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

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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

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[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.

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ANTHROPOLOGY GEOLOGY

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

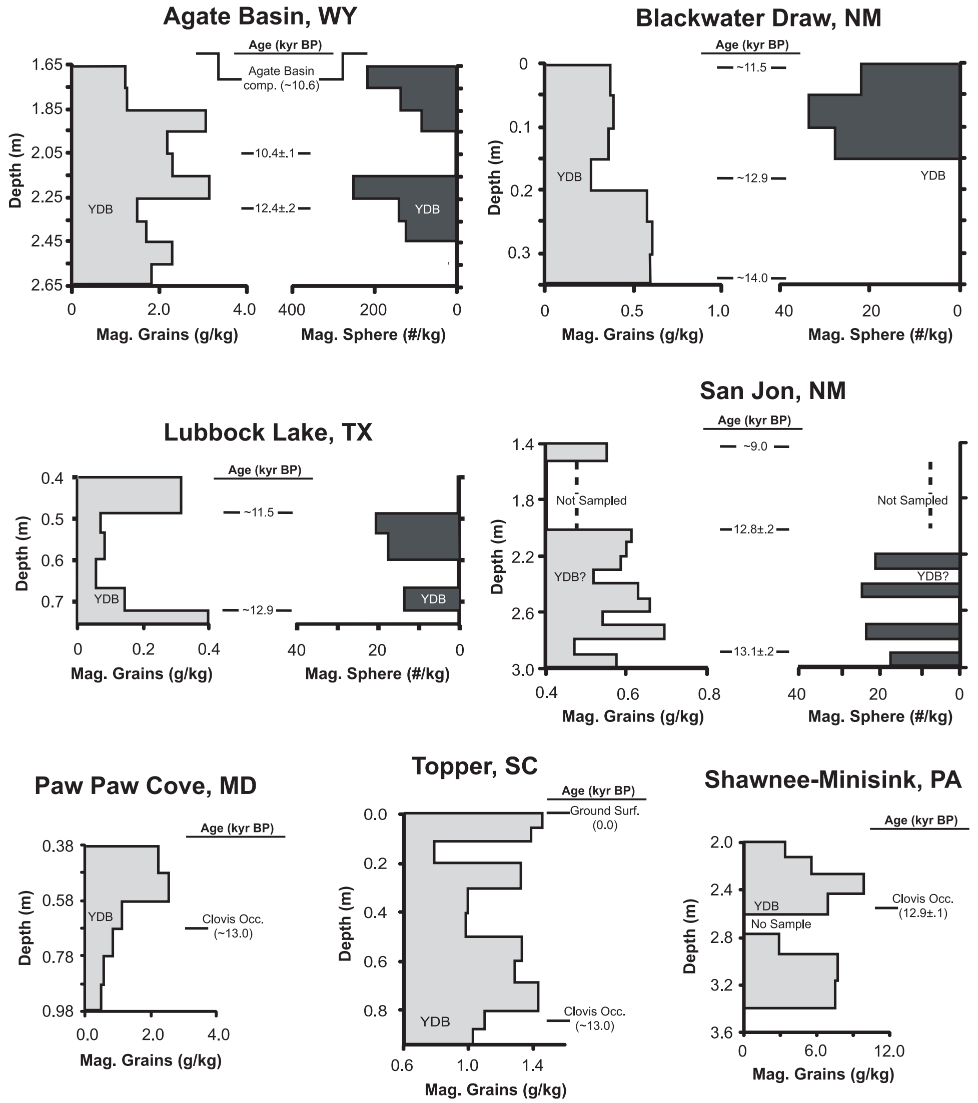

Fig. 1. Concentrations of magnetic grains and microspherules in stratigraphic sections from seven sites across North America showing no evidence for enhanced levels uniquely associated with the Younger Dryas boundary (YDB). Microspherule concentrations are not shown for Paw Paw Cove, Topper, and Shawnee-Minisink 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

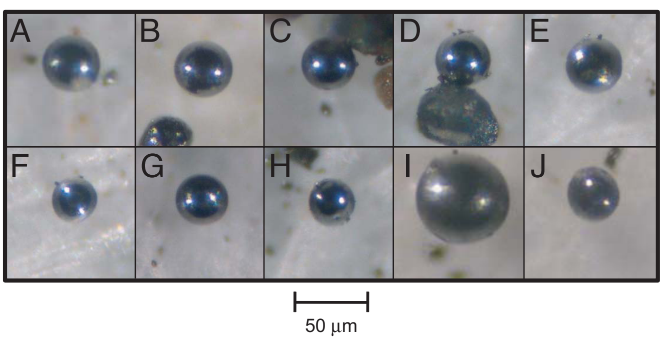

Fig. 2. Photomicrographs of magnetic microspherules from non-Younger Dryas boundary samples: (*A–C*) Agate Basin, WY; (*D–F*) Blackwater Draw, NM; (*G* and *H*) San Jon, NM; (*I* and *J*) Lubbock Lake, TX.

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.

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.

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Supporting Information

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SI Text

Our laboratory procedures were based on those used in the original study (1) and followed a detailed laboratory manual, titled "Separation of YD Event Markers (8/10/2007)," which was provided by one of its authors (Allen West, GeoScience Consulting).

Magnetic Minerals. Air-dried samples were lightly disaggregated with a ceramic pestle in a plastic tub and passed through a no. 18 1-mm sieve to remove the coarse fraction (if present). Depending upon the available sample size, between 200 and 500 g of the fine fraction were placed in clean plastic tub filled with ample amounts of water to produce a slurry. A $2 \times 1 \times 0.5''$ grade-42 neodymium magnet was placed in a 4-mL plastic bag, and the slurry was circulated allowing magnetic particles to accumulate on the bag. At intervals of $\approx$1 min, the bag was removed, and the particles were transferred to a bath of clean water. We found that this process could be repeated for many hours without the yields ever dropping to zero. Initially, we repeated magnetic extraction until yields dropped to minimal levels, but for later sets of samples, we extracted magnetics for a standardized 30-min time interval. After extraction, magnetic grains were cleaned by transfer through a series of water baths (2–4 depending upon texture) to remove clays. Once clean, magnetic fractions were dried and weighed.

Magnetic Microspherules. To identify magnetic spherules, two to four aliquots of magnetic grains from each sample were dusted onto a standard microscope slide coated with adhesive white paper to create an opaque background for increased visual contrast. The mass of particles on each slide typically varied between 8 and 20 mg depending upon sediment texture and their density on the slide. Each sedimentary grain was examined at 100× magnification with a binocular compound microscope, which was top-lit with a dual-gooseneck fiber optic light source. A digital camera connected to a monitor was mounted to the microscope to speed the process. When possible microspherules were identified, we zoomed to 300×, using the optical zoom of the camera, to determine if the grain should be counted as a microspherule. We recorded the location of each microspherule on the graduated microscope stage to prevent double counting, and each microspherule was photographed. We typically examined 10–40 mg of sediment per sample, from which we extrapolated to the entire sample, to estimate the total concentration of microspherules per kg of sediment to make our results directly comparable with Firestone et al. (1). We found that a single slide could be scanned for microspherules in $\approx$30 min to 1 h.

After consultation with Allen West, an author of the original study (1), we used extremely conservative criteria for the identification of microspherules. Our counts of microspherules from the Lubbock Lake site are largely based on West's identifications. We only counted those grains that were unfaceted, well rounded, highly spherical, and exhibited a smooth glassy or metallic surface. We found that the most efficient and replicable method for microspherule identification was to use the reflective properties of highly spherical and shiny grains. With a dual light source, microspherules invariably show two very bright and circular reflections on their surfaces (see Fig. 2 for examples). Once a possible microspherule was identified, we manually manipulated the light sources to observe how their reflections migrated across the surface. If even slight faceting was present on the grain surface, the movement of surface reflections tended to "jump" rather than migrating smoothly. Possible microspherules were photographed at least twice with the light sources positioned at multiple angles, and by doing so, we were able to eliminate a number of particles that at first glance appeared to be highly spherical but were not.

Study Sites. In this section, we provide a brief background to the sites and stratigraphic sections used in the study. In addition to site-specific sampling methods, we briefly describe the geomorphology and geochronology of stratigraphic sections. Although the identification of the precise position of the Younger Dryas Boundary (YDB) in some sections is not known with a high degree of confidence, we are certain that it does occur within all sampled sections. From the perspective of testing the ET impact hypothesis, the exact location of the YDB within sections is not critical because all that is predicted is that the YDB samples should have enhanced concentrations of magnetic grains and microspherules, no matter where they fall stratigraphically.

Agate Basin, Wyoming. The Agate Basin site contains numerous localities of Paleoindian archaeology occurring in alluvial terraces of Moss Agate Creek and its tributaries in eastern Wyoming just to the southeast of the southern Black Hills (2). The site has seen numerous episodes of investigation by archaeologists over more than 60 years (2–5). Archaeological components at the site span much of the Paleoindian period ranging in age from Clovis through Hell Gap (Fig. S1). Agate Basin is the type site for the Agate Basin Paleoindian technocomplex.

Our sample column was taken from Area 1 stratigraphically beneath the Agate Basin complex bone bed originally investigated by Roberts (5). Paleoindian artifacts occur within fine-grained alluvium deposits within the second alluvial terrace (6, 7). Four well-developed dark colored horizons (or "black mats") are present (Fig. S1). Consistent with Reider's (7) description of a similar section at Area 1, gleying was observed throughout much of the profile with intermittent horizontal banding of redoximorphic mottling. From this section, we recovered a continuous 1-m sample column in 10-cm increments.

From each of the lowermost two black layers, we dated paired humic/humin soil organic matter samples by using an accelerator mass spectrometer (AMS) (Fig. S1). For both samples, the humin or residue fractions were considerably older than the humic acid fractions and were inconsistent with the known chronology of the site (2, 8). We suspect that humin fractions have been affected by the inclusion of particulate carbon contributed by local Cretaceous Carlile Shale. The humic acid dates are more reasonable but still somewhat problematic. The uncalibrated humic acid date on the lower most buried soil of 10,506 ± 82 BP (AA-81792) is consistent with the dating of Younger Dryas black mats elsewhere (9). Therefore, we consider the basal contact of the lowermost black layer to be the most likely position of the Younger Dryas Boundary (YDB). The upper humic acid age of 9,195 ± 48 BP (AA-82374) is likely too young as it is stratigraphically beneath the Agate Basin bone bed. Dates on Agate Basin components elsewhere in the site are generally older, but they have fairly low precision: 10430 ± 570 BP; 9,990 ± 225 BP (10, 11).

Although it is possible that we have incorrectly identified the exact location of the YDB at Agate Basin, additional stratigraphic evidence suggests that it is within the section we sampled. At Area 2 of the site <100 m to the west, the Younger Dryas aged Folsom component occurs $\approx$30–60 cm beneath the

Agate Basin complex and typically overlies organic-rich "dark" horizons (3, 12), and at the Sheaman locality of Agate Basin, the Clovis component appears to occur within or at the base of a black mat (4, 13). Therefore, the YDB occurs within this section even if our estimation of its exact position is incorrect.

Blackwater Draw, NM. The Blackwater Draw site (also known as the Clovis site and the type site for the Clovis technocomplex) is a stratified archaeological site on the west-central Southern High Plains in a paleo-basin that drains into upper Blackwater Draw (14–17). The Clovis archaeology is from spring-generated sandy alluvial deposits and from sandy slope deposits. Post-Clovis, typically Folsom archaeology is from overlying lacustrine and paludal diatomite, diatomaceous earth, and muds. Archaeology and geology of the basin fill were exposed since the 1930s as the basin was subjected to quarrying for gravel. The site was largely destroyed by the early 1970s. Today the most complete and accessible section is the "South Bank," where the paleo-basin once drained into the draw. This section is described, dated, and discussed by Haynes (17). This profile is where samples reported by Firestone et al. (1) and by us were collected (Fig. S2). Our sampling columns were within ≈10 cm of one another, grid unit N1151 E1028. We collected a 35-cm column in continuous 5-cm increments through the diatomite and into the underlying sands (Fig. S2), essentially reproducing the sequence reported by Firestone et al. (1).

No Clovis or Folsom archaeology is known from the sample section but is correlated stratigraphically with archaeological features found elsewhere in the site. A number of radiocarbon ages from the South Bank are reported and discussed by Haynes (14), but the dates for the Clovis and Folsom levels (including the YDB "black mat") illustrated by Firestone et al. (1) and mentioned by Kennett et al. (18) are from a section ≈320 m away on the "North Bank."

Lubbock Lake, TX. Lubbock Lake is a stratified archeological site on the east-central Southern High Plains on the northwest side of the city of Lubbock, TX, in a meander of Yellowhouse Draw (19). The site was discovered after excavation for a reservoir in 1936. The stratigraphy of the Paleoindian (Clovis and Folsom) levels is very similar to that described for Blackwater Draw (16, 20, 21). Clovis-age bone and artifacts are in the upper few tens of centimeters of alluvium (stratum 1C) from a stream that once meandered across the floor of the draw. Resting conformably on the alluvium is interbedded diatomite and mud (stratum 2A). Above is homogeneous mud (stratum 2B). These layers produced the Folsom and some of the other Paleoindian archaeological features. The samples reported in this article were collected from Trench 65 on the west side of the old reservoir cut (Fig. S3) Six samples were collected in a continuous sequence from the base of 2B through 2A into upper 1C. Samples were collected on the basis of microstratigraphic units. Dating of the section is based on stratigraphic correlation with other exposures and excavation areas that yielded archaeology and radiocarbon samples (22, 23). These correlations are reasonable because Clovis-age fauna is found only in the alluvium and Folsom archaeology is found only in the bedded diatomite/mud.

Paw Paw Cove, MD. The Paw Paw Cove site is located on a low Coastal Plain upland a short distance from the Chesapeake Bay on the west side of the Delmarva Peninsula. Paw Paw Cove consists of a complex of sites that were identified through a survey of eroded shorelines along Tilghman Island, MD (24). Throughout the area, a conspicuous buried A-horizon is commonly present, marking late to terminal Pleistocene deposits that are then buried by loess. Clovis artifacts have been found at the top of this buried surface at Paw Paw Cove and other locations, providing a chronological marker for the start of YD age sediments (24). Therefore, we consider the Younger Dryas Boundary (YDB) to be marked by the overlying mantle of loess that buries this distinctive land surface used by Clovis.

Excavations at Paw Paw Cove have confirmed the existence of intact Clovis deposits resting atop the buried A-horizon (2BAtgb), and Early Archaic deposits in some areas just below the plow zone (24), thus effectively bracketing the loess mantle within the YD. In 2007, soil samples were collected near the site by auger. These samples were collected in 10-cm increments starting at 38 cm below the surface and extending to 98 cm (Table S1). In this profile we define the YDB at 68 cm resting at the top of the buried surface (2BAtgb).

San Jon, NM. San Jon is a stratified archaeological site in a playa basin on the northwest escarpment of the Southern High Plains (16, 26–28). Erosion exposed both a large playa with stratified basin fill and a smaller "subplaya" (29) with weakly stratified fill. The fill in the basins is a gray to dark gray mud, typical of most playa basins in the region (Fig. S4) (29). The samples for both magnetic extraction and radiocarbon dating were collected directly from the exposed section of the smaller subplaya. The radiocarbon ages were determined on bulk decalcified mud by conventional methods. Our radiocarbon samples bracketed the YDB zone. We estimated the position of the YDB zone based on calculated sedimentation rates, but the exact position is not especially important, because the dates show that it is near the middle of our sampling column (Fig. S4). Samples for separation of magnetic materials were collected through a 1-m column in continuous 10-cm increments.

Shawnee-Minisink, PA. The Shawnee-Minisink site in the Upper Delaware Valley of northeastern Pennsylvania has a thick well-stratified geological and archaeological record with Clovis, Late Paleoindian, and Early Archaic through Woodland occupations (30, 31). At a height of 6.5 m above the Delaware River at the confluence of Brodhead Creek, Shawnee-Minisink remains one of the most spatially intact Clovis deposits known in eastern North America (30, 32, 33). The Paleoindian deposits are buried by ≈240 cm of alluvial and eolian sediments. The cultural zone that contains the Clovis-age occupation has been tentatively interpreted as a silt loam loess deposit (33–35). During the Holocene, overbank alluvium was responsible for much of the deposition in the upper 2 m of the profile (Fig. S5).

The Clovis occupation at Shawnee-Minisink is well dated with six AMS radiocarbon assays from three hearth features, directly associated with Paleoindian artifacts (32). Using the protocol described by Long and Rippeteau (36), these six dates produce an average age of 10,935 ± 15 BP (*ca*. 12,900 Cal yr BP). Based on these dates and the location of artifacts, which occur only within the central portion of stratum 7Bwb (240–268 cm), we consider the upper portion of this level to represent the Younger Dryas Boundary (YDB). Although no other radiocarbon dates have been obtained from the lower levels of the profile, a Late Paleoindian deposit resting at the top of 5Bwb in some of the excavation units (31) may represent the end of the Younger Dryas dating to approximately 10,000 ^{14}C BP (*ca*. 11.6 kyr BP) (32) (Fig. S5).

Our sample column was taken from Unit 1 of the new excavation block (32, 33, 38) (Fig. S5). Samples were collected by stratigraphic horizon beginning at a depth of 199 cm below surface and ending at a depth of 350 cm. This strategy allowed for an even number of samples to be collected both from above and below the YDB (Fig. S5). Only one sample from this sequence was not collected, stratum 8C. Stratum 8C is a 10-cm sand lens and did not provide sufficient sediment for analysis.

Topper, SC. The Topper site is a multicomponent site in Allendale County, SC in the Savannah River Valley. The site contains a relatively complete cultural sequence, including Clovis and a possible pre-Clovis component (39). 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. The sediment column includes 11 samples continuously spanning a depth of 92 cm (Fig. S6). Limited chronological control is available beyond the presence of time-diagnostic cultural materials. An OSL date taken in association with the Clovis component in another area of the site produced an age of 13.5 ± 1.0 kyr BP (35), consistent with the dating of Clovis elsewhere (25). In our sample column, the Clovis component occurs at a depth of ≈80–90 cm beneath the surface, and, like Firestone et al. (1), we assume that the YDB falls within this interval.

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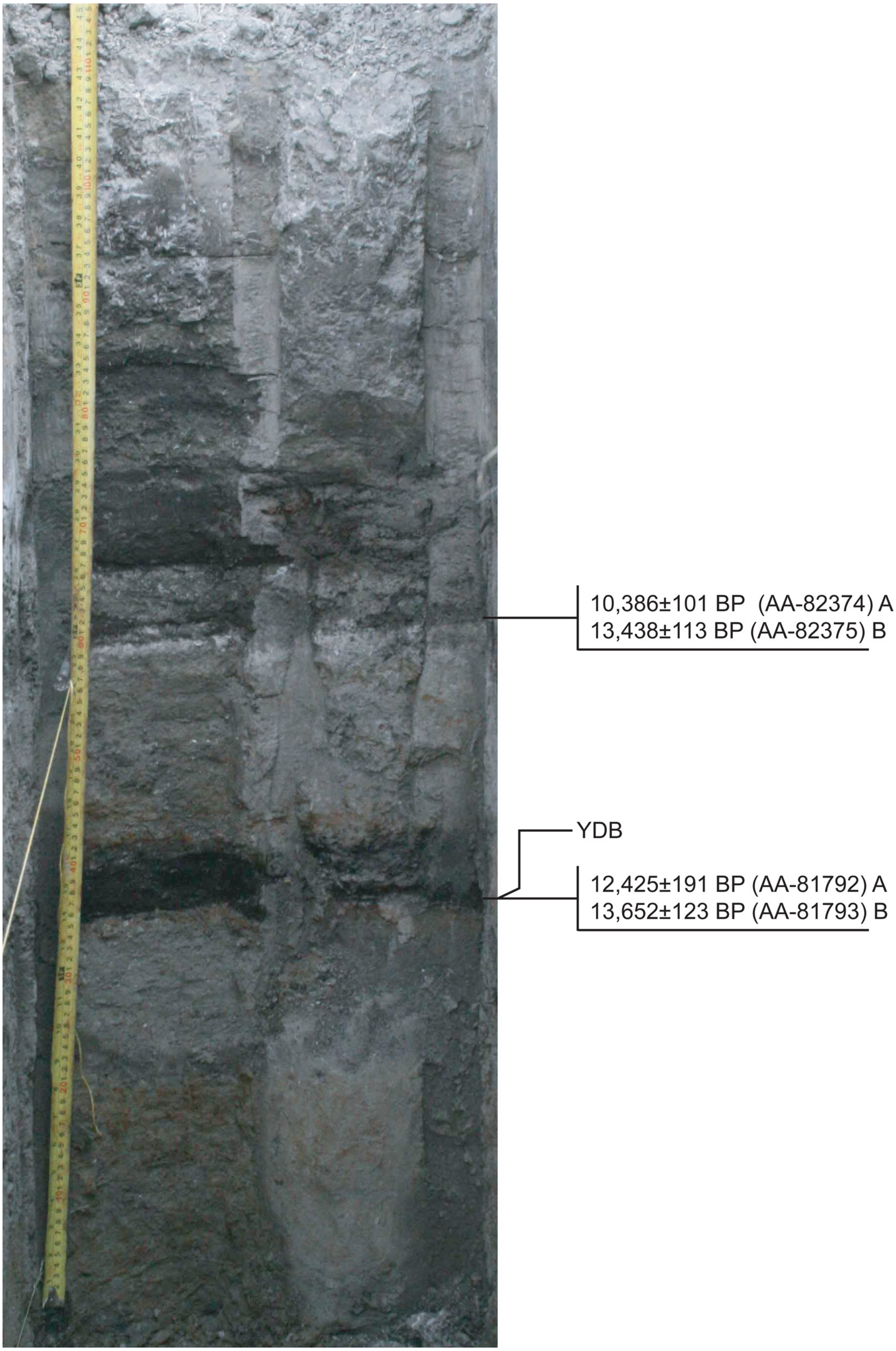

Fig. S1. The sampled section from Agate Basin Area 1, stratigraphically beneath the Agate Basin complex bison bone bed with uncalibrated radiocarbon ages. Abbreviations: YDB, estimated position of the Younger Dryas Boundary; A, humic acid fraction; B, humin fraction.

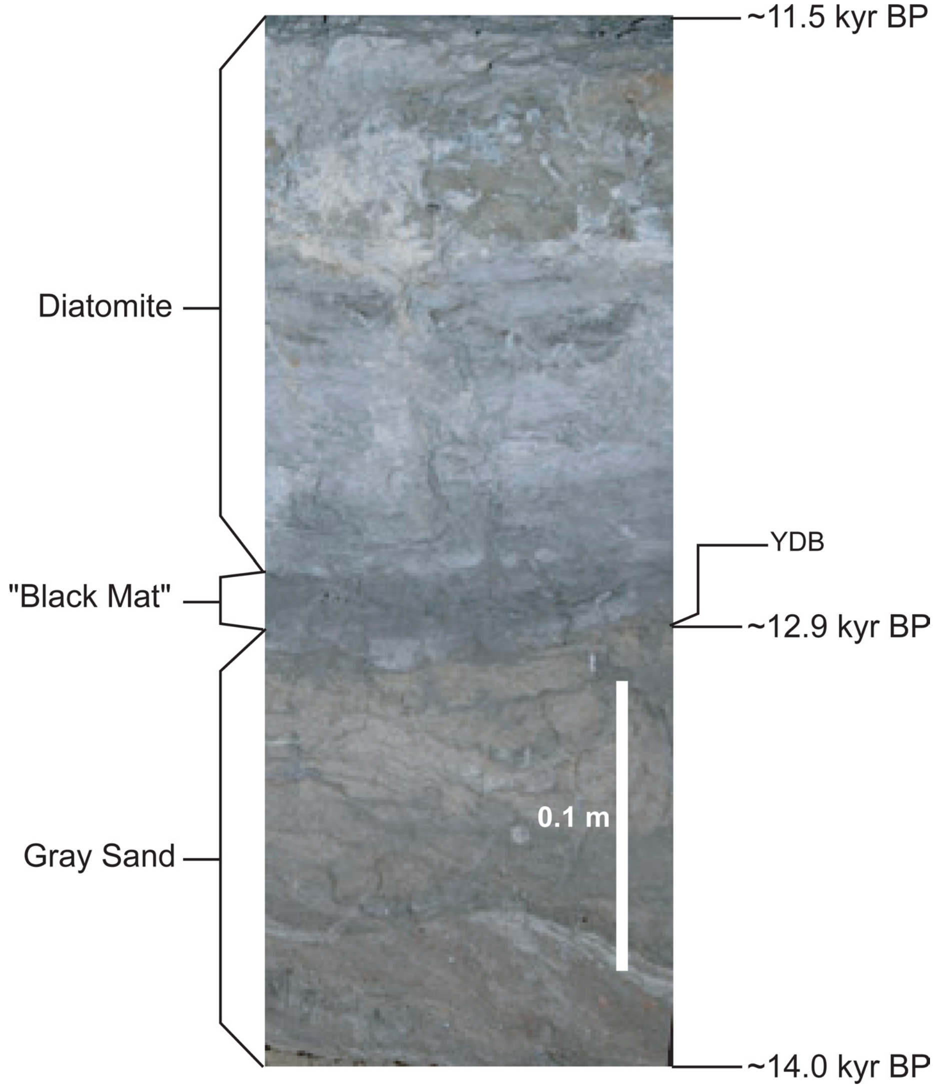

Fig. S2. The sampled section from Blackwater Draw. YDB marks the estimated position of the Younger Dryas Boundary.

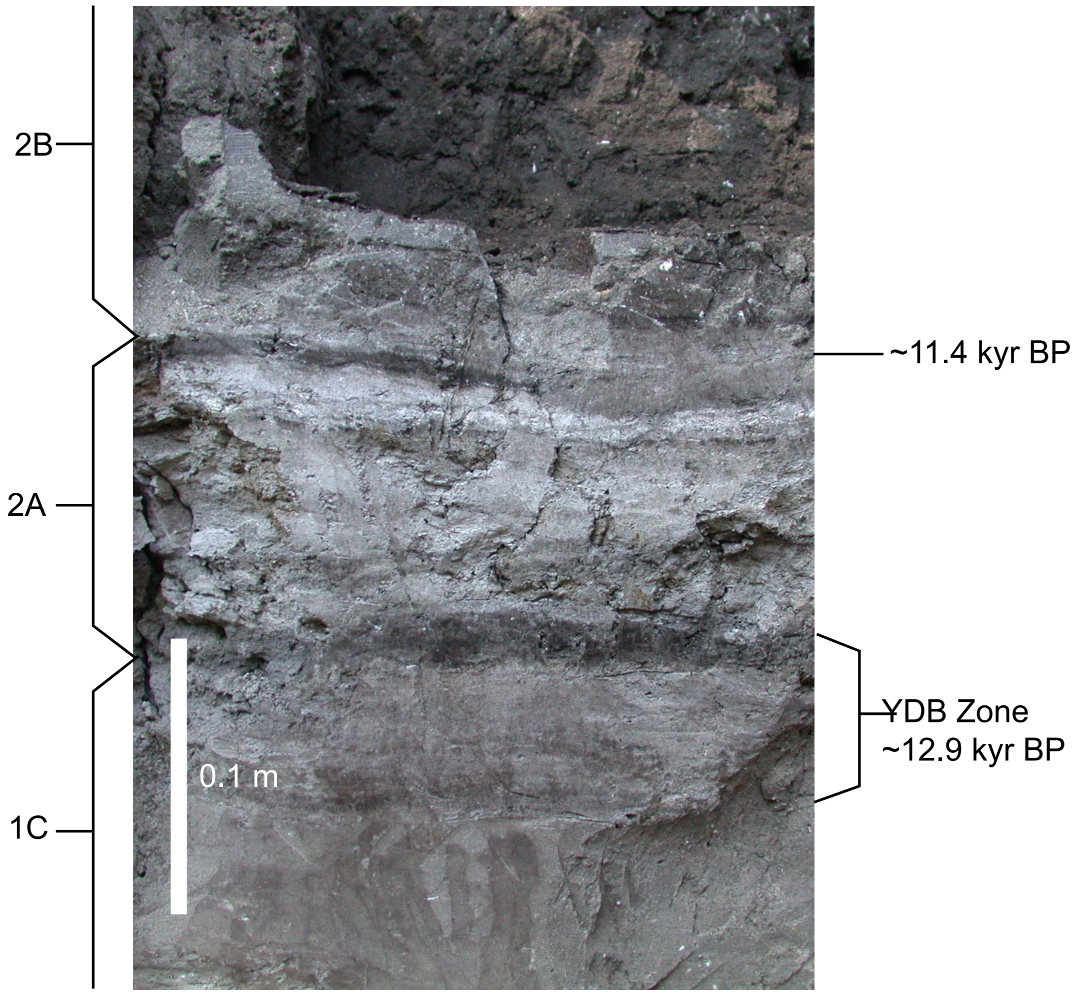

Fig. S3. The sampled section from Lubbock Lake. YDB Zone marks the approximate position of the Younger Dryas Boundary. Stratigraphic designations (*Left*) are taken from Holliday (20).

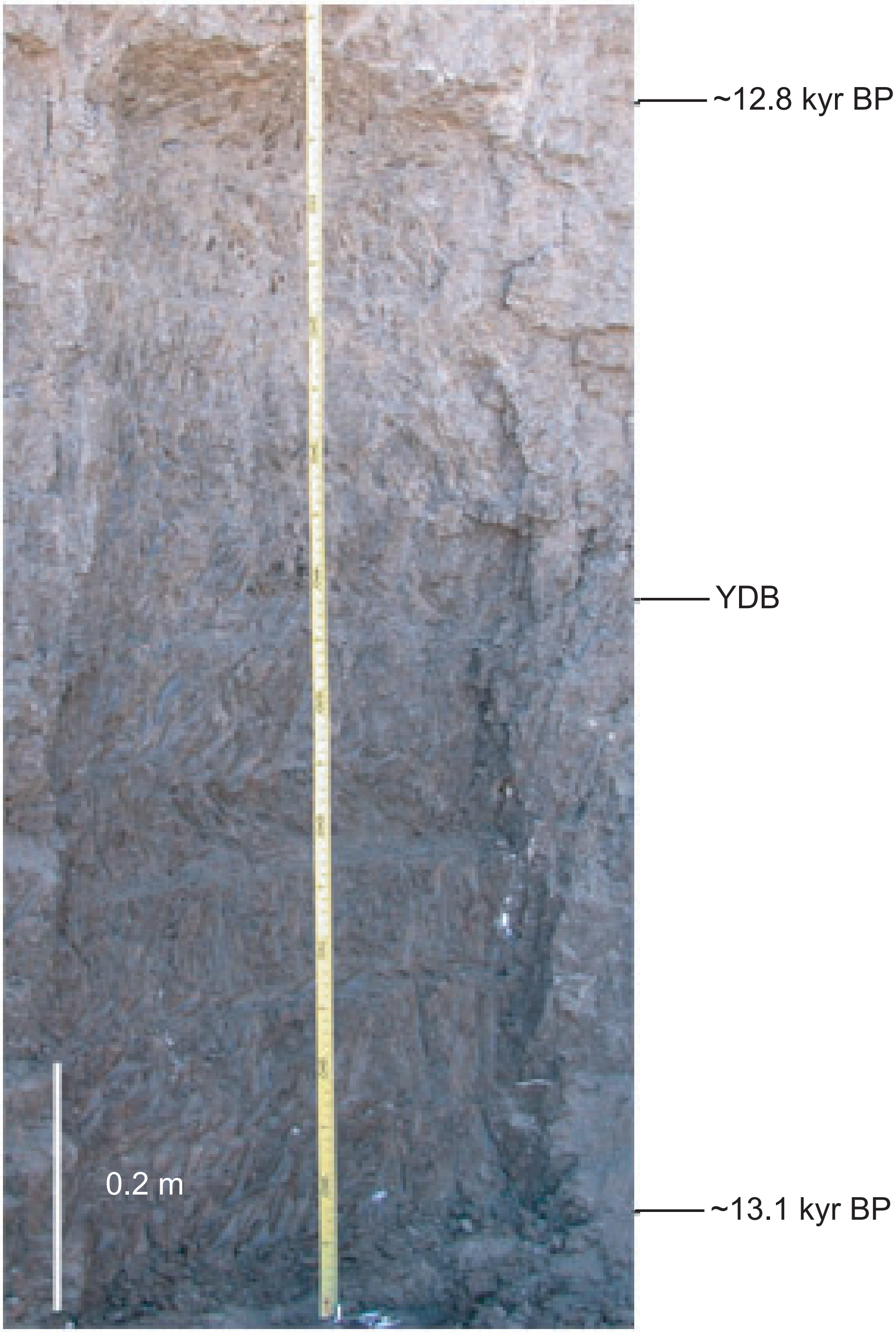

Fig. S4. The sampled section from the San Jon site. YDB marks the approximate position of the Younger Dryas Boundary.

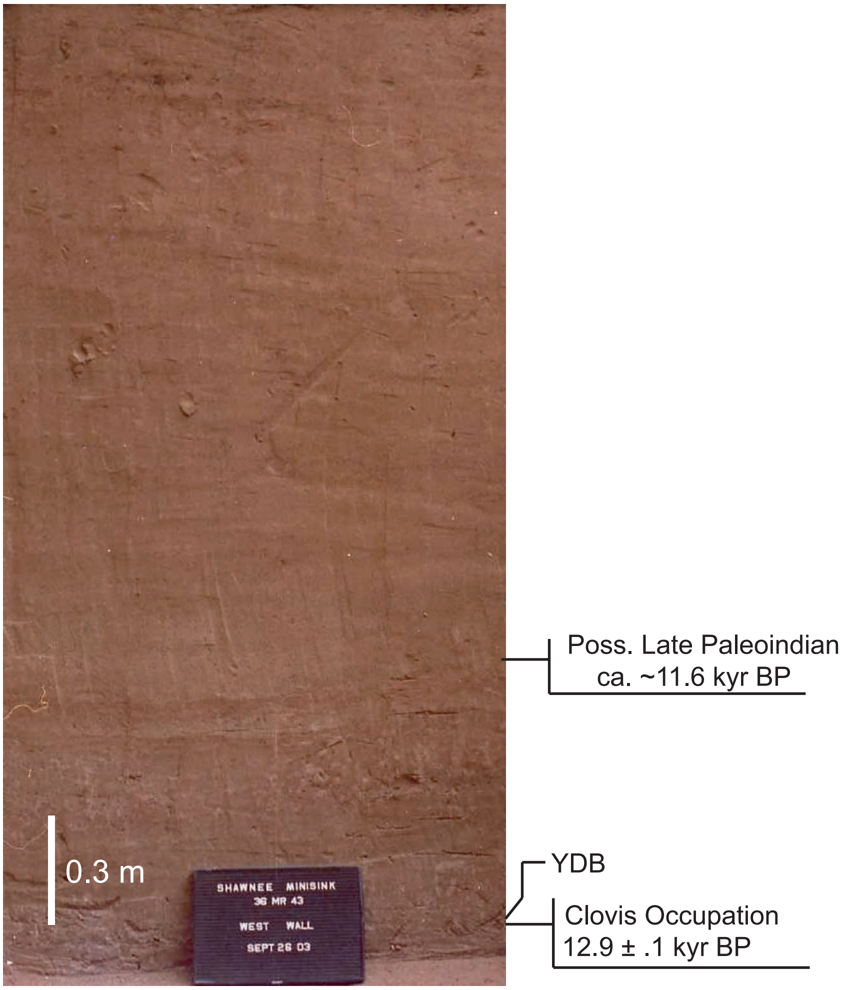

Fig. S5. Stratigraphic section from Shawnee-Minisink, PA. The sampled section was from the same excavation unit. Age control for the Clovis occupation is based on an average of six radiocarbon dates.

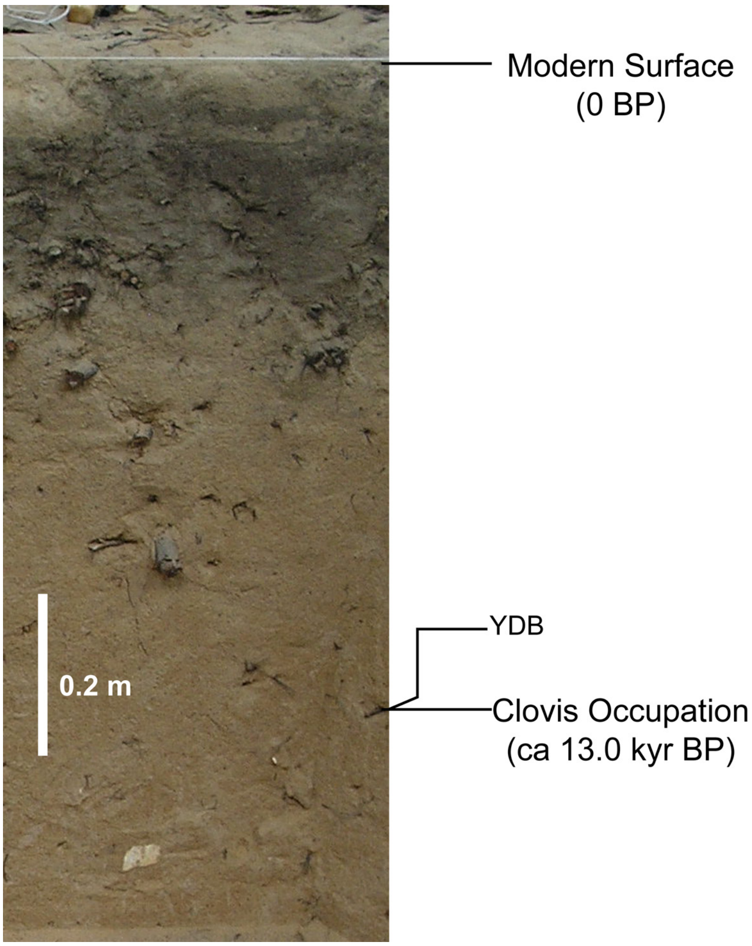

Fig. S6. The sampled section from the Topper site. YDB marks the estimated position of the Younger Dryas Boundary.

Table S1. Concentrations of magnetic grains and microspherules by site and sample

Site	Depth, cm	Magnetic grains, g/kg	Magnetic spherules, no./kg
Agate Basin, WY	165–175	1.222	217
Agate Basin, WY	175–185	1.261	139
Agate Basin, WY	185–195	3.063	88
Agate Basin, WY	195–205	2.198	0
Agate Basin, WY	205–215	2.286	0
Agate Basin, WY	215–225	3.137	255
Agate Basin, WY*	225–235	1.480	141
Agate Basin, WY	235–245	1.698	124
Agate Basin, WY	245–255	2.322	0
Agate Basin, WY	255–265	1.801	0
Blackwater Draw, NM	0–5	0.363	11
Blackwater Draw, NM	5–10	0.388	17
Blackwater Draw, NM	10–15	0.352	14
Blackwater Draw, NM*	15–20	0.256	0
Blackwater Draw, NM	20–25	0.579	0
Blackwater Draw, NM	25–30	0.602	0
Blackwater Draw, NM	30–35	0.598	0
Topper, SC	0–5	1.461	0
Topper, SC	5–10	1.390	0
Topper, SC	10–20	0.794	0
Topper, SC	20–30	1.327	0
Topper, SC	30–40	0.991	0
Topper, SC	40–50	0.986	0
Topper, SC	50–60	1.334	0
Topper, SC	60–70	1.288	0
Topper, SC	70–80	1.436	0
Topper, SC*	80–90	1.111	0
Topper, SC	90–92	1.033	0
Paw Paw Cove, MD	38–48	2.228	0
Paw Paw Cove, MD	48–58	2.525	0
Paw Paw Cove, MD*	58–68	1.099	0
Paw Paw Cove, MD	68–78	0.815	0
Paw Paw Cove, MD	78–88	0.567	0
Paw Paw Cove, MD	88–98	0.493	0
Lubbock Lake, TX	40–49	0.285	0
Lubbock Lake, TX	49–53	0.064	20
Lubbock Lake, TX	53–60	0.075	17
Lubbock Lake, TX	60–67	0.053	0
Lubbock Lake, TX*	67–73	0.132	13
Lubbock Lake, TX	73–75	0.357	0
San Jon, NM	140–150	0.552	0
San Jon, NM	200–210	0.613	0
San Jon, NM	210–220	0.602	0
San Jon, NM	220–230	0.587	22
San Jon, NM*	230–240	0.520	0
San Jon, NM	240–250	0.630	24
San Jon, NM	250–260	0.658	0
San Jon, NM	260–270	0.544	0
San Jon, NM	270–280	0.691	24
San Jon, NM	280–290	0.473	0
San Jon, NM	290–300	0.576	17
Shawnee-Minisink, PA	199–212	3.568	0
Shawnee-Minisink, PA	212–229	5.798	0
Shawnee-Minisink, PA	229–240	10.081	0
Shawnee-Minisink, PA*	240–268	7.1284	0
Shawnee-Minisink, PA	273–299	3.117	0
Shawnee-Minisink, PA	299–311	7.970	0
Shawnee-Minisink, PA	311–350	7.721	0

*Younger Dryas boundary sample.