An independent evaluation of the Younger Dryas extraterrestrial impact hypothesis

Todd A. Surovell[a,1], Vance T. Holliday[b], Joseph A. M. Gingerich[a], Caroline Ketron[a], C. Vance Haynes, Jr.[b], Ilene Hilman[a], Daniel P. Wagner[c], Eileen Johnson[d], and Philippe Claeys[e]

[a]Department of Anthropology, University of Wyoming, Laramie, WY 82070; [b]Departments of Anthropology and Geosciences, University of Arizona, Tucson, AZ 85721; [c]Geo-Sci Consultants, Inc. , 4410 Van Buren Street, University Park, MD 20782; [d]Museum of Texas Tech University, Box 43191, Lubbock, TX 79409; and [e]Department of Geology, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium

Edited by David Jeffrey Meltzer, Southern Methodist University, Dallas, TX, and approved September 3, 2009 (received for review July 15, 2009)

Based on elevated concentrations of a set of ''impact markers'' at the onset of the Younger Dryas stadial from sedimentary contexts across North America, Firestone, Kennett, West, and others have argued that 12.9 ka the Earth experienced an impact by an extraterrestrial body, an event that had devastating ecological consequences for humans, plants, and animals in the New World [Firestone RB, et al. (2007) *Proc. Natl. Acad. Sci. USA* 104:16016–16021]. Herein, we report the results of an independent analysis of magnetic minerals and microspherules from seven sites of similar age, including two examined by Firestone et al. We were unable to reproduce any results of the Firestone et al. study and find no support for Younger Dryas extraterrestrial impact.

Clovis | magnetic grains | magnetic microspherules | Pleistocene extinctions

Firestone, West, Kennett, and others have proposed that 12.9 ka the Earth or its atmosphere experienced an impact from an extraterrestrial body, either a comet or asteroid (1–5). They argue for a single or multiple airburst and/or impact events that triggered the Younger Dryas (YD) stadial, ignited widespread wildfires, and produced large clouds of dust and soot, all of which devastated grassland and forest environments, thereby causing the extinction of the New World Pleistocene megafauna and dramatically impacting human populations and adaptations. Herein, we report the results of an independent analysis of magnetic minerals and magnetic microspherules[2] from seven sites of similar age, including Blackwater Draw, NM and Topper, SC, both examined by Firestone et al. (1). In all seven sites, we found no distinct peak in magnetic grains or microspherules uniquely associated with the YD and therefore find no support for an extraterrestrial cause of the YD event and New World Pleistocene extinctions.

The primary evidence for impact is the apparent presence of a suite of markers that occur in increased concentrations in sediments dating to *ca*. 12.9 ± 1.0 ka from sites across North America including 10 Clovis-age archaeological sites and 15 Carolina Bays on the Atlantic Coastal Plain (1–5). Clovis occupation features date within a narrow time range between 13.3 and 12.8 ka; some are buried by organic-rich sediments or soils, commonly termed "black mats" (6, 7). Markers found in YD black mats and contemporaneous sedimentary contexts include magnetic microspherules, magnetic grains, iridium and nickel, charcoal, soot and polycyclic hydrocarbons, carbon spherules, fullerenes and ET helium, glass-like carbon, and nanodiamonds. Some markers are more widespread than others.

A series of critiques of the original Firestone et al. article (1) have been published recently (8–10). Pinter and Ishman (8) argue that the suite of markers used to indicate impact are inconsistent with "any single impactor or any known event." Furthermore, they provide alternative explanations for many of the observed marker peaks. For example, glassy and metallic microspherules are known components of atmospheric dust derived from the constant influx of micrometeorites. An independent evaluation of the charcoal evidence was recently published by Marlon et al. (9). Examining concentrations of charcoal from 35 pollen cores across North America, they found no evidence for large-scale, continent-wide wildfires specifically associated with the onset of the YD.

These studies highlight two questions critical to testing the YD impact hypothesis: 1) Do the supposed markers of extraterrestrial impact peak only at the onset of the YD in sedimentary contexts across a broad geographic area? In other words, are the Firestone et al. (1) results replicable? 2) Do these markers necessarily indicate an impact event, or can they be explained by some other process or processes? In this study, we are concerned with the former. Using methods from the original Firestone et al. (1) study (see *SI Text*), we examined concentrations of magnetic minerals and microspherules from sediment columns spanning the Younger Dryas boundary (YDB) in seven sites across North America, including two sites examined in the original study. Like Marlon et al. (9), we seek to determine whether the results of the original study are reproducible and provide support for extraterrestrial impact.

Our sites, like those of Firestone et al. (1), span a large geographic region: three from the Southern Great Plains of Texas and New Mexico, one from Wyoming, and three from the Atlantic coast (Figs. S1–S6). All are archaeological sites with Clovis and/or other Paleoindian occupations. Each has sediments of YD age dated by radiocarbon and/or by the presence of temporally diagnostic artifacts (see *SI Text*), and each preserves magnetic grains comprised primarily of iron bearing minerals. If high concentrations of magnetic particles and microspherules were deposited across the North American landscape as a result of some sort of ET event at 12.9 ka, unique peaks in these markers should occur in that time-stratigraphic interval at all, or perhaps most, of our study sites, as found by Firestone et al. (1).

The Blackwater Draw, Lubbock Lake, and San Jon sites are on the Southern Great Plains (11–15). Blackwater Draw and Lubbock Lake are in similar settings, along northwest to southeast trending drainages that cross the Southern High Plains. Blackwater Draw (a.k.a. Clovis) was sampled and reported by Firestone et al. (1) to have clear peaks in both magnetic grains and microspherules at 12.9 ka. San Jon is within an ancient playa basin inset in the flat, semiarid High Plains landscape. Lubbock

Author contributions: T.A.S. and V.T.H. designed research; T.A.S., V.T.H., J.A.M.G., C.K., C.V.H., I.H., D.P.W., E.J., and P.C. performed research; C.V.H., D.P.W., and E.J. contributed new reagents/analytic tools; T.A.S., J.A.M.G., and C.K. analyzed data; and T.A.S., V.T.H., and J.A.M.G. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

[1]To whom correspondence should be addressed. E-mail: surovell@uwyo.edu.

[2]Firestone et al. (1) examined two types of spherules in their study, magnetic microspherules and carbon spherules. In our study, we examined only the former.

This article contains supporting information online at www.pnas.org/cgi/content/full/0907857106/DCSupplemental.

Lake and San Jon are 180 and 80 km, respectively, from Clovis. The San Jon site is particularly likely to preserve peaks in impact markers due to its proximity to Clovis and because it represents slow, continuous, and uniform sedimentation through 12.9 ka. At Clovis, we sampled the same section collected by Firestone et al. (1).

The Agate Basin site includes a series of Paleoindian localities from an alluvial terrace of Moss Agate Creek in eastern Wyoming (16, 17). Our sample column was taken beneath the Agate Basin complex bison bone bed at Area 1, where multiple black mats occur within fine-grained alluvium.

Shawnee-Minisink occurs within a 6.5-m high alluvial terrace above the Delaware River in northeastern Pennsylvania. The Late Pleistocene deposits are buried by ≈240 cm of alluvial and eolian deposits (18, 19). Shawnee-Minisink is geographically the closest site in our sample to the proposed point of impact, and the floodplain was aggrading at 12.9 ka. Therefore, it would be expected to have clearly enhanced concentrations of impact markers associated with the Clovis occupation. Our sample column was collected from the profile of a recent excavation unit, which extended through the Clovis occupation.

The Paw Paw Cove site is located along a low coastal plain of the Delmarva Peninsula of Maryland where a buried late to terminal Pleistocene A-horizon is found along its eastern shore (20). At Paw Paw and across the region, Clovis artifacts buried by late Pleistocene and Holocene loess frequently are found at the upper contact of this buried soil. Our sample column was taken by auger from sediments adjacent to the site.

The Topper site is located on the Savannah River in southern South Carolina. The Clovis occupation is <1 m beneath the surface and occurs within coarse sands that mantle uplands adjacent to the floodplain (21). Topper was one of the sites examined by Firestone et al. (1) and showed peaks in numerous markers, including magnetic grains, roughly associated with the YDB. Our sample column was collected from a profile in an excavation unit in the 2008 Upper Firebreak excavations within colluvial sands that bury the Clovis occupation.

Results

We found little concordance between our results and those of the original study. Although concentrations of magnetic grains vary by more than two orders of magnitude among all study sites, no individual site shows clear evidence of uniquely enhanced levels of magnetic grains in YDB samples (Fig. 1, Table S1). In fact, in six of seven sites, YDB samples have reduced concentrations of magnetic grains compared with the mean value for non-YDB samples.

In contrast, Firestone et al. (1) found enhanced concentrations of magnetic grains to be among their most reliable geologic markers of impact, showing a "distinct peak" in all Clovis-age sites examined (10 of 10). Not only were we unable to find that distinct peak, but we also were unable to replicate results from the two sites they also examined. At the Topper site, Firestone et al. (1) did not have a peak in magnetic grains associated with the YDB, but instead one 15 cm beneath the Clovis occupation in sediments associated with a luminescence date of 15.2 ± 1.5 ka. Although our sample column at Topper does not extend to this depth, our samples extended to and slightly through the Clovis occupation, and we found no peak associated with the YDB (Fig. 1). Furthermore, there appears to be little correspondence between our data and theirs for samples extending from the Clovis occupation to the modern ground surface. At Blackwater Draw, Firestone et al. (1) reported the greatest concentration of magnetic grains in YDB sediments, but we found just the opposite. Our YDB sample had the lowest concentration of magnetic grains of any sample from the site. The geologic significance of Firestone et al.'s (1) nearly ubiquitous and distinct peaks in magnetic grains is unclear, presumably thought to represent the fragmented impactor and/or target rock. Regardless, the significance of magnetic grains as an impact marker is largely irrelevant because we found no distinct peaks in magnetic grains associated with the YDB in any of the seven sites examined, a discrepancy between the two studies that is particularly troublesome.

Magnetic microspherules were present in very low frequencies in four of the seven sites examined: Agate Basin, Blackwater Draw, Lubbock Lake, and San Jon (Figs. 1 and 2). Where present, they typically occurred in concentrations on the order of 10^1–10^2 spherules/kg of sediment. At Agate Basin, concentrations of microspherules varied between 0 and 255 per kg of sediment with two broad peaks occurring, one roughly coincident with the onset of the YD, and a second peak well above it. Lower concentrations of microspherules occurred in the Southern High Plains sites generally on the order of 0–25 microspherules per kg of sediment. At Blackwater Draw, sporadic microspherules occur with the YD aged diatomite, but no microspherules were encountered in the sample dating to the onset of the YD. At Lubbock Lake, microspherules were encountered in small frequencies in both the YDB sample and samples postdating the YD. At San Jon, small numbers of microspherules were found in samples pre- and postdating the YDB.

In contrast, Firestone et al. (1) found YDB peaks in microspherules at eight of nine Clovis sites and in all five Carolina Bays examined. Although Firestone et al. (1) did not graph their microspherule results from the Topper site, they reported a concentration of 97 spherules/kg of sediment for the YDB sample. In contrast, we were unable to identify any microspherules from the site whatsoever. Likewise, we were unable to replicate their results from Blackwater Draw. At this site, they estimated ≈800 microspherules per kg of sediment for the YDB sample, but we found 0, a difference that cannot be explained by sample size. For our sample of 22.5 mg of magnetic grains examined, we should have counted upwards of 70 microspherules to obtain a similar concentration, but we encountered none (Fig. 1.).

With the possible exception of our results from Agate Basin, we find no evidence for a peak in microspherules associated with the YDB. We have good reason to doubt whether the YDB peak at Agate Basin has anything to do with extraterrestrial impact. Not only does it reach its maximum in sediments stratigraphically overlying the YDB sample, but also a second peak of nearly identical magnitude occurs higher in the profile. It remains unclear what factors control the presence, absence, and relative abundance of magnetic microspherules, but in general, they seem to be most common in fine-grained alluvial or paludal deposits, in which they occur sporadically and show little if any patterning through time. They occur in sediments both pre- and postdating the YDB, and do not appear to be necessarily diagnostic of an ET impact, at least not a YD impact. Of the 10 microspherules shown in Fig. 2, none are from YDB samples.

Discussion

In both the resampled sites and our additional sites, using methods taken from Firestone et al. (1), we failed to reproduce their results. We have found no peaks in magnetic particles or magnetic microspherules unique to 12.9-ka level in any of our sample sites that were significantly different from peaks in these materials at other levels in the stratigraphy. This situation is the case even at Blackwater Draw, where our samples were collected within a few centimeters of the sections sampled previously. Assuming an ET impact occurred, perhaps the lack of reproducibility indicates that the methods used for recovering the magnetic material are not appropriate for the task at hand. Recognition and identification of the spherules is especially difficult and somewhat subjective. However, that difficulty

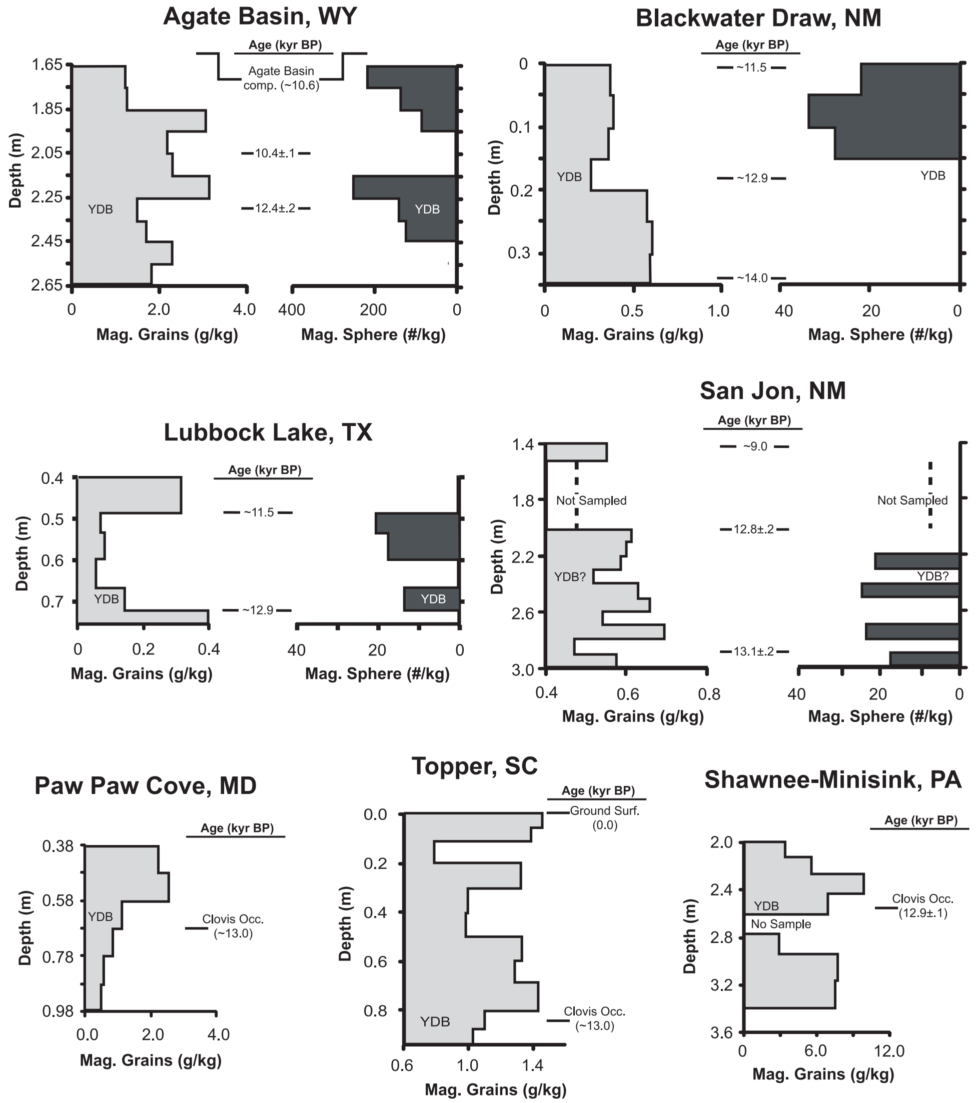

Fig. 1. Concentrations of magnetic grains and microspherules in stratigraphic sections from seven sites across North America showing no evidence for enhanced levels uniquely associated with the Younger Dryas boundary (YDB). Microspherule concentrations are not shown for Paw Paw Cove, Topper, and Shawnee-Minisink because no microspherules were recovered from these sites. Dates are shown in calendar years BP as age estimates approximated by stratigraphic correlation (dates preceded by ~) or as radiocarbon dates (dates with error estimates).

should not have prevented us from seeing the distinctive pattern reported by Firestone et al. (1). The same methods were used at all sites, and our identifications of the magnetic spherules from Lubbock Lake have been confirmed by Allen West, one of the authors of the Firestone et al. (1) article, who was involved in much of the laboratory analysis for that work.

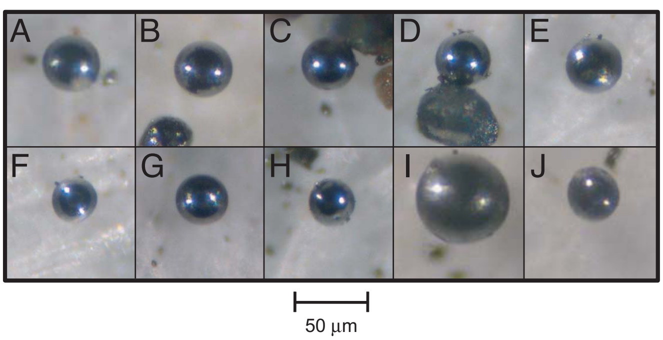

Fig. 2. Photomicrographs of magnetic microspherules from non-Younger Dryas boundary samples: (*A–C*) Agate Basin, WY; (*D–F*) Blackwater Draw, NM; (*G* and *H*) San Jon, NM; (*I* and *J*) Lubbock Lake, TX.

Alternatively, it may be that the presence, absence, and relative abundance of magnetic materials, especially the spherules, is due to characteristics of the parent material and depositional environment instead of some sort of continent-wide extraterrestrial process. The characteristics of the local depositional setting before, during, and after 12.9 ka have not been addressed by the proponents of the impact hypothesis. The zones producing the YDB "impact markers" are typically associated with soils (stable surfaces) or shifts in the depositional environment (e.g., alluvial to lacustrine conditions at Blackwater Draw, Lubbock Lake, Murray Springs, and Lake Hind; buried soils in the Carolina Bays and at Lommel, Belgium).

Replicability is fundamental to the scientific method and hypothesis testing; results that are not reproducible cannot be considered reliable or supportive of a hypothesis. Marlon et al. (8) have examined cores from lakes and bogs for charcoal indicative of "massive burning" associated with a 12.9-ka impact and found no such evidence. We have been unable to find high concentrations of magnetic particles and spherules, considered key impact indicators, at the 12.9-ka level in seven sites that should exhibit this evidence if the impact hypothesis is credible. In short, we find no support for the extraterrestrial impact hypothesis as proposed by Firestone et al. (1).

Materials and Methods

Our methods followed those of the original Firestone et al. (1) study and are described in further detail in *SI Text*. Except for the Paw Paw Cove site, where samples where collected by auger, our samples were taken from stratigraphic profiles, in standardized 5- or 10-cm increments or by stratigraphic unit. Magnetic grains were isolated by saturating sediment samples with water, and by passing a grade-42 neodymium magnet within a 4-mL plastic bag through the resultant slurry. Magnetic grains were cleaned of clays by passing them through a series of water baths. Magnetic microspherule concentrations were measured by dusting aliquots of magnetic grains onto a standard microscope slide coated with an opaque background and examining all particles at 100× magnification. Conservative criteria were used in microspherule identification. We only counted those grains that were unfaceted, well-rounded, highly spherical, and exhibited a smooth glassy or metallic surface. Following Firestone et al. (1), concentrations of both magnetic grains and microspherules were standardized to per kg of sediment units.

ACKNOWLEDGMENTS. Darrin Lowery, Jason LaBelle, James Mayer, and Joseph Daniele provided support in sample collection, and Joseph Daniele and John Laughlin participated in initial laboratory analyses. Albert Goodyear kindly allowed us to collect a sample column from the Topper site, as did Marcel Kornfeld from the Agate Basin site. This work was supported by a Basic Research Grant from the College of Arts and Sciences at the University of Wyoming and by the Argonaut Archaeological Research Fund. For E.J., this article represents part of the ongoing Lubbock Lake regional research program (under the auspices of the Museum of Texas Tech University). Sampling at Lubbock Lake was done under Texas Historical Commission antiquities permit 4196.

1. Firestone RB, 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 USA* 104:16016–16021.
2. Firestone RB, West A, Warwick-Smith S (2006) *The Cycle of Cosmic Catastrophes*: *How a Stone-Age Comet Changed the Course of World Culture* (Bear & Company, Rochester, Vermont).
3. Kennett DJ, et al. (2009) Nanodiamonds in the Younger Dryas boundary sediment layer. *Science* 323:94.
4. Kennett DJ, et al. (2008) Wildfire and abrupt ecosystem disruption on California's Northern Channel Islands at Allerød-Younger Dryas (13.0–12.9 ka). *Quat Sci Rev* 27:2530–2545.
5. Kennett DJ, et al. (2009) Shock-synthesized hexagonal diamonds in Younger Dyras boundary sediments. *Proc Natl Acad Sci USA* 106:12623–12628.
6. Haynes CV (2008) Younger Dryas ''black mats'' and the Rancholabrean termination in North America. *Proc Natl Acad Sci USA* 105:6520–6525.
7. Waters MR, Stafford TW, Jr (2007) Redefining the age of Clovis: Implications for the peopling of the Americas. *Science* 315:1122–1126.
8. Pinter N, Ishman S (2008) Impacts, mega-tsunami, and other extraordinary claims. *GSA Today* 18:37–38.
9. Marlon JR, et al. (2009) Wildfire responses to abrupt climate change in North America. *Proc Natl Acad Sci USA* 106:2519–2524.
10. Buchanan B, Collard M, Edinborough K (2008) Paleoindian demography and the extraterrestrial impact hypothesis. *Proc Natl Acad Sci USA* 105:11651–11654.
11. Haynes CV, Jr (1995) Geochronology of paleoenvironmental change, Clovis type site, Blackwater Draw, New Mexico. *Geoarch* 10:317–388.
12. Holliday VT (1997) *Paleoindian Geoarchaeology of the Southern High Plains* (Univ of Texas Press, Austin, TX).
13. Holliday VT, Mayer JH, Fredlund GG (2008) Late Quaternary sedimentology and geochronology of small playas on the Southern High Plains, Texas and New Mexico, USA. *Quat Res* 70:11–25.
14. Johnson E (1987) *Lubbock Lake. Late Quaternary Studies on the Southern High Plains* (Texas A&M Univ Press, College Station, TX).
15. Sellards EH (1952) *Early Man in America*: *A Study in Prehistory* (Univ of Texas Press, Austin, TX).
16. Frison GC, Stanford DJ (1982) *The Agate Basin Site*: *A Record of the Paleoindian Occupation of the Northwestern High Plains* (Academic, New York).
17. Haynes CV, Jr, Kornfeld M, Frison GC (2004) Short contribution: New geochronological and archaeological data for the Sheaman Clovis site, eastern Wyoming, U.S.A. *Geoarch* 19:369–379.
18. Foss J (1977) in *Amerinds and Their Paleoenvironments at Several Paleoindian Sites in the Northeast*, eds Newman WS, Salwen B (Annals of the New York Academy of Sciences), pp 234–244.
19. Gingerich JAM (2007) Shawnee-Minisink revisited: Re-evaluating the Paleoindian occupation. M.A. thesis (Univ of Wyoming, Laramie, WY).
20. Lowery DL (2002) *A Time of Dust*: *Archaeological and Geomorphological Investigations at the Paw Paw Cove Paleo-Indian Site Complex in Talbot County*, *Maryland* (Chesapeake Bay Watershed Archaeological Research Foundation, Tilghman, MD).
21. Goodyear AC (2006) in *Paleoamerican Origins*: *Beyond Clovis*, eds Bonnichsen R, Lepper BT, Stanford D, Waters MR (Texas A&M Univ Press, College Station, TX), pp 103–112.