

Arguments and Evidence Against a Younger Dryas Impact Event

M. Boslough,¹ K. Nicoll,² V. Holliday,³ T. L. Daulton,⁴ D. Meltzer,⁵ N. Pinter,⁶ A. C. Scott,⁷ T. Surovell,⁸ P. Claeys,⁹ J. Gill,¹⁰ F. Paquay,¹¹ J. Marlon,¹⁰ P. Bartlein,¹² C. Whitlock,¹³ D. Grayson,¹⁴ and A. J. T. Jull¹⁵

We present arguments and evidence against the hypothesis that a large impact or airburst caused a significant abrupt climate change, extinction event, and termination of the Clovis culture at 12.9 ka. It should be noted that there is not one *single* Younger Dryas (YD) impact hypothesis but several that conflict with one another regarding many significant details. Fragmentation and explosion mechanisms proposed for some of the versions do not conserve energy or momentum, no physics-based model has been presented to support the various concepts, and existing physical models contradict them. In addition, the a priori odds of the impact of a >4 km comet in the prescribed configuration on the Laurentide Ice Sheet during the specified time period are infinitesimal, about one in 10^{15} . There are three broad classes of counterarguments. First, evidence for an impact is lacking. No impact craters of the appropriate size and age are known, and no unambiguously shocked material or other features diagnostic of impact have been found in YD sediments. Second, the climatological, paleontological, and archeological events that the YD impact proponents are attempting to explain are not unique, are arguably misinterpreted by the proponents, have large chronological uncertainties, are not necessarily coupled, and do not require an impact. Third, we believe that proponents have misinterpreted some of the evidence used to argue for an impact, and several independent researchers have been unable to reproduce reported results. This is compounded by the observation of contamination in a purported YD sample with modern carbon.

¹Sandia National Laboratories, Albuquerque, New Mexico, USA.

²Department of Geography, University of Utah, Salt Lake City, Utah, USA.

³School of Anthropology and Department of Geosciences, University of Arizona, Tucson, Arizona, USA.

⁴Department of Physics and Center for Materials Innovation, Washington University, St. Louis, Missouri, USA.

⁵Department of Anthropology, Southern Methodist University, Dallas, Texas, USA.

⁶Department of Geology, Southern Illinois University, Carbondale, Illinois, USA.

⁷Department of Earth Sciences, Royal Holloway University of London, Egham, UK.

⁸Department of Anthropology, University of Wyoming, Laramie, Wyoming, USA.

⁹Earth System Science, Vrije Universiteit Brussel, Brussels, Belgium.

¹⁰Department of Geography, University of Wisconsin-Madison, Madison, Wisconsin, USA.

¹¹Department of Geology and Geophysics, University of Hawai'i at Mānoa, Honolulu, Hawaii, USA.

¹²Department of Geography, University of Oregon, Eugene, Oregon, USA.

¹³Department of Earth Sciences, Montana State University, Bozeman, Montana, USA.

¹⁴Department of Anthropology, University of Washington, Seattle, Washington, USA.

¹⁵AMS Radiocarbon Facility, University of Arizona, Tucson, Arizona, USA.

1. INTRODUCTION

The earliest form of the “Younger Dryas (YD) impact hypothesis” was published by *Firestone and Topping* [2001] and was substantially extended in a book by *Firestone et al.* [2006]. Adopting some (but not all) of these earlier ideas, the YD impact hypothesis was formally presented in 2007 [*Firestone et al.*, 2007]. *Firestone et al.* [2007] proposed their impact hypothesis as a unifying causal mechanism to explain the abrupt cooling that marks the onset of the YD at 12.9 ka, extinctions of Pleistocene megafauna, and a presumed termination of the Clovis lithic technology/culture. According to the impact hypothesis, one or more large, low-density extraterrestrial objects exploded over the Laurentide Ice Sheet around 12,900 years ago. The resulting shock wave destabilized the ice sheet, causing the sudden cooling. Heat from the explosion ignited wildfires across the North American continent. The combined effects resulted in profound environmental change that forced a major ecological reorganization and food deprivation that adversely affected megafauna as well as human populations.

As stated by *Firestone et al.* [2007], the impact hypothesis is based on the interpretation of a purported carbon-rich “black mat” stratigraphic layer and its constituent minerals, which are presumed to represent a single horizon of the YD boundary. The term “black mat” refers to a wide array of late Quaternary wetland deposits and soils found in stream, lake, and pond settings, primarily across the Southwest and Great Plains of North America ranging in age from 6 to more than 40 ka [*Pigati et al.*, 2012]. The impact hypothesis is based upon seven indicators present in the black mat that are described as evidence for an extraterrestrial impact and associated biomass burning: magnetic grains associated with elevated iridium (Ir) concentrations, magnetic microspherules, charcoal, soot, carbon spherules, glass-like carbon, nanodiamonds, and fullerenes with extraterrestrial helium (^3He). Other professed evidence includes Pt-group element peaks, geochemical evidence for biomass burning during the YD in Greenland ice cores, and radioactive animal bones at the YD boundary.

Coauthors of the original work presented by *Firestone et al.* [2007] have subsequently published papers in support of YD impact hypothesis variants [e.g., *Kennett et al.*, 2008, 2009b; *Firestone*, 2009; *Firestone et al.*, 2010; *Kurbatov et al.*, 2010; *Israde-Alcántara et al.*, 2012]. A number of key details in previous versions conflict with later versions of the hypothesis, but have not been abandoned. The YD impact hypothesis is therefore not a single concise or coherent evolving explanation, but rather an overlapping set of multiple hypotheses that are sometimes conflated. The YD impact hypothesis proponents make a variety of inferences about the

nature of the impactor and the impact mechanisms. Support for the hypothesis is drawn entirely from indirect evidence and, paradoxically, from the lack of observed physical evidence. For instance, the lack of any recognized impact structure of YD age in North America prompted speculation that the impactor struck the Laurentide Ice Sheet or detonated as multiple fragments in the atmosphere. However, there is no direct physical evidence that either of these events occurred (see discussion in the following sections). Regarding purported markers of the impactor or products of the impact, independent studies conclude that this physical evidence is irreproducible, misidentified, and/or misinterpreted as unique to only impact mechanisms. For a detailed review, see the work of *Pinter et al.* [2011a].

The proposed nature of the hypothetical impact event was not uniquely defined by *Firestone et al.* [2007], but the proponents seem to rule out an asteroid in favor of a low-density comet that may or may not have broken up, may or may not have exploded before it reached the surface, and if it impacted, it did so at an oblique angle on thick ice. However, *Firestone et al.* [2007] estimate the impactor size by assuming that it had effects over the entire continent. They argue that it needed to be more than 4 km wide and explode at the optimum height for blast damage at the surface. Moreover, the authors suggest that it may have fragmented to produce a barrage of airbursts that generated continental-scale wildfires and destabilized the ice sheet, but produced no craters.

A more recent YD impact paper [*Israde-Alcántara et al.*, 2012] was coauthored by several of the original proponents of the impact hypothesis and proposes that the impactor could have been either a comet or asteroid with an initial diameter greater than several hundred meters. It may or may not have been fragmented, and its entry angle could have been as great as 30° from the horizontal. This hypothesis is a major departure from the *Firestone et al.* [2007] concept. The proposed object is now 3 orders of magnitude smaller in terms of mass and energy, and unusual and low-probability characteristics (low-density comet, fragmented state, low impact angle, ice sheet target) are not prescribed.

We begin our critique with a summary of the *Firestone et al.* [2007] YD impact hypothesis. Although it is not well constrained, the impact mechanism has variously been described as an airburst, a cluster of airbursts, an ice sheet impact, and multiple continent-spanning impacts, there are theoretical arguments that can be applied to the proposed YD impact scenarios.

The scenarios are inconsistent with our understanding of impact and airburst physics. There is no process capable of causing a comet or asteroid to break up or explode at sufficiently high altitude to lead to the claimed effects on the Earth’s surface, whereas an impact into the Laurentide Ice

Sheet by a 4 km diameter comet would shock the underlying rock strata, leaving an impact structure. Moreover, the probability of the fragmented comet impact event is infinitesimal. The combination of proposed size, configuration, and trajectory of the putative impactor is exceedingly unlikely to have occurred together as a single event in the entire history of the Earth.

We discuss three broad classes of evidence-based counter arguments.

1. Evidence for impact is lacking. There are no impact craters of the appropriate size and age. None of the classic markers of impact shock processing, unambiguously shocked material (coesite, stishovite, shatter cones, etc.), and no meteoritic material from an impactor, have been found in any YD dated material. Proposed impact markers such as magnetic grains, soot, charcoal, and carbon spherules are not diagnostic of impact and occur in other environments. The black mats in which these materials are found do not represent a single stratigraphic horizon and, in many cases, have not been age dated. Suggested YD impact craters, the Carolina Bays (unusual elliptical depressions across the Atlantic Coastal Plain from Georgia to Virginia) do not exhibit impact crater morphology nor are they of YD age.

2. Effects that the impact proponents are attempting to explain, namely, a cooling event, megafaunal extinctions, and termination of the Clovis culture, may not be instantaneous or synchronous and may not have any common causal link. Moreover, none of these transitions require impact as a cause. The abrupt cooling at 12.9 ka is of no greater magnitude or climatological consequence than many such climate variations that occurred throughout the Quaternary [Broecker *et al.*, 2010]. Any special status of the YD derives from the fact that it was the last such event before the Holocene and is the most recent and therefore best characterized. The extinction event was not abrupt, and at least some members of the Pleistocene megafauna were already in decline before 12.9 ka [Grayson, 2007; Faith and Surovell, 2009]. The YD time frame does not mark the termination of the Clovis culture or a population collapse, but coincides broadly with a change in lithic technology.

3. In our view, there has been a pattern of irreproducibility and misinterpretation of evidence used to support a YD impact hypothesis. Independent investigators have failed to confirm the reports of enhanced concentrations of spherules and platinum-group elements in YD boundary sediments. Specimens collected during an expedition for the 2008 filming of the PBS NOVA documentary “The Last Extinction,” that were purported to contain shock-formed (lonsdaleite) nanodiamonds [Kurbatov *et al.*, 2010] have not yet been made available for independent analysis. The data published by Kurbatov *et al.* [2010] are inconsistent with lonsdaleite,

and Daulton *et al.* [2010] concluded that the same research group misidentified graphene/graphane aggregates as lonsdaleite in YD boundary sediments. In addition, arthropod coprolites and fungal sclerotia in the sediments were mistaken for fire-generated carbon spherules [Scott *et al.*, 2010]. An aliquot of carbon spherules that was provided by this group for the detection and verification of nanodiamonds was contaminated with a modern-aged carbon spherule.

Taken together, these observations provide arguments against the idea that an impact was responsible for an environmental catastrophe, extinction, and culture change at the onset of the YD.

2. FUNDAMENTAL FLAWS

Even in the absence of counterevidence, we consider the Firestone *et al.* [2007] impact hypothesis to be fatally flawed because it violates physical conservation laws and is inconsistent with conventional understanding of impact physics. Several subsequent elaborations of the hypothesis incorporate increasingly low probability events, leading to a proposed impact configuration that has only an infinitesimal probability.

2.1. Inconsistencies and Contradictions

The scope of analysis in the present paper is limited to the hypothesis stated by Firestone *et al.* [2007] and subsequent publications by coauthors. For context, it should be noted that the 2007 hypothesis is an outgrowth of the book “Cycle of Cosmic Catastrophes” by Firestone *et al.* [2006], in which the hypothesized comet was just one manifestation of a much greater cycle of catastrophes initiated by a nearby supernova at 41 ka that subjected the Earth to cosmic and thermal neutron radiation so strong that terrestrial materials still remain radioactive. According to the 2006 book, the supernova also generated an interstellar shock wave that reached the Earth at 34 ka and then a wave of cosmic debris at the YD. The 2006 version of the hypothesis proposed a large impact that created the present-day Hudson Bay, generating ejecta that formed the Carolina bays, which the authors described as secondary impact craters. This event also destabilized the Earth’s magnetic field and exposed it to another wave of particle irradiation at its surface.

The title of Firestone *et al.* [2007, p. 16,016] asserts, “Evidence for an extraterrestrial impact. . .” and according to the abstract, the authors “. . . provide evidence for an extraterrestrial (ET) impact event at ~12.9 ka. . .” The list includes seven markers, all of which they say “are evidence for an ET impact and associated biomass burning at ~12.9 ka.” The Carolina Bays are highlighted as “unique, elliptical depressions” in the

2007 paper, but their relevance is unclear; they propose but do not document evidence for 15 bays with impact-related markers and provide no stratigraphic data or numerical dating. The previous conjecture that these features are secondary impact craters appears to have been abandoned in current versions of the hypothesis.

2.2. Physical Implausibility

There are three aspects to the hypothesis that are inconsistent with conventional physics: (1) a 4 km diameter comet cannot possibly explode at its optimum height; (2) an object traveling at escape velocity or greater cannot sufficiently disperse fragments, even if it is disrupted at the Roche limit (the distance from the Earth at which tidal forces exceed self-gravity of an orbiting or approaching object); and (3) for any plausible entry angle, even a 2 km impactor would not fail to penetrate a 2 km thick ice, leaving a crater in the underlying strata.

Firestone et al. [2007] place constraints on the impactor (>4 km diameter comet generating 10^7 megaton (Mt) explosive event) based on the surface damage model of *Toon et al.* [1997] and cite the model to suggest that such an impact is capable of continental-scale damage. However, the *Toon et al.* [1997] model invokes a crater-forming impact that ejects solid debris at high velocity that reenters as shooting stars whose thermal radiation ignites wildfires. Simply stated, such ballistic ejecta will not be produced in the absence of crater formation. Crater-forming impact is a necessary component because that is how the ballistic ejecta are produced. However, there is no physical evidence of a crater in North America dating to the YD. To explain this lack, *Firestone et al.* [2007] argue that prior fragmentation prevented a crater from forming, but this argument contradicts prior assumptions invoked in the *Toon et al.* [1997] model. As such, the hypothesis is internally inconsistent.

Firestone et al. [2007] also cite *Toon et al.* [1997] as noting that “. . . if airbursts explode with energy of 10^7 megatons at optimum height, they will cause blast damage over an area the size of North America. . .” Optimum height of burst is a concept from the nuclear weapons effects literature. It is the prescribed altitude for a point-source explosion to maximize surface damage. According to *Glasstone and Dolan* [1977], it is “that at which it is estimated a weapon of a specified energy yield will produce a certain desired effect over the maximum possible area.” For the YD impact hypothesis, the “desired effect” is damage due to blast waves.

Optimum height of burst is a function of explosive yield, so it can be expressed as a locus of altitudes. The altitude at which an object actually explodes is determined by physics and also depends on other parameters such as impactor

strength and density, entry angle, and velocity. *Toon et al.* [1997] plotted the burst height for various impactor classes as a family of curves (Figure 1). For a given class of object (every other variable held constant), there is only one size that will naturally explode at its optimum altitude and damage a greater area on the ground than if it had exploded at a different altitude. It can be determined from the curve intersection points in Figure 1. The highest possible optimal airburst altitude for any object is defined as the point where the *Glasstone and Dolan* [1977] curve intersects with the long-period comet curve, corresponding to a 120 m comet at 15 km altitude. More recent work by *Boslough and Crawford* [2008] shows that the effective airburst altitude of a given-sized impactor is significantly lower than the *Toon et al.* [1997] curves indicate, suggesting that the intersection point in Figure 1 actually overestimates the highest possible airburst altitude.

When the optimum altitude for creating blast waves (which neglects the Earth’s curvature) is extrapolated, a 10^7 Mt explosion must be detonated at 500 km to generate continental-wide effects [*Glasstone and Dolan*, 1977]. Whereas nuclear weapons can be set off at any altitude, there is no physical mechanism that can cause a comet to explode in outer space (e.g., 500 km). Such an explosion would require the conversion of significant kinetic energy to internal energy for heating and vaporizing the comet. This would necessitate momentum loss through drag on the cometary mass. In the absence of air, there is no mass to which momentum can be transferred, and such an explosion would violate the laws of physics. Therefore, one cannot use the

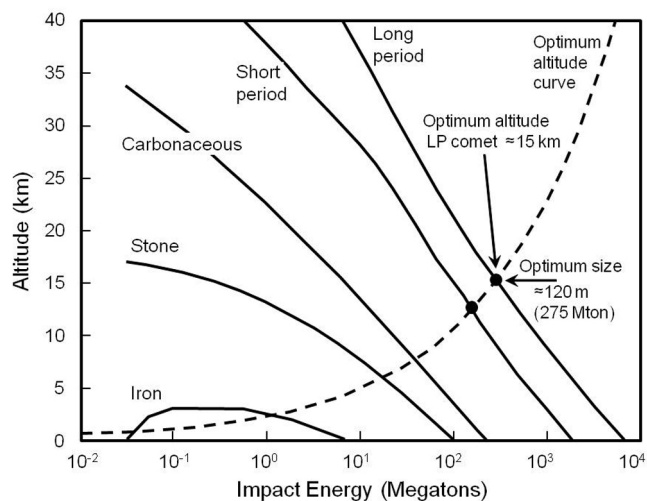


Figure 1. Airburst altitude for comets and asteroids [from *Toon et al.*, 1997] with optimum height of burst [from *Glasstone and Dolan*, 1977].

optimum height concept to constrain the mass (and explosive equivalence) of large comets.

Firestone et al. [2007] also suggest that a debris shower from a heavily fragmented comet “would have produced an airburst barrage that was similar to, although exponentially larger than Tunguska, while causing continent-wide biomass burning and ice-sheet disruption.” The Tunguska event refers to the only unambiguous example of an observed naturally occurring low-altitude airburst. It occurred in 1908 over central Siberia and is estimated to have exploded with an effective yield of 3 to 5 Mt [*Boslough and Crawford*, 1997]. This description is consistent with the hypothesis presented at the 2007 AGU Joint Congress, where an animation from the 2006 National Geographic documentary “Ancient Asteroid” was shown in which a tumbling asteroid breaks apart as it approaches the Earth, resulting in an array of explosions and plumes across Southeast Asia. (The animation was produced by TV6 Limited, a British production company, based on simulations by M. Boslough. It is available on Youtube: <http://www.youtube.com/watch?v=CpYCKLSGH84#t=3m1s>. One of the impact proponents (A. West) presented it at a press conference in Acapulco, May 2007, stating “. . . we think a similar thing happened for this event.” (<http://www.youtube.com/watch?v=I2ld-lohrPw#t=4m47s>.)

For continent-wide effects, the fragmented comet would need to significantly disperse over hundreds of kilometers along its trajectory to create widely spaced airbursts. However, there is no lateral aerodynamic force that can separate fragments by a large distance between the upper and lower atmosphere. Likewise, no lateral force exists to accelerate pieces apart between the Roche limit and atmospheric entry. Fragments of a broken comet would drift apart at a speed of tens of centimeters per second if spun apart by tidal disruption, even if boosted by release of volatiles. In the 10 min or so between fragmentation and impact, fragments would be separated by much less than the initial diameter of the object. The impact of such a tight cluster would be indistinguishable from a single impact of a lower-density object because the total mass and kinetic yield are the same, regardless of the fragmentation state of the impactor. Greater fragment separation would require radial velocities that are a significant fraction of escape velocity. There is no source of energy that can provide sufficient radial acceleration.

Additionally, *Firestone et al.* [2007] cite unpublished data suggesting that a low-impedance layer such as an ice sheet would minimize cratering in the underlying target rock. They argue on this basis that multiple 2 km objects could strike the 2 km thick central zone of the Laurentide Ice Sheet at a shallow angle, leaving little evidence of craters other than depressions in the Great Lakes or Hudson Bay. *Firestone et al.* [2007] based their argument on laboratory-scale impact

experiments for which the crater formation is dominated by strength effects such as spall. It is inappropriate to extrapolate from scales of millimeters to kilometers without accounting for the change from strength-dominated to gravity-dominated crater growth; for a detailed discussion of scaling laws and impact cratering, see the work of *Melosh* [1989].

For high-strain rate phenomena at kilometer scales, the strength of the ice is negligible, and cratering is dominated by its hydrodynamic equation of state that is very similar to that of liquid water. It is therefore instructive to consider an ocean impact as an analog to an impact into thick ice. Numerical models of such an impact were performed by *Shuvalov* [2003] to determine the size of an impactor for which a bottom crater does not form in 4 km deep water. The vertical impact of a 1.5 km stony asteroid excavated a clearly pronounced 2 km deep crater in the ocean floor. According to *Shuvalov and Trubetskaya* [2007], the cratering process depends critically on impactor diameter-to-water depth ratio d/H . For $0.1 < d/H < 1$, the water layer significantly influences the size and morphology of the resulting crater, but does not prevent crater formation. For $d/H > 1$, the water column has little effect on the cratering process. The Laurentide Ice Sheet is estimated to be ~2–3 km thick during the YD period [*Paterson*, 1972]. Therefore, a 4 km diameter comet would need to fragment into at least several thousand (<0.2–0.3 km diameter), well-separated, impactors during atmospheric entry in order not to shock the underlying rock upon impact on the ice sheet. This particular scenario is implausible.

2.3. Infinitesimal Likelihood

The burden of evidence for a hypothesis increases with its a priori improbability. *Firestone et al.* [2007] invoke an extraordinary sequence of events that compounds improbability to the point of virtual impossibility. This puts an extraordinary onus on the proponents to show that there are no other explanations compatible with the evidence. Impacts on the Earth became rare events after its initial planetary formation and the late heavy bombardment period. The best method to estimate the current impact flux on the Earth is by using the observed population of near-Earth objects (NEOs) [*Stuart*, 2001; *Harris*, 2002], which are in orbits that can bring them close to the Earth. Observed bolide frequencies constrain the population of small objects [*Brown et al.*, 2002]. The full population can be used to determine the probability of impact per year as a function of size (Figure 2). This can be converted to mean impact interval. A 4 km asteroid collides with the Earth, on average, about once every 14 million years [*NASA NEO Science Definition Team*, 2003, Table 3.1], which is a number that is consistent with lunar crater counts [*Werner et al.*, 2002]. The flux can also be

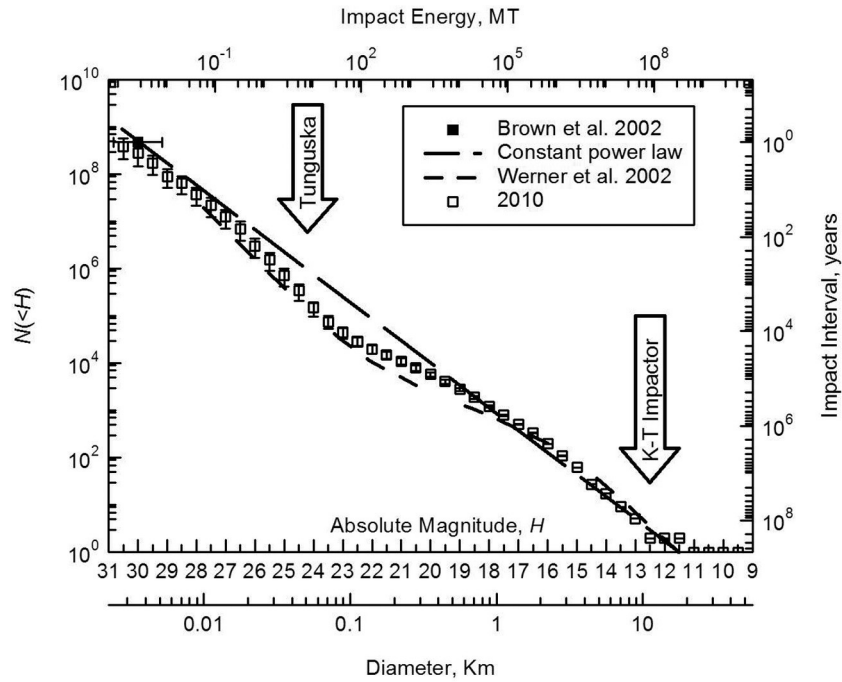


Figure 2. Observed population of near-Earth objects [NASA NEO Science Definition Team, 2003] with updates by A. Harris (personal communication, 2012).

converted to a probability density function that indicates the probability that an impact of an asteroid of a given size will be the largest in a specified time. The best estimate for the largest impact of the past 20 ka is about 250 m (Figure 3).

The population of comets in the kilometer size range in the inner solar system is about 1% that of asteroids (D. Yeomans, Jet Propulsion Laboratory, personal communication, 2011), and the mean impact interval for impact by a 4 km comet is about once every 2.5 billion years [see NASA NEO Science

Definition Team, 2003, Table 3.6]. The timescale for significant reduction in the population of NEOs by orbital interactions is millions of years [Hut et al., 1987], so current fluxes are an upper-bound limit for determining the probability of impact at the YD.

Each attribute of the hypothetical impact scenario can be assigned an approximate a priori probability to arrive at an order-of-magnitude estimate. The following factors are rounded to the nearest order of magnitude and are not

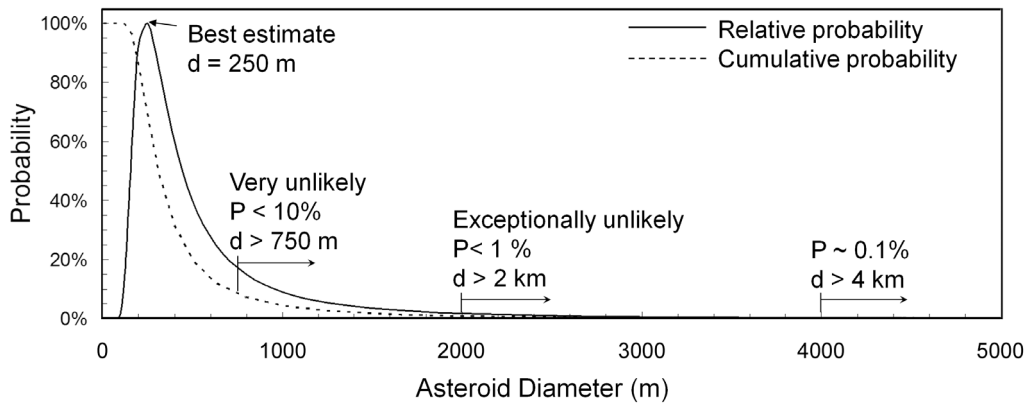


Figure 3. The largest asteroid impact expected over a 20,000 year interval is 250 m. Impact by an object larger than 2 km is exceptionally unlikely (probability less than 1%).

intended to be precise estimates. Given the known flux, the probability that a NEO with a kinetic energy of 10^7 Mt will collide with the Earth in any given 13,000 year period is about 0.001 (once every 14 million years on average), and the probability of a comet impact with the same kinetic energy is about 0.00001 [*NASA NEO Science Definition Team*, 2003]. The ratio of the area of the Laurentide Ice Sheet target to the Earth's surface area was about 0.01. The fraction of comets that are broken is less than 0.01 (A. Harris, Space Science Institute, personal communication, 2011, estimates 0.001 based on crater chains on the Galilean satellites). The fraction of time the fragments of a broken comet remain within an Earth diameter is roughly 0.001 of the broken comet's lifetime (based on the dispersion of Shoemaker-Levy 9 after it fragmented in 1992). The fraction of objects that collide with the Earth at a grazing angle less than 4° is about 0.01, based on the distribution of isotropic collisions with a sphere with a cumulative probability of $1 - \cos(\theta)$. Therefore, the a priori probability of the putative YD impact of a comet in the defined configuration on the Laurentide Ice Sheet during the prescribed time period is about 10^{-15} . The expected recurrence interval for such an event using current flux rates is about 10^{19} years or about 10^9 times the age of the universe. As such, the probability of this occurring is infinitesimal and is an event that is so improbable it can be called "statistically impossible."

It is worth noting that the Cretaceous-Tertiary (K/T) impact scenario, using the same line of argument, is not a low-probability event. The mean recurrence interval for a 10 km diameter asteroid impact is about 100 million years, and there are no special requirements (fragmentation state, impact angle, or a priori location or time interval) that make the K/T event unusual within the last 100 million years. A subset of the new YD impact scenarios recently published by *Israde-Alcántara et al.* [2012] are likewise unremarkable in terms of probability because of the much smaller size and lack of a prescribed unusual configuration and composition.

3. EVIDENCE-BASED ARGUMENTS

Many papers presenting arguments against the YD impact hypothesis are based on lack of evidence [e.g., *Pinter et al.*, 2011a]. The most striking lack of physical evidence for the YD impact is the absence of any impact crater of the appropriate age. Regardless of which version of the hypothesis is being considered, multiple small impacts and airbursts across two continents or large impacts into ice, the lack of a crater or other geomorphic evidence is fundamentally problematic. Another core problem is the presupposition that there are events that an impact hypothesis is needed to explain. A prerequisite set of hypotheses is that the YD was unique,

mammalian extinctions were abrupt, environmental change caused the collapse of the Clovis culture, and continental-scale wildfires took place, all of which are lacking evidence. The most frequent criticism of the evidence for an impact is based on irreproducibility and misinterpretations of marker evidence as preserved in black mat deposits, which may not correlate chronostratigraphically across regions. The most comprehensive review is that of *Pinter et al.* [2011a]. Because of space limitations, we only address the key criteria related to first-order impact evidence.

3.1. No Impact Markers or Crater

Various versions of the 2007 hypothesis give the following reasons for the absence of an impact crater for the hypothesized YD impact event: (1) it was similar to, but larger than the 1908 Tunguska explosion, which did not produce a crater; (2) the crater or craters were in ice, which melted away and destroyed any impact features in the substrate; and (3) the Chicxulub crater was not recognized for 10 years after the *Alvarez et al.* [1980] impact hypothesis, and so there is no expectation of immediate discovery of a YD crater. For reasons outlined earlier, however, it is not physically possible for a 4 km comet to generate a Tunguska-like airburst, eliminating the first reason. The estimated kinetic yield of the Tunguska explosion is 3–5 Mt [*Boslough and Crawford*, 1997], and the putative 4 km, 10^7 Mt comet would need to break into around a million fragments to avoid producing a single crater-forming event. However, in the case of a disintegrating comet, the individual fragments would not be separated by enough lateral distance to avoid reinforcing one another. They would effectively become a single large low-density crater-forming impact, instead of one that was capable of affecting areas across multiple continents.

It should be noted that the Chicxulub crater has an age of 65 Ma, more than 5000 times older than the YD interval. A YD impact structure should be "fresh" because erosion processes have not had sufficient time to operate during the short time that has elapsed since the YD. A good example of a relatively fresh impact crater is Barringer (Meteor Crater), Arizona, which at 49 ka is more than three times as old as the proposed YD impact and was formed by a solid impact of less than one millionth the energy [*Melosh and Collins*, 2005] of the event postulated by YD impact proponents. Meteor Crater is an unambiguous example of a well-preserved impact structure [*Grieve and Therriault*, 2004; *French and Koeberl*, 2010], but not a single similar geomorphic feature from an impact event is known for YD time [*Grieve*, 1997; Earth Impact Database, Planetary and Space Science Centre, unpublished data, 2011, <http://www.passc.net/EarthImpactDatabase/index.html>]. The proposed YD impactor of

Firestone et al. [2007] would have had enough mass to produce more than a million Meteor Craters, and even the much smaller *Israde-Alcántara et al.* [2012] YD impactor would be capable of producing thousands.

Another argument used to support the YD impact hypothesis is the claim of evidence for cratering in the Great Lakes basin. *Firestone et al.* [2007] state that “if multiple 2 km objects struck the 2 km thick Laurentide Ice Sheet at $<30^\circ$, they may have left negligible traces after deglaciation. . . [perhaps] limited to enigmatic depressions or disturbances in the Canadian Shield (e.g., under the Great Lakes or Hudson Bay).” However, by 12.9 ka, only the Lake Superior basin was still under glacial ice [*Dyke et al.*, 2003]. *Firestone et al.* [2010] suggested that “deep holes” beneath four of the Great Lakes could represent impact craters. They dismiss the possibility that these holes were the result of glacial erosion, citing nineteenth century research [*Dawson*, 1891], despite more than a century of glacial and Quaternary geological research on the Great Lakes. If these holes were caused by an impact at 12.9 ka (and *Firestone et al.* [2010] provide no evidence the holes are that old), then the impacts produced elongated craters at different orientations. However, each hole is parallel to local ice flow in the up-ice end of its lake basin.

Israde-Alcántara et al. [2012] also mention a “crater named Corossol in the Gulf of St. Lawrence, containing basal sedimentary fill dating to 12.9 ka.” The cited study [*Higgins et al.*, 2011], however, based the date of ~ 12.9 ka on extrapolation from dates higher in the section and suggest that the crater formed sometime between 12.9 ka and the end of the Ordovician, a dating uncertainty that spans hundreds of millions of years.

3.2. Nonunique and Misinterpreted Events

One of the major flaws with the impact hypothesis is the leading premise that climate changes, faunal extinctions, and cultural transitions occurring during the YD require a common explanation.

3.2.1. Climate change. There was indeed an abrupt climate change around 12.9 ka, but the abruptness of the YD is not unique, and the cooling is of no greater magnitude or climatological consequence than many other events occurring throughout the Quaternary [*Broecker et al.*, 2010]. Dozens of similar rapid climate-change events, such as Dansgaard-Oeschger and Heinrich events have taken place over the last 100 ky, yet none of these are associated with impacts. Such events recur at a much greater frequency than large (km-scale) impacts and do not require impacts as a causal mechanism. The YD is notable simply because it is recent and the last such climate event before the Holocene.

3.2.2. Extinctions. Environmental change in the late Pleistocene was a very complex process. The extinction of megafauna was one component of this process, but the relationship of the extinctions to climate change is far from clear [e.g., *Barnosky et al.*, 2004; *Grayson*, 2007; *Faith and Surovell*, 2009]. For example, some late Pleistocene mammal populations were in decline before the YD, and the timing of the extinction varied among some species and across continents [*Grayson and Meltzer*, 2003]. The dung fungus (*Sporormiella*) proxy for megafauna presence indicates that some Pleistocene megaherbivores declined from 14.6 to 13.7 ka, well before the proposed impact; the precise chronology of extinction remains unresolved [*Gill et al.*, 2009].

3.2.3. Stratigraphy. Intensive study of the chronostratigraphic and sedimentological details of the black mat layers and associated paleontological evidence of multiple YD sites reveal that there are no continent-wide or regional stratigraphic marker beds, and there are no other indicators of widespread geomorphic or ecological instability at 12.9 ka [*Haynes*, 2008; *Meltzer and Holliday*, 2010; *Straus and Goebel*, 2011, papers]. The fidelity of the YD time interval in black mats is questionable because they are time-transgressive units, especially in western North America [*Quade et al.*, 1998; *Haynes*, 2008; *Haynes et al.*, 2010] and can result from a wide array of environmental drivers [*Meltzer and Holliday*, 2010]. More relevant here, stratigraphic analyses conducted by *Surovell et al.* [2009] and *Paquay et al.* [2009] have failed to reproduce patterns of purported YD impact marker indicators in documented stratigraphic contexts, including the same sections reported by *Firestone et al.* [2007]. More recently, *Pigati et al.* [2012] found that similar markers are ubiquitous within or at the base of black mats of non-YD age.

3.2.4. Archaeology. The late Pleistocene, in general, and the YD interval, in particular, were times of rapid environmental changes, but the timing, magnitude, and direction of those environmental changes varied across North America [*Meltzer and Holliday*, 2010; see *Straus and Goebel*, 2011]. Some researchers speculate that environmental shifts during the YD affected Paleoindian populations, especially the Clovis culture [e.g., *Haynes*, 1991, 2007]. Archaeological, geochronological, and stratigraphic data, however, do not provide strong evidence linking YD changes with significant adaptations or to a demographic collapse of Clovis populations [*Holliday and Meltzer*, 2010].

3.2.5. Paleoclimate/Paleoecology. The YD impact hypothesis proposes that continental-scale wildfires resulted. North American charcoal and pollen records do show rapid

changes in environment, vegetation, and fire regimes, consistent with the climate changes during the last glacial-interglacial transition ~15 to 10 ka [Meltzer and Holliday, 2010; Marlon *et al.*, 2009; Pinter *et al.*, 2011b]. The records over the YD interval do not, however, indicate continental-scale wildfire at any time. Instead, the record demonstrates that large scattered fires occurred asynchronously throughout the transition, peaking around 13.2 ka and again at 11.6 ka (when no comet impact is proposed) [Marlon *et al.*, 2009]. The pattern of increased biomass burning in response to both abrupt warming and cooling is replicated by data on biomass-burning variations during Greenland interstadials (Dansgaard/Oeschger events), stadials, and Heinrich events over the interval from 85 to 15 ka [Danialu *et al.*, 2010].

3.3. Irreproducibility and Misinterpretations of Evidence

Firestone et al. [2007] list seven professed markers that they interpret as evidence for extraterrestrial impact and associated biomass burning: magnetic grains with Ir, magnetic microspherules, charcoal, soot, carbon spherules, glass-like carbon containing nanodiamonds, and fullerenes with extraterrestrial ^3He . *Surovell et al.* [2009] and *Paquay et al.* [2009] conducted independent assessments to identify some of these markers in samples from key YD sites; they could not reproduce the findings published by Firestone and other YD impact proponents. In addition to this problem reproducing the results, the “putative markers for impact” and those proxies related to wildfire are conflated. An impact does not necessarily cause significant biomass burning, and evidence for a fire (such as charcoal and soot) is not a diagnostic indicator of an impact.

Subsequent papers by the proponents of the YD impact event include the reported discovery of hexagonal diamonds (lonsdaleite) in sediments from Santa Rosa Island, California [Kennett *et al.*, 2009b], from the Greenland ice sheet [Kurbatov *et al.*, 2010], and from lake sediments in Mexico [Israde-Alcántara *et al.*, 2012]. However, Pinter *et al.* [2011a] reviewed most of this evidence in detail, as well as related claims that had already been largely rejected by the scientific community, including particle tracks in archeological chert, meteoritic particles embedded in Pleistocene bones [Hagstrum *et al.*, 2010], an impact origin for Carolina Bays, and enrichments of radioactive materials. Pinter *et al.* [2011a] evaluated the 12 original lines of evidence invoked to support an extraterrestrial impact [Firestone *et al.*, 2007] and concluded that 7 of the 12 are irreproducible, and the other five are consistent with noncatastrophic and/or terrestrial processes, as outlined below.

3.3.1. Magnetic Grains With Iridium. *Firestone et al.* [2007] reported elevated concentrations of Ir in bulk sediments and in magnetic grains only from YD boundary sediments.

However, subsequent efforts by others to replicate claims of high Ir concentrations and high magnetic grain concentrations have failed. *Surovell et al.* [2009] demonstrated that magnetic grains are ubiquitous throughout the same stratigraphic sections. There is no “Ir spike” in concentration at the YD; the highest Ir concentrations measured by *Paquay et al.* [2009] was ~100 ppt, which is well below the ppb levels reported by *Firestone et al.* [2007]. In addition to making Ir measurements, *Paquay et al.* [2009] also measured osmium (Os) isotopes on bulk sample splits collected from the same measured sections presented in the *Firestone et al.* [2007] paper, and large quantities were used to avoid nugget effects (artificially high apparent concentrations that arise when a small sample includes an enriched grain). Os is a very sensitive tracer for extraterrestrial components in sediments, yet all samples showed Os isotopic ratios similar to average crustal values. From these results, it was concluded that there is no significant meteoritic Os contribution to these YD sediments, therefore excluding the involvement of all meteorite classes of chondritic nature [Paquay *et al.*, 2009].

3.3.2. Magnetic Microspherules. Magnetic microspherule abundance results published by the impact proponents have not been reproducible by other workers. Analyses of the same YD site stratigraphy by *Surovell et al.* [2009] could not replicate observations for two of the impact markers published by *Firestone et al.* [2007]. The study by *Surovell et al.* [2009] found no peaks of abundance unique to the YD time interval.

3.3.3. Carbonaceous Spherules. Microspherules are fairly abundant and occur sporadically throughout late Quaternary sediments. At least some of the supposed impact-derived spherules are in fact fungal sclerotia [Scott *et al.*, 2010]. In addition, new radiocarbon dates on carbon spherules cast doubt on the provenance of YD boundary samples (see next section).

3.3.4. Charcoal and Soot. Evidence for fire exists at the YD, but fire is not a unique evidence for impact [van der Hammen and van Geel, 2008; Bowman *et al.*, 2009]. *Peros et al.* [2008] demonstrate that there were wide fluctuations in the Pleistocene paleoecology and fire history, including the continental-scale vegetation response to rapid climate change, competition, and disturbance. The idea of the charcoal data providing evidence of a high-intensity fire is also flawed. No temperature data based upon charcoal reflectance [Scott *et al.*, 2010] is provided. In addition, for reasons discussed above, it is highly implausible that there would be a continent-wide wildfire. Continental-scale wildfires have been dismissed for the K/T impact [Belcher *et al.*, 2003, 2005, 2009; Belcher, 2009].

3.3.5. *Fullerenes with ^3He* . Fullerenes (carbon allotropes in the topological form of closed caged structures) have been reported in YD black mat deposits. The fullerenes, themselves, do not provide a diagnostic indicator of an impact event since they form terrestrially, e.g., from wildfire [Heymann *et al.*, 1994], and they have been identified in candle soot [Su *et al.*, 2011]. Furthermore, claims of meteoritic fullerenes isolated from stratigraphic impact horizons have been repeatedly challenged [e.g., Taylor and Abdul-Sada, 2000; Braun *et al.*, 2001; Buseck, 2002]. Nevertheless, it was not the fullerenes, themselves, but what they contained, that offered intriguing evidence. It was reported that fullerenes contained an extraterrestrial-trapped noble gas signature enriched in ^3He relative to terrestrial compositions [Firestone *et al.*, 2007]. However, these results have never been replicated, and the original study [Becker *et al.*, 1999] has been criticized for a number of years for methodological shortcomings and nonreproducible results [Farley and Mukhopadhyay, 2001; Buseck, 2002; Farley *et al.*, 2005].

3.3.6. *Nanodiamonds*. With many of the proposed impact markers encountering strong skepticism, proponents of a YD impact have increasingly focused upon reporting the presence of abundant nanometer-sized (2 to 300 nm) diamonds (cubic and hexagonal) in purported YD boundary sediments and carbon spherules at multiple localities across North America and in Greenland ice [Firestone *et al.*, 2007; Kennett *et al.*, 2009a, 2009b; Kurbatov *et al.*, 2010; Israde-Alcántara *et al.*, 2012]. While cubic and hexagonal (lonsdaleite) diamond have been found in shock metamorphosed meteorites and are associated with terrestrial impact structures, cubic diamonds are well known to occur in terrestrial rocks that have no association with impact processes. Sub-micron and smaller-sized cubic diamond crystals have been recently demonstrated to exist in carbon spherules within surface soils sampled from various sites in Germany and Belgium [Yang *et al.*, 2008]. While the origin of these diamonds remains unclear, they were evidently not produced by impact processes because they are present in modern soil and lack any links to impact structures. Consequently, the value of cubic diamonds as impact markers is highly suspect.

Israde-Alcántara *et al.* [2012] quote Tian *et al.* [2011] as independent confirmation of cubic nanodiamonds in YD boundary sediments; however, they do not mention that only a limited range of sediment horizons above and below the Belgium YD boundary were studied in that work. Further, they do not mention the results of Yang *et al.* [2008], which, taken together with Tian *et al.* [2011], suggest that nanodiamonds may be distributed throughout the Belgium sediments.

Another independent study of YD boundary sediments sampled from the same collection sites as that of Kennett *et*

al. [2009a, 2009b] failed to find nanodiamonds [Daulton *et al.*, 2010]. While it is possible that cubic nanodiamonds were heterogeneously distributed within carbonaceous materials in YD boundary “black mat” sediments and not present in the limited samples available to Daulton *et al.* [2010], the presence of cubic diamonds is irrelevant to the YD impact hypothesis as discussed above.

Lonsdaleite, on the other hand, is often associated with shock pressures related to impacts where it has been found to occur naturally, [see Bundy and Kasper, 1967; Hanneman *et al.*, 1967; Frondel and Marvin, 1967; Erlich and Hausel, 2002]. Therefore, the presence of lonsdaleite in sediments suggests (but does not necessary prove) that materials have been shocked. The Russian literature reports the occurrence of lonsdaleite within metamorphosed and metasomatically modified rocks of the Kumdykol diamond deposit in North Kazakhstan [Shumilova *et al.*, 2011], as well as in titanium placers of the Ukrainian shield, diamond placers in Yakutiya, and eclogites in Sal’niye Tundra, Kola Peninsula, and the Urals (for a review, see the works of Kaminsky [1994] and Erlich and Hausel [2002]).

Relevant to the YD impact hypothesis is whether or not lonsdaleite is present in YD-aged materials (while absent in overlying and underlying sediments). Daulton *et al.* [2010] demonstrated that previous studies of YD boundary sediments [Kennett *et al.*, 2009b] misidentified graphene/graphane aggregates (ubiquitous in several types of carbon-rich materials from sediments) as lonsdaleite. Further, Tian *et al.* [2011] found no evidence of lonsdaleite in Belgium YD boundary sediments. The high-resolution (HR)-lattice image of a nanocrystal from residues of Greenland ice that was used to identify lonsdaleite by Kurbatov *et al.* [2010] is crystallographically inconsistent with lonsdaleite (or cubic diamond, graphite, graphene, and graphane) and *must* be a nondiamond (and possibly noncarbon) mineral. The published HR-lattice image of the nanocrystal identified as lonsdaleite displays lattice fringes with two sets of 0.206 nm spaced planes (crossing one another at $62^\circ \pm 2^\circ$ as measured from the work of Kurbatov *et al.* [2010], Figure 6) and one set of 0.193 nm spaced planes. For lonsdaleite, these lattice spacings correspond to the {002} and {101} planes, respectively. However, no zone axis (i.e., crystallographic direction) of lonsdaleite exists that can display two different sets of 0.206 nm spaced {002} planes. Further, the electron diffraction pattern of Kurbatov *et al.* [2010, Figure 6], identified as lonsdaleite, lacks a spatial calibration scale and is also consistent with graphite.

The work of Israde-Alcántara *et al.* [2012], coauthored by members of the previous studies in which lonsdaleite was misidentified, reported the presence of lonsdaleite in purported YD-aged lake sediments in Mexico (although the dating has

been challenged, see next section). This identification is problematic in that it is based on a fast Fourier transform (FFT) of an HR-lattice image of a nanocrystal that is not imaged along a high-symmetry zone axis. Only one set of lattice planes is discernible in the HR-lattice image [Israde-Alcántara *et al.*, 2012, Figure 8]. Provided the weak ~ 2.16 Å peak in the FFT is not an artifact, the FFT is consistent with the lonsdaleite structure. However, a nonexhaustive search of the American Mineralogist Crystal Structure Database and Materials Data Incorporated (MDI) JADE database yielded the following materials (unit cell parameters are in parentheses; zone axis, plane spacings, and angle between planes are in wavy brackets) largely consistent with the FFT: Achavalite-FeSe (a: 3.61 Å, c: 5.87 Å) {[2-21], 2.14 Å, 1.81 Å, 53.6°}; Algodonite-Cu₆As (a: 2.6 Å, b: 4.23 Å) {[101], 2.24 Å, 1.98 Å, 63.8°}; Mn₂AsSb (a: 3.84 Å, c: 5.78 Å) {[2-21], 2.18 Å, 1.92 Å, 55.4°}; and CrSb_{0.5}As_{0.5} (a: 3.81 Å, c: 5.718 Å) {[2-21], 2.16 Å, 1.91 Å, 55.5°}, all of the P63/mmc (194) space group. We are not suggesting that *Israde-Alcántara et al.* [2012] mistook these particular phases as lonsdaleite; we cite these examples to demonstrate that other materials (oriented along various zone axes) are consistent with any single HR-lattice image.

3.4. Radiocarbon Dating

Precise dating of the stratigraphic record of the purported YD impact is crucial in making the case for such a single, continent-wide catastrophic event as argued by *Firestone et al.* [2007]. The geochronologic record is far from precise, however. Of the nine sites used to make the initial argument for an impact, only three, Murray Springs, Arizona; Daisy Cave, California; and Lake Hind, Manitoba, have robust numerical age control constrained by radiocarbon dating. Establishing a putative impact zone that spans several sites requires direct ages that enable chronostratigraphic correlation and ties with the YD interval.

A key aspect of the *Israde-Alcántara et al.* [2012] study is dating of the boundary layer with purported impact indicators. The authors unambiguously state that they recovered such indicators from a 10 cm thick zone dating to 12.9 ka, but in fact, they provide no direct numerical age control at or near that date. They cite the original study of the core, in which 16 ¹⁴C dates were reported. The zone in question was bracketed by calibrated dates of 18.8 ka (3.35m) and 9.9 ka (1.95m) and then dated on the basis of a linear extrapolation.

Israde-Alcántara et al. [2012] present an additional six radiocarbon dates for the 3.35–1.95 m interval. These six dates were rejected because they are significantly older: 37.8 to 17.2 ka, bottom to top. They are consistent stratigraphically both internally and in comparison with overlying dates.

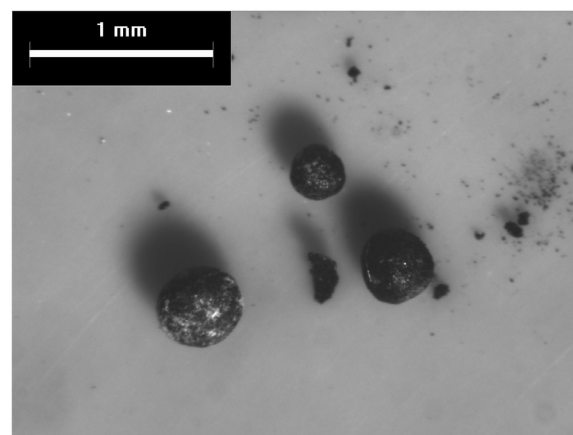


Figure 4. Carbon spherules collected from Gainey, Michigan, provided by A. West.

No reason is given for rejecting these, other than that they are older dates than predicted by their age model. The authors invoked reworking of the deposits to explain the anomalous radiocarbon ages. The age model is, in part, anchored by a tephra layer at 4.7–4.5 m depth, identified as the Cieneguillas rhyolitic tephra, which has been dated elsewhere at 31 ka cal. However, no evidence is provided that it is actually the Cieneguillas tephra. The tephra could be reworked, or it could be another one of a series of older rhyolitic tephra that are reported in the region [Pradal and Robin, 1994].

Finally, one of us (MB) acquired carbon microspherules (Figure 4) collected from the Gainey site in Michigan from one of the original YD impact proponents (A. West). Gainey is one of the nine key YD sites, and one of the undated ones, presented by *Firestone et al.* [2007]. To verify the age of the samples, we submitted one set of spherules for accelerator mass spectrometry radiocarbon dating at the University of Arizona. Only one microspherule has been dated thus far and is 207 ± 87 years BP (AMS lab number AA92197). This result suggests that there are geochronology problems. One key problem is that particles identified as diamond-containing carbon microspheres and presumed to be related to the purported YD impact may actually be younger than the YD, unrelated to the YD or to an impact, and might be modern contaminants.

4. CONCLUSIONS

An impact event as proposed by *Firestone et al.* [2007] is not consistent with conventional understanding of the physics of impacts and airbursts. We conclude that the YD impact hypothesis is not supportable, either physically or statistically. Much of the putative evidence for a YD impact

is irreproducible. It is highly improbable that a significant impact event happened during YD, as conceived by Firestone *et al.* [2007]. Although the works published by the proponents of an impact event vary in description about the impactor, consideration of basic laws of physics indicate that such a fragmentation or high-altitude airburst event would not conserve momentum or energy, would lie outside any realistic range of probability, and therefore did not occur during the YD as described by Firestone *et al.* [2007]. This conclusion is supported by the present work, as well as a broad review of all the other lines of evidence critiqued by Pinter and Ishman [2008a, 2008b], Surovell *et al.* [2009], and Pinter *et al.* [2011a, 2011b].

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REFERENCES

- Alvarez, L. W., W. Alvarez, F. Asaro, and H. V. Michel (1980), Extraterrestrial cause for the Cretaceous-Tertiary extinction, *Science*, *208*, 1095–1108.
- Barnosky, A. D., P. L. Koch, R. S. Feranec, S. I. Wing, and A. B. Shabel (2004), Assessing the causes of late Pleistocene extinctions on the continents, *Science*, *306*, 70–75.
- Becker, L., R. J. Poreda, and T. E. Bunch (1999), Fullerenes: An extraterrestrial carbon carrier phase for noble gases, *Proc. Natl. Acad. Sci. U. S. A.*, *97*, 2979–2983, doi:10.1073/pnas.97.7.2979.
- Belcher, C. M. (2009), Reigniting the Cretaceous-Palaeogene fire-storm debate, *Geology*, *37*, 1147–1148.
- Belcher, C. M., M. E. Collinson, A. R. Sweet, A. R. Hildebrand, and A. C. Scott (2003), Fireball passes and nothing burns—The role of thermal radiation in the Cretaceous-Tertiary event: Evidence from the charcoal record of North America, *Geology*, *31*, 1061–1064, doi:10.1130/G19989.1.
- Belcher, C. M., M. E. Collinson, and A. C. Scott (2005), Constraints on the thermal energy released from the Chicxulub impactor: New evidence from multi-method charcoal analysis, *J. Geol. Soc.*, *162*, 591–602, doi:10.1144/0016-764904-104.
- Belcher, C. M., P. Finch, M. E. Collinson, A. C. Scott, and N. V. Grassineau (2009), Geochemical evidence for combustion of hydrocarbons during the K-T impact event, *Proc. Natl. Acad. Sci. U. S. A.*, *106*, 4112–4117, doi:10.1073/pnas.0813117106.
- Boslough, M. B. E., and D. A. Crawford (1997), Shoemaker-Levy 9 and plume forming collisions on Earth, in *Annals of the New York Academy of Sciences*, vol. 822, *Near-Earth Objects: The United Nations Conference*, edited by J. L. Remo, pp. 236–282, The N. Y. Acad. of Sci., New York.
- Boslough, M. B. E., and D. A. Crawford (2008), Low-altitude airbursts and the impact threat, *Int. J. Impact Eng.*, *35*, 1441–1448.
- Bowman, D. M. J. S., et al. (2009), Fire in the Earth system, *Science*, *324*, 481–484.
- Braun, T., E. Osawa, C. Detre, and I. Toth (2001), On some analytical aspects of the determination of fullerenes in samples from the Permian/Triassic boundary layers, *Chem. Phys. Lett.*, *348*, 361–362.
- Broecker, W. S., G. H. Denton, R. L. Edwards, H. Cheng, R. B. Alley, and A. E. Putnam (2010), Putting the Younger Dryas cold event into context, *Quat. Sci. Rev.*, *29*, 1078–1081, doi:10.1016/j.quascirev.2010.02.019.
- Brown, P., R. E. Spalding, D. O. ReVelle, E. Tagliaferri, and S. P. Worden (2002), The flux of small near-Earth objects colliding with the Earth, *Nature*, *420*, 294–296.
- Bundy, F. P., and J. S. Kasper (1967), Hexagonal diamond—A new form of carbon, *J. Chem. Phys.*, *46*, 3437–3446.
- Buseck, P. R. (2002), Geological fullerenes; review and analysis, *Earth Planet. Sci. Lett.*, *203*, 781–792.
- Daniau, A. L., S. P. Harrison, and P. J. Bartlein (2010), Fire regimes during the Last Glacial, *Quat. Sci. Rev.*, *29*, 2918–2930.
- Daulton, T. L., N. Pinter, and A. C. Scott (2010), No evidence of nanodiamonds in Younger-Dryas sediments to support an impact event, *Proc. Natl. Acad. Sci. U. S. A.*, *107*, 16,043–16,047.
- Dawson, J. W. (1891), *Acadian Geology: The Geological Structure, Organic Remains, and Mineral Resources of Nova Scotia, New Brunswick, and Prince Edward Island*, 4th ed., MacMillan, London, U. K.
- Dyke, A. S., A. Moore, and L. Robertson (2003), Deglaciation of North America, *Open file 1574*, Geol. Surv. of Canada, Ottawa.
- Erlich, E. I., and W. D. Hausel (2002), *Diamond Deposits: Origin, Exploration, and History of Discovery*, Soc. for Min., Metal., and Explor., Littleton, Colo.
- Faith, J. T., and T. A. Surovell (2009), Synchronous extinction of North America's Pleistocene mammals, *Proc. Natl. Acad. Sci. U. S. A.*, *106*, 20,641–20,645, doi:10.1073/pnas.0908153106.
- Farley, K. A., and S. Mukhopadhyay (2001), An extraterrestrial impact at the Permian–Triassic boundary?, *Science*, *293*, 2343, doi:10.1126/science.293.5539.2343a.
- Farley, K. A., P. Ward, G. Garrison, and S. Mukhopadhyay (2005), Absence of extraterrestrial ³He in Permian–Triassic age sedimentary rocks, *Earth Planet. Sci. Lett.*, *240*, 265–275.
- Firestone, R. (2009), The case for the Younger Dryas extraterrestrial impact event: Mammoth, megafauna, and Clovis extinction, 12,900 years ago, *J. Cosmology*, *2*, 256–285.
- Firestone, R. B., and W. Topping (2001), Terrestrial evidence of a nuclear catastrophe in Paleoindian times, *Mammoth Trumpet*, *16*(2), 9–16.
- Firestone, R. B., A. West, and S. Warwick-Smith (2006), *The Cycle of Cosmic Catastrophes: Flood, Fire, and Famine in the History of Civilization*, Bear, Rochester, Vermont.

- Firestone, R. B., et al. (2007), Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling, *Proc. Natl. Acad. Sci. U. S. A.*, *104*, 16,016–16,021.
- Firestone, R. B., A. West, Z. Revay, J. T. Hagstrum, T. Belgya, S. S. Que Hee, and A. R. Smith (2010), Analysis of the Younger Dryas impact layer, *J. Sib. Fed. Univ. Eng. Technol.*, *3*, 30–62.
- French, B. M., and C. Koeberl (2010), The convincing identification of terrestrial meteorite impact structures: What works, what doesn't, and why, *Earth Sci. Rev.*, *98*, 123–170.
- Frondel, C., and U. B. Marvin (1967), Lonsdaleite, a hexagonal polymorph of diamond, *Nature*, *214*, 587–589.
- Gill, J. L., J. W. Williams, S. T. Jackson, K. B. Lininger, and G. S. Robinson (2009), Pleistocene megafaunal collapse, novel plant communities, and enhanced fire regimes in North America, *Science*, *326*, 1100–1103.
- Glasstone, S., and P. J. Dolan (1977), *The Effects of Nuclear Weapons*, U.S. Gov. Print. Off., Washington, D. C.
- Grayson, D. K. (2007), Deciphering North American Pleistocene extinctions, *J. Anthropol. Res.*, *63*, 185–213.
- Grayson, D. K., and D. J. Meltzer (2003), A requiem for North American overkill, *J. Archaeol. Sci.*, *30*, 585–593.
- Grieve, R. A. F. (1997), Extraterrestrial impact events: The record in the rocks and the stratigraphic column, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *132*, 5–23.
- Grieve, R. A. F., and A. M. Therriault (2004), Observations at terrestrial impact structures: Their utility in constraining crater formation, *Meteorit. Planet. Sci.*, *39*, 199–216, doi:10.1111/j.1945-5100.2004.tb00336.x.
- Hagstrum, J. T., R. B. Firestone, A. West, Z. Stefanka, and Z. Revay (2010), Micrometeorite impacts in Beringian mammoth tusks and a bison skull, *J. Sib. Fed. Univ. Eng. Technol.*, *3*, 123–132.
- Hanneman, R. E., H. M. Strong, and F. P. Bundy (1967), Hexagonal diamonds in meteorites: Implications, *Science*, *155*, 995–997.
- Harris, A. W. (2002), A new estimate of the population of small NEAs, *Bull. Am. Astron. Soc.*, *34*, 835.
- Haynes, C. V., Jr. (1991), Geoarchaeological and paleohydrological evidence for a Clovis age drought in North America and its bearing on extinction, *Quat. Res.*, *35*, 438–450.
- Haynes, C. V., Jr. (2007), *Murray Springs: A Clovis Site With Multiple Activity Areas in the San Pedro Valley, Arizona*, edited by C. V. Haynes Jr. and B. B. Huckell, pp. 229–239, Univ. of Ariz. Press, Tucson.
- Haynes, C. V., Jr. (2008), Younger Dryas “black mats” and the Rancholabrean termination in North America, *Proc. Natl. Acad. Sci. U. S. A.*, *105*, 6520–6525.
- Haynes, C. V., Jr., J. Boerner, K. Domanik, D. Lauretta, J. Ballenger, and J. Goreva (2010), The Murray Springs Clovis site, Pleistocene extinction, and the question of extraterrestrial impact, *Proc. Natl. Acad. Sci. U. S. A.*, *107*, 4010–4015.
- Heymann, D., L. P. F. Chibante, R. R. Brooks, W. S. Wolbach, and R. E. Smalley (1994), Fullerenes in the Cretaceous-Tertiary boundary layer, *Science*, *265*, 645–647, doi:10.1126/science.265.5172.645.
- Higgins, M. D., P. Lajeunesse, G. St-Onge, J. Locat, M. Duchensne, and R. Sanfaçon (2011), Bathymetric and petrological evidence for a young (Pleistocene?) 4-km diameter impact crater in the Gulf of Saint Lawrence, Canada, paper presented at the 42nd Lunar and Planetary Science Conference, The Woodlands, Tex.
- Holliday, V. T., and D. J. Meltzer (2010), The 12.9 ka ET impact hypothesis and North American Paleoindians, *Curr. Anthropol.*, *51*, 575–607.
- Hut, P., W. Alvarez, W. P. Elder, T. Hansen, E. G. Kauffman, G. Keller, E. M. Shoemaker, and P. R. Weissman (1987), Comet showers as a cause of mass extinctions, *Nature*, *329*, 118–126, doi:10.1038/329118a0.
- Israde-Alcántara, I., et al. (2012), Evidence from central Mexico supporting the Younger Dryas extraterrestrial impact hypothesis, *Proc. Natl. Acad. Sci. U. S. A.*, *109*, E738–E747, doi:10.1073/pnas.1110614109.
- Kaminsky, F. V. (1994), Carbonado and yakutite: Properties and possible genesis, in *Proceedings of the Fifth International Kimberlite Conference*, vol. 2, *Diamonds: Characterization, Genesis, and Exploration*, edited by H. O. A. Meyer and O. H. Leonardos, pp. 136–143, Companhia de Pesquisa de Recursos Minerais, Rio de Janeiro, Brazil.
- Kennett, D. J., J. P. Kennett, G. J. West, J. M. Erlandson, J. R. Johnson, I. L. Henty, A. West, B. J. Culleton, T. L. Jones, and T. W. Stafford Jr. (2008), Wildfire and abrupt ecosystem disruption on California's Northern Channel Islands at the Allerød–Younger Dryas boundary (13.0–12.9 ka), *Quat. Sci. Rev.*, *27*, 2530–2545.
- Kennett, D. J., J. P. Kennett, A. West, C. Mercer, S. S. Que Hee, L. Bement, T. E. Bunch, M. Sellers, and W. S. Wolbach (2009a), Nanodiamonds in the Younger Dryas boundary sediment layer, *Science*, *323*, 94.
- Kennett, D. J., et al. (2009b), Shock-synthesized hexagonal diamonds in Younger Dryas boundary sediments, *Proc. Natl. Acad. Sci. U. S. A.*, *106*, 12,623–12,638.
- Kurbatov, A. V., et al. (2010), Discovery of a nanodiamond-rich layer in the Greenland ice sheet, *J. Glaciol.*, *56*, 749–759.
- Marlon, J. R., et al. (2009), Wildfire responses to abrupt climate change in North America, *Proc. Natl. Acad. Sci. U. S. A.*, *106*, 2519–2524.
- Melosh, H. J. (1989), *Impact Cratering: A Geologic Process*, Oxford Univ. Press, New York.
- Melosh, H. J., and G. S. Collins (2005), Meteor crater formed by a low-velocity impact, *Nature*, *434*, 157.
- Meltzer, D. J., and V. T. Holliday (2010), Would North American Paleoindians have noticed Younger Dryas age climate changes?, *J. World Prehist.*, *23*, 1–41.
- NASA Near-Earth Object Science Definition Team (2003), Study to determine the feasibility of extending the search for near-earth objects to smaller limiting diameters, Off. of Space Sci., Sol. Syst. Explor. Div., Washington, D. C.
- Paquay, F. S., S. Goderis, G. Ravizza, F. Vanhaeck, M. Boyd, T. A. Surovell, V. T. Holliday, C. V. Haynes Jr., and P. Claeys (2009), Absence of geochemical evidence for an impact event at the Bølling–Allerød/Younger Dryas transition, *Proc. Natl. Acad. Sci. U. S. A.*, *106*, 21,505–21,510.

- Paterson, W. S. B. (1972), Laurentide ice sheet: Estimated volumes during late Wisconsin, *Rev. Geophys.*, 10(4), 885–917.
- Peros, M. C., K. Gajewski, and A. E. Viau (2008), Continental-scale tree population response to rapid climate change, competition, and disturbance, *Global Ecol. Biogeogr.*, 17, 658–669.
- Pigati, J. S., C. Latorre, J. A. Rech, J. L. Betancourt, K. E. Martinez, and J. R. Budahn (2012), Accumulation of impact markers in desert wetlands and implications for the Younger Dryas impact hypothesis, *Proc. Natl. Acad. Sci. U. S. A.*, 109, 7208–7212, doi:10.1073/pnas.1200296109.
- Pinter, N., and S. E. Ishman (2008a), Impacts, mega-tsunami, and other extraordinary claims, *GSA Today*, 18, 37–38.
- Pinter, N., and S. E. Ishman (2008b), Reply to comments on “Impacts, mega-tsunami, and other extraordinary claims”, *GSA Today*, 18(6), e14.
- Pinter, N., A. C. Scott, T. L. Daulton, A. Podoll, C. Koeberl, R. S. Anderson, and S. E. Ishman (2011a), The Younger Dryas impact hypothesis: A requiem, *Earth Sci. Rev.*, 106, 247–264, doi:10.1016/j.earscirev.2011.02.005.
- Pinter, N., S. J. Fiedel, and J. E. Keeley (2011b), Fire and vegetation shifts in the Americas at the vanguard of Paleoindian migration, *Quat. Sci. Rev.*, 30, 269–272, doi:10.1016/j.quascirev.2010.12.010.
- Pradal, E., and C. Robin (1994), Long-lived magmatic phases at Los Azufres volcanic center, Mexico, *J. Volcanol Geotherm. Res.*, 63, 201–215.
- Quade, J., R. M. Forester, and W. L. Pratt (1998), Black mats, spring-fed streams, and late-glacial-age recharge in the southern Great Basin, *Quat. Res.*, 49, 129–148.
- Scott, A. C., N. Pinter, M. E. Collinson, M. Hardiman, R. S. Anderson, A. P. R. Brain, S. Y. Smith, F. Marone, and M. Stambanoni (2010), Fungus, not comet or catastrophe, accounts for carbonaceous spherules in the Younger Dryas “impact layer”, *Geophys. Res. Lett.*, 37, L14302, doi:10.1029/2010GL043345.
- Shumilova, T. G., E. Mayer, and S. I. Isaenko (2011), Natural monocrystalline lonsdaleite, *Dokl. Earth Sci.*, 441, 1552–1554.
- Shuvalov, V. V. (2003), Numerical modeling of the Eltanin impact, paper presented at Lunar and Planetary Science XXXI, Houston, Tex.
- Shuvalov, V. V., and I. A. Trubetskaya (2007), Numerical modeling of the formation of the Eltanin submarine impact structure, *Sol. Syst. Res.*, 41(1), 56–64, doi:10.1134/S0038094607010066.
- Straus, L. G., and T. Goebel (Eds.) (2011), Humans and Younger Dryas: Dead end, short detour, or open road to the Holocene?, *Quat. Int.*, 242, 259–584.
- Stuart, J. S. (2001), A near-Earth asteroid population estimate from the LINEAR survey, *Science*, 294, 1691–1693.
- Su, Z., W. Zhou, and Z. Yang (2011), New insight into the soot nanoparticles in a candle flame, *Chem. Commun.*, 47, 4700–4702, doi:10.1039/c0cc05785a.
- Surovell, T. A., V. T. Holliday, J. A. M. Gingerich, C. Ketron, C. V. Haynes Jr., I. Hilman, D. P. Wagner, E. Johnson, and P. Claeys (2009), An independent evaluation of the Younger Dryas extra-terrestrial impact hypothesis, *Proc. Natl. Acad. Sci. U. S. A.*, 106, 18,155–18,158.
- Taylor, R., and A. K. Abdul-Sada (2000), There are no fullerenes in the K–T boundary layer, *Fullerene Sci. Technol.*, 8, 47–54.
- Tian, H., D. Schryvers, and P. Claeys (2011), Nanodiamonds do not provide unique evidence for a Younger Dryas impact, *Proc. Natl. Acad. Sci. U. S. A.*, 108, 40–44, doi:10.1073/pnas.1007695108.
- Toon, O. B., K. Zahnle, D. Morrison, R. P. Turco, and C. Covey (1997), Environmental perturbations caused by the impacts of asteroids and comets, *Rev. Geophys.*, 35(1), 41–78.
- van der Hammen, T., and B. van Geel (2008), Charcoal in soils of the Allerød-Younger Dryas transition were the result of natural fires and not necessarily the effect of an extra-terrestrial impact, *Neth. J. Geosci.*, 87, 359–361.
- Werner, S. C., A. W. Harris, G. Neukum, and B. A. Ivanov (2002), The near-Earth asteroid size-frequency distribution: A snapshot of the lunar impactor size-frequency distribution, *Icarus*, 156, 287–290.
- Yang, Z. Q., J. Verbeeck, D. Schryvers, N. Tarcea, J. Popp, and W. Rosler (2008), TEM and Raman characterisation of diamond micro- and nanostructures in carbon spherules from upper soils, *Diamond Relat. Mater.*, 27, 937–943.
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- P. Bartlein, Department of Geography, University of Oregon, Eugene, OR 97403-1251, USA.
- M. Boslough, Sandia National Laboratories, Albuquerque, NM 87185, USA. (mbeb@unm.edu)
- P. Claeys, Earth System Science, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium.
- T. L. Daulton, Department of Physics and Center for Materials Innovation, Washington University, St. Louis, MO 63130, USA.
- J. Gill and J. Marlon, Department of Geography, University of Wisconsin, 550 N. Park St., Madison, WI 53706, USA.
- D. Grayson, Department of Anthropology, University of Washington, Box 353100, Seattle, WA 98195, USA.
- V. Holliday, School of Anthropology and Department of Geosciences, University of Arizona, Tucson, AZ 85721, USA.
- A. J. T. Jull, AMS Radiocarbon Facility, University of Arizona, Tucson, AZ 85721, USA.
- D. Meltzer, Department of Anthropology, Southern Methodist University, Dallas, TX 75275-0336, USA.
- K. Nicoll, Department of Geography, University of Utah, Salt Lake City, UT 84112, USA.
- F. Paquay, Department of Geology and Geophysics, University of Hawai‘i at Mānoa, Honolulu, HI 96822, USA.
- N. Pinter, Department of Geology, Southern Illinois University, Carbondale, IL 62901-4324, USA.
- A. C. Scott, Department of Earth Sciences, Royal Holloway University of London, Egham TW20 0EX, UK.
- T. Surovell, Department of Anthropology, University of Wyoming, Laramie, WY 82070, USA.
- C. Whitlock, Department of Earth Sciences, Montana State University, Bozeman, MT 59715, USA.