rates following an impact.

6. Conclusions

[33] The idea that heat and fire caused by reentrant ejecta within hours of the Chicxulub impact created global wildfires is consistent with geological evidence as well as data from computer modeling of the impact process. The arguments against a global firestorm depend critically on carbon in the pre-impact rocks at Chicxulub as the source of the soot, cenospheres, and other carbon in the boundary sediments, yet the stratigraphy shows that the amount of carbon at Chicxulub was inadequate to produce the observed soot. In addition, the forms of carbon in the K-Pg layer (soot, PAHs, and cenospheres) do not provide any evidence that is inconsistent with an origin in global wildfires. The new numerical models of radiation from the ejecta indicate sufficient energy to ignite tinder, and there are several reasons to believe that these radiation calculations may be too low. The presence of non-charred material at some sites only indicates that these sites were covered in standing water at the time of the impact, while reduced rainfall would have led to reduced erosion in surrounding burned areas. Moreover, the low amounts of charcoal in the K-Pg layer relative to surrounding layers reported by *Belcher et al.* [2003; 2004; 2005; 2009] are almost certainly caused by a combination of failure to correct for differences in sedimentation rate and destruction of charcoal in high-temperature firestorms.

[34] Thermal radiation from the reentry of the impact debris and global wildfires would have largely incinerated terrestrial ecosystems, thus causing mass mortality of animals. Taxa with burrowing habits, which would have sheltered them from heat, would have been least likely to have experienced mass mortality. The model of an IR heat pulse followed by

global firestorms is consistent with all the geological evidence from the boundary clays as well as with the physical modeling of the impact, and it easily produces the observed patterns of terrestrial survival in the early Cenozoic as described by *Robertson et al.* [2004a].

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