Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling

R. B. Firestone[a,b], A. West[c], J. P. Kennett[d], L. Becker[e], T. E. Bunch[f], Z. S. Revay[g], P. H. Schultz[h], T. Belgya[g], D. J. Kennett[i], J. M. Erlandson[i], O. J. Dickenson[j], A. C. Goodyear[k], R. S. Harris[h], G. A. Howard[l], J. B. Kloosterman[m], P. Lechler[n], P. A. Mayewski[o], J. Montgomery[j], R. Poreda[p], T. Darrah[p], S. S. Que Hee[q], A. R. Smith[a], A. Stich[r], W. Topping[s], J. H. Wittke[f], and W. S. Wolbach[r]

[a]Lawrence Berkeley National Laboratory, Berkeley, CA 94720; [c]GeoScience Consulting, Dewey, AZ 86327; [d]Department of Earth Sciences and [e]Institute of Crustal Studies, University of California, Santa Barbara, CA 93106; [f]Northern Arizona University, Flagstaff, AZ 86011; [g]Institute for Isotope and Surface Chemistry, H-1525, Budapest, Hungary; [h]Department of Geological Sciences, Brown University, Providence, RI 02912; [i]Department of Anthropology and Museum of Natural and Cultural History, University of Oregon, Eugene, OR 97403; [j]Eastern New Mexico University, Portales, NM 88130; [k]South Carolina Institute of Archaeology and Anthropology, University of South Carolina, Columbia, SC 29208; [l]Restoration Systems, LLC, Raleigh, NC 27604; [m]Rozenstraat 85, 1018 NN, Amsterdam, The Netherlands; [n]Bureau of Mines and Geology, University of Nevada, Reno, NV 89557; [o]Climate Change Institute, University of Maine, Orono, ME 04469; [p]University of Rochester, Rochester, NY 14627; [q]Department of Environmental Health Sciences, University of California, Los Angeles, CA 90095; [s]P.O. Box 141, Irons, MI 49644; and [r]Department of Chemistry, DePaul University, Chicago, IL 60614

Communicated by Steven M. Stanley, University of Hawaii at Manoa, Honolulu, HI, July 26, 2007 (received for review March 13, 2007)

A carbon-rich black layer, dating to ≈12.9 ka, has been previously identified at ≈50 Clovis-age sites across North America and appears contemporaneous with the abrupt onset of Younger Dryas (YD) cooling. The *in situ* bones of extinct Pleistocene megafauna, along with Clovis tool assemblages, occur below this black layer but not within or above it. Causes for the extinctions, YD cooling, and termination of Clovis culture have long been controversial. In this paper, we provide evidence for an extraterrestrial (ET) impact event at ≅12.9 ka, which we hypothesize caused abrupt environmental changes that contributed to YD cooling, major ecological reorganization, broad-scale extinctions, and rapid human behavioral shifts at the end of the Clovis Period. Clovis-age sites in North American are overlain by a thin, discrete layer with varying peak abundances of (*i*) magnetic grains with iridium, (*ii*) magnetic microspherules, (*iii*) charcoal, (*iv*) soot, (*v*) carbon spherules, (*vi*) glass-like carbon containing nanodiamonds, and (*vii*) fullerenes with ET helium, all of which are evidence for an ET impact and associated biomass burning at ≈12.9 ka. This layer also extends throughout at least 15 Carolina Bays, which are unique, elliptical depressions, oriented to the northwest across the Atlantic Coastal Plain. We propose that one or more large, low-density ET objects exploded over northern North America, partially destabilizing the Laurentide Ice Sheet and triggering YD cooling. The shock wave, thermal pulse, and event-related environmental effects (e.g., extensive biomass burning and food limitations) contributed to end-Pleistocene megafaunal extinctions and adaptive shifts among PaleoAmericans in North America.

comet | iridium | micrometeorites | nanodiamonds | spherules

A carbon-rich black layer, dating to ≅12.9 ka (12,900 calendar years B.P.) (1), has been identified by C. V. Haynes, Jr. (2), at >50 sites across North America as black mats, carbonaceous silts, or dark organic clays [supporting information (SI) Fig. 5]. The age of the base of this black layer coincides with the abrupt onset of Younger Dryas (YD) cooling, after which there is no evidence for either *in situ* extinct megafaunal remains or Clovis artifacts. Increasing evidence suggests that the extinction of many mammalian and avian taxa occurred abruptly and perhaps catastrophically at the onset of the YD, and this extinction was pronounced in North America where at least 35 mammal genera disappeared (3), including mammoths, mastodons, ground sloths, horses, and camels, along with birds and smaller mammals. At Murray Springs, AZ, a well known Clovis site, mammoth bones and Clovis-age stone tools lie directly beneath the black layer where, as described by Haynes (4): "[T]he sudden extinction of the Pleistocene megafauna would be dramatically revealed by explaining that all were gone an instant before the black mat was deposited."

The cause of this extinction has long been debated and remains highly controversial due, in part, to the limitations of available data but also because the two major competing hypotheses, human overkill (5) and abrupt cooling (6), fall short of explaining many observations. For example, Grayson and Meltzer (7) summarized serious problems with the overkill hypothesis, such as the absence of kill sites for 33 genera of extinct mammals, including camels and sloths. In addition, although abrupt cooling episodes of magnitudes similar to the YD occurred often during the past 80 ka, none are known to be associated with major extinctions. The possibility of pandemic disease also has been suggested (8), but there is no evidence for that in the Pleistocene record. Thus, the end-Pleistocene extinction event is unique within the late Quaternary and is unlikely to have resulted only from climatic cooling and human overkill. The extinctions were too broad and ecologically deep to support those hypotheses.

Extraterrestrial (ET) catastrophes also have been proposed. For example, LaViolette (9) suggested that a large explosion in our galactic core led to the extinctions. Brakenridge (10) postulated that a supernova killed the megafauna and caused the worldwide deposition of the black layer. Clube and Napier (11) proposed multiple encounters with remnants of the mega comet progenitor of the Taurid meteor stream and Comet Encke. Although ET events have long been proposed as a trigger for mass extinctions, such as at the K/T (≈65 Ma) (12) and P/T (≈250 Ma) (13), there has been no compelling evidence linking impacts to the late Pleistocene megafaunal extinctions and YD cooling.

In the 1990s, W. Topping (14) discovered magnetic microspherules and other possible ET evidence in sediment at the Gainey

Author contributions: R.B.F., A.W., J.P.K., L.B., and W.T. designed research; R.B.F., A.W., J.P.K., L.B., T.E.B., Z.S.R., P.H.S., D.J.K., J.M.E., O.J.D., A.C.G., R.S.H., G.A.H., J.B.K., P.L., P.A.M., J.M., R.P., T.D., S.S.Q.H., A.R.S., A.S., W.T., J.H.W., and W.S.W. performed research; R.B.F., A.W., J.P.K., L.B., T.E.B., Z.S.R., T.B., D.J.K., O.J.D., A.C.G., G.A.H., J.B.K., P.L., J.M., R.P., S.S.Q.H., W.T., J.H.W., and W.S.W. contributed new reagents/analytic tools; R.B.F., A.W., J.P.K., L.B., T.E.B., Z.S.R., P.H.S., D.J.K., J.M.E., R.S.H., G.A.H., P.A.M., R.P., T.D., S.S.Q.H., A.R.S., A.S., W.T., J.H.W., and W.S.W. analyzed data; and R.B.F., A.W., J.P.K., and P.H.S. wrote the paper.

The authors declare no conflict of interest.

Freely available online through the PNAS open access option.

Abbreviations: YD, Younger Dryas; YDB, YD boundary; ET, extraterrestrial.

[b]To whom correspondence should be addressed. E-mail.com rbfirestone@lbl.gov.

This article contains supporting information online at www.pnas.org/cgi/content/full/0706977104/DC1.

Table 1. Information about the YDB research sites, along with concentrations of selected YDB markers

			Carbon	Magnetic microspherules			Magnetic grains						Bulk
Clovis-age YDB Sites	Date, ka	Misc. markers	Spherules #/kg	#/kg	FeO, %	TiO_2, %	g/kg	H_2O	FeO, %	TiO_2	Ni, ppm	IrM, ppb	IrB, ppb
Gainey, MI	≈12.4	AGC	1,232	2,144	41	25	3.2	3.2	14	1.6	54	<2	<0.5
Murray Springs, AZ	12.99	AKGCFPSB	0	109			2.6	5.1	21	16	40	<1	2.3
Blackwater Draw, NM	12.98	AKGCFPB	0	768	56	33	2.1	1.5	27	8.1	256	24	2.3
Chobot, AB	≈13	AGCB	11	578			1.9	5.0	14	0.9			
Wally's Beach, AB	12.97	AK	—	6			7.8	1.6	41	8.3	190	51	<1
Topper, SC	<13.5	AG	2	97			1.1	0.7	25	49	440	2	<1
Lommel, Belgium	12.94	ACB	0	16	14	67	0.8	0.8	23	21	23	117	<1
Morley Drumlin, AB	≈13	GCB	16	1,020	60	29	9.9	3.7	14	1.4	240	<0.1	
Daisy Cave, CA	13.09	GCFPB	>0	>0			>0						<1
Lake Hind, MB	12.76	GCB	184	0			0.3						3.8
Carolina Bays, Min		GCFS	142	20			0.5	0.3	18	21		<1	0.5
Carolina Bays, Max			1,458	205			17	1.3	26	34	<200	15	3.8

Radiocarbon ages are calibrated. More site age information is in SI Table 2. Percentages are by weight. A, artifacts from Clovis or contemporaries; K, megafaunal kill-site; G, glass-like carbon; C, charcoal; F, fullerenes with ET He-3; S, soot; P, polycylic aromatic hydrocarbons; B, black mat; Ni, nickel in magnetic fraction; IrM, Ir in magnetic fraction; IrB, Ir in bulk sediment. No measurable Ir was found outside the YDB. Ir uncertainties are ±10% at 117 ppb and ±90% at 0.5 ppb. Geochemical values are less than ±20%.

PaleoAmerican site in Michigan (see also ref. 15), and Lougheed (16) and Bi (17) reported that late Pleistocene glacial drift contained similar cosmic spherules. We now report substantial additional data from multiple, well dated stratigraphic sections across North America supporting a major ET airburst or collision near 12.9 ka. Directly beneath the black mat, where present, we found a thin, sedimentary layer (usually <5 cm) containing high concentrations of magnetic microspherules and grains, nanodiamonds, iridium (Ir) at above background levels, and fullerenes containing ET helium. These indicators are associated with charcoal, soot, carbon spherules, and glass-like carbon, all of which suggest intense wildfires. Most of these markers are associated with previously recorded impacts, but a few are atypical of impact events. We identify this layer as the YD boundary (YDB), and we refer to this incident as the YD event.

At the sites studied, independent radiocarbon (1) and optically stimulated luminescence dates that tend to cluster near 13 ka were used to establish the age of the YDB. For example, the end-Clovis stratum (the YDB) is well dated at Murray Springs, AZ, (eight dates averaging 10,890 ^{14}C yr or calendar 12.92 ka) and the nearby Lehner site (12 dates averaging 10,940 ^{14}C yr or 12.93 calendar ka). Haynes (2) correlated the base of the black mat (the YDB) with the onset of YD cooling, dated to 12.9 ka in the GISP2 ice core, Greenland (see GISP2 chronology in SI Fig. 6) (18). Therefore, we have adopted a calendar age of 12.9 ± 0.1 ka for the YD event.

We propose that the YD event resulted from multiple ET airbursts along with surface impacts. We further suggest that the catastrophic effects of this ET event and associated biomass burning led to abrupt YD cooling, contributed to the late Pleistocene megafaunal extinction, promoted human cultural changes, and led to immediate decline in some post-Clovis human populations (19).

Results

Research Sites. Ten Clovis and equivalent-age sites were selected because of their long-established archeological and paleontological significance, and, hence, most are well documented and dated by previous researchers (see SI Table 2). Two are type-sites where unique PaleoAmerican projectile point styles were first named: the Clovis-point style at Blackwater Draw, NM, and the Gainey-point style at Gainey, MI. Three of the sites are confirmed megafaunal kill sites, and six of 10 have a black mat overlying the YDB. At Blackwater Draw and Murray Springs, the YDB is found directly beneath the black mat and overlying Clovis artifacts with extinct megafaunal remains.

The other sample sites were in and around 15 Carolina Bays, a group of ≈500,000 elliptical lakes, wetlands, and depressions that are up to ≈10 km long and located on the Atlantic Coastal Plain (SI Fig. 7). We sampled these sites because Melton, Schriever (20), and Prouty (21) proposed linking them to an ET impact in northern North America. However, some Bay dates are reported to be >38 ka (22), older than the proposed date for the YD event.

Each of the 10 Clovis-age sites displays a YDB layer (average thickness of 3 cm) that contains a diversity of markers (magnetic microspherules and grains, charcoal, soot, carbon spherules, glass-like carbon, nanodiamonds, and fullerenes with ET helium). The Ir levels are above background in both bulk sediment and magnetic fractions at up to 117 parts per billion (ppb), which is 25% of levels in CI (Ivuna type) chondritic meteorites (23). The YDB also exhibits uranium (U) and thorium (Th) in high concentrations that are up to 25× crustal abundance. At the 15 Bay sites examined, basal sediments and rim sands contain peaks in the same ET assemblage found in the YDB at Clovis sites elsewhere.

YD Event Markers. The various markers are summarized in Table 1 and described in *SI Text*, "Research Sites." Seven representative North American sediment profiles are shown in Fig. 1.

Magnetic microspherules. Magnetic microspherules measuring 10–250 μm peaked in or near the YDB at eight of nine Clovis-age sites and in sediments from five of five Bays tested. Fig. 2 shows representative microspherules from Canada, New Mexico, Michigan, and North Carolina. Several sites also yielded microspherules that appear to be silicates, requiring further analysis. Microspherule abundances average 390 per kilogram and are highest in the north, ranging up to 2,144 per kilogram at Gainey. Analyses from Gainey, the Morley drumlin, and Blackwater Draw found the microspherules to be enriched in titanomagnetite.

Magnetic grains. Magnetic grains measuring 1–500 μm, irregularly shaped and often subrounded, are more abundant than microspherules, and they show a distinct peak in the YDB at all 10 Clovis-age sites and are in all 15 Bays, reaching peaks above the pre-Bay paleosols at four sites. All had lower abundances at other stratigraphic levels. Magnetic grains are mostly dark brown or black, although the magnetic fraction often contains terrestrial silicates with magnetite inclusions. Concentrations of magnetic grains and microspherules vary greatly between YDB sites, averaging 3.4 g/kg, with higher abundances at northern sites, such as Gainey, Chobot, and the Morley drumlin. Lower abundances were found in the Carolinas and the southwestern U.S. Magnetic grains from southern sites and Lommel, along with some YDB microspherules, are enriched in titanomagnetite.

GEOPHYSICS

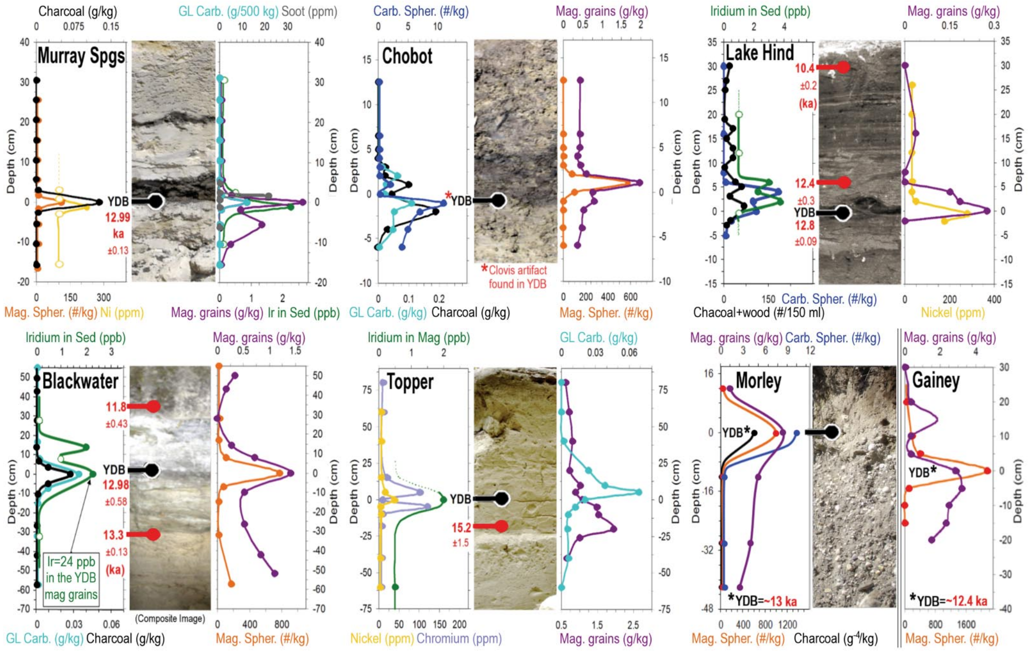

Fig. 1. Sediment profiles for seven sites. Concentrations are shown for magnetic grains, microspherules, charcoal, soot, glass-like carbon, carbon spherules, Ir, Cr, and Ni, which peak mostly in a narrow stratigraphic section spanning only a few hundred years. Ir open circles indicate values below detection, typically <0.5–1 ppb. Ir uncertainties are ±10% at 117 ppb and ±90% at 2 ppb. Cr and Ni are less than ±20%. Keys are color-coded to match the respective curves, and graph points correspond to sampling locations on the photograph. The depth is in centimeters above or below the YDB. The Blackwater Draw image is a composite of three photos. There is no photo for Gainey. A profile for the Belgian site at Lommel is shown in SI Fig. 8. The locations of all sites that were sampled are shown in SI Fig. 9.

Iridium and nickel. YDB sediments, but not the magnetic fractions, are modestly enriched in Ni. For Ir, YDB magnetic grains from seven of 12 sites exhibited a range of 2 (±90%) to 117 (±10%) ppb, and of those seven sites, three also had detectable Ir in the YDB bulk sediment. The highest Ir value is ≈25% that of typical chondrites (455–480 ppb) (24) and >5,000× crustal abundance (0.02 ppb) (25). In 17 measurements at these sites, no Ir was detected in magnetic grains above or below the YDB. For bulk sediment, YDB Ir abundances at five of 12 sites range from 0.5 (±90%) to 3.75 (±50%) ppb. However, the bulk sediment results are near the detection limits of neutron activation analysis, and further testing is required.

Upon retesting aliquots of high-Ir samples, five from nine sites were confirmed, but Ir abundances were below detection in four retests. Sample sizes were small, and variations are likely due to the "nugget effect." In summary, no detectable Ir was found above or below the YDB and black mat at seven sites in 62 samples of both bulk sediments and magnetic grains. Elevated Ir concentrations were found only in the YDB and black mat at nine of 14 widely separated sites (see Fig. 1, Table 1, and SI Table 3).

Charcoal. Charcoal displays peaks in the YDB at eight of nine Clovis-age sites and is present in 15 of 15 Bays, reaching peaks in four Bays with paleosols. The charcoal was identified optically and by SEM based on its distinctive cellular structure and was found in concentrations ranging from 0.06 to 11.63 g/kg.

Soot and polycyclic aromatic hydrocarbons (PAHs). Observed at the K/T boundary (26) and distinguished by its aciniform morphology (see SI Fig. 10) (27), soot forms only in flames through direct condensation of carbon from the gas phase. Soot was identified by using SEM imaging and quantified by particle size analysis and weighing. Of eight sites examined, soot was observed only in the YDB at two sites, Murray Springs (21 ± 7 ppm) and Bay T13 (1,969 ± 167 ppm), where preservation possibly resulted from anoxic burial conditions. In addition, the combustion of wood at very high temperatures produces diagnostic PAHs. High-temperature PAHs, which were found at the K/T boundary (28), are present in the YDB, but not above or below it at each of three sites analyzed (Daisy Cave, Murray Springs, and Blackwater Draw), suggesting that intense fires occurred at these locations.

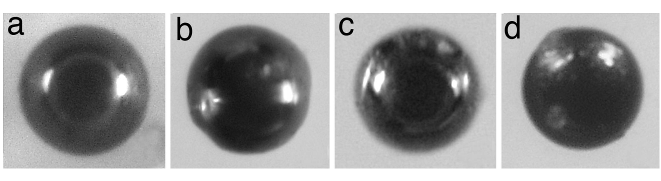

Fig. 2. High-titanomagnetite microspherules from Blackwater Draw, NM (120 μm) (*a*); Chobot, AB, Canada (150 μm) (*b*), Gainey, MI (90 μm) (*c*), and Howard Bay, NC (100 μm) (*d*).

Carbon spherules. Carbon spherules (0.15–2.5 mm) are black, highly vesicular, subspherical-to-spherical objects (Fig. 3). SEM analyses show them to have cracked and patterned surfaces, a thin rind, and honeycombed (spongy) interiors. SEM/energy dispersive spectrometer and microprobe analyses show that the spherules are dominantly carbon (>75%), with no evidence of seed-like morphology or cellular plant structure, as in charcoal. They were found in 13 of 15 Bays and only in the YDB at six of nine Clovis-age sites in concentrations up to ≈1,500 per kilogram. In addition, we recovered them from one of four modern forest fires (see *SI Text*, "Research Sites"), confirming that they can be produced by intense heat in high-stand wildfires. At the P/T boundary, Miura[t] discovered carbon spherules up to 90 wt% C and up to 20 μm in size, which he attributes to a controversial cosmic impact ≈250 Ma. More recently, Rösler *et al.*[u] reported finding carbon spherules from undated sediment across Europe, and these appear identical to spherules from the YDB layer. The authors report that they contain fullerenes and nanodiamonds, the latter of which are extraordinarily rare on Earth but are found in meteorites and at ET impact sites (29), leading those authors to propose an ET association for the carbon spherules.

Fullerenes and ET helium. Of four sites analyzed, fullerenes with ET helium, which are associated with meteorites and ET impacts (30), were present in YDB sediments at three Clovis-age sites (Blackwater, Murray Springs, and Daisy Cave). In Bay M33, they

[t]Miura, Y., 37th Annual Lunar and Planetary Science Conference, March 13–17, 2006, League City, TX, Vol. 2441, pp. 1–2 (abstr.).

[u]Rösler, W., Hoffmann, V., Raeymaekers, B., Yang, Z. Q., Schryvers, D., Tarcea, N. (2006) First International Conference on Impact Cratering in the Solar System, May 7–12, 2006, Noordwijk, The Netherlands, abstr. 295464.

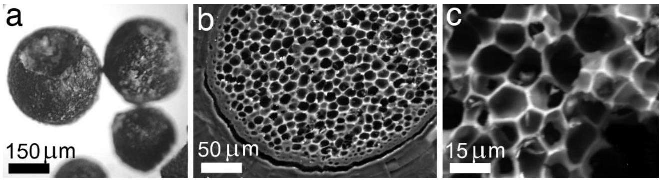

Fig. 3. Low-density carbon spherules are shown whole from the Chobot site (*a*), sectioned and by SEM from Bay T13 (*b*), and at high magnification by SEM from Bay B14 (*c*).

Fig. 4. Examples of glass-like carbon from Gainey, Bay M31, and Topper.

also were found in glass-like carbon with an ET helium ratio that is 84 times that of air. By comparison, the ratio of the Tagish Lake meteorite was 90 times that of air.

Glass-Like Carbon. Pieces up to several cm in diameter (Fig. 4) were found associated with the YDB and Bays, and their glassy texture suggests melting during formation, with some fragments grading into charcoal. Continuous flow isotope ratio MS analysis of the glass-like carbon from Carolina Bay M33 reveals a composition mainly of C (71%) and O (14%). Analysis by ^{13}C NMR of the glass-like carbon from Bay M33 finds it to be 87 at.% (atomic percent) aromatic, 9 at.% aliphatic, 2 at.% carboxyl, and 2 at.% ether, and the same sample contains nanodiamonds, which are inferred to be impact-related material (see SI Fig. 11). Concentrations range from 0.01 to 16 g/kg in 15 of 15 Bays and at nine of nine Clovis-age sites in the YDB, as well as sometimes in the black mat, presumably as reworked material. Somewhat similar pieces were found in four modern forest fires studied (see *SI Text*, "Research Sites").

Quantities for selected markers are shown in Table 1, and abundances of all markers are given in SI Table 4.

Discussion

Age of the YDB. The YDB at the 10 Clovis- and equivalent-age sites has been well dated to ≈12.9 ka, but the reported ages of the Carolina Bays vary. However, the sediment from 15 Carolina Bays studied contain peaks in the same markers (magnetic grains, microspherules, Ir, charcoal, carbon spherules, and glass-like carbon) as in the YDB at the nearby Topper Clovis site, where this assemblage was observed only in the YDB in sediments dating back >55 ka. Therefore, it appears that the Bay markers are identical to those found elsewhere in the YDB layers that date to 12.9 ka. Although the Bays have long been proposed as impact features, they have remained controversial, in part because of a perceived absence of ET-related materials. Although we now report that Bay sediments contain impact-related markers, we cannot yet determine whether any Bays were or were not formed by the YD event.

Peaks in Markers. We investigated whether peaks in YDB markers might be attributed to terrestrial processes. The 25 sites examined represent a wide range of depositional environments (fluvial, lacustrine, eolian, alluvial, colluvial, and glacial), soil conditions (aerobic/well drained to anaerobic/saturated), sediment composition (dense clay to gravelly sand), climatic regimes (semiarid to periglacial), and biomes (grasslands to forests). The presence of identical markers found under such a wide range of conditions argues against formation by terrestrial processes and is consistent with an impact origin. We also examined whether the YDB might represent an interval of reduced deposition, allowing the accretion of interplanetary dust particles enriched in ET markers, such as Ir, Ni, and ET helium. At Blackwater Draw, based on 24 calibrated ^{14}C dates from 13.30 to 10.99 ka, Haynes (31, 32) suggested that any hiatus at the level representing the YDB most likely lasted less than a decade, which is insufficient to have produced a local Ir bulk sediment level that is >100× crustal abundance. Furthermore, abundances of microspherules and magnetic grains decrease with increasing distance from the Great Lakes region (see SI Fig. 12). This nonrandom distribution is unlikely to be due to terrestrial factors or interplanetary dust storms, but it is consistent with airburst/impacts over northern North America.

Magnetic Microspherules and Grains. High concentrations of microspherules (glass, clinopyroxene, spinel, or metallic) are accepted as evidence for at least 11 older ET impact events (33). Alternately, microspherules are sometimes associated with volcanism, but when YDB microspherules were analyzed by SEM/x-ray fluorescence and compared with known cosmic and volcanic microspherules (34, 35), they appear to be nonvolcanic in origin. Analysis suggests an ET origin, but because of high titanium (Ti) concentrations, the microspherules differ from typical meteoritic ones.

The magnetic grains and microspherules are anomalously enriched in Ir and Ti (see Table 1 and SI Table 5) and are enriched in water (up to 28 at.%), especially at northern sites. TiO_2/FeO ratios of microspherules (0.48 ratio) and magnetic grains (0.76) are 4- to 250-fold higher than Alaskan terrestrial magnetite (<0.12 ratio in 347 samples) (36), crustal abundance (0.13) (25), CI chondrites (0.003) (23), and K/T impact layers (0.07) (12). These ratios and the similarity in composition of YDB magnetic microspherules and magnetic grains (e.g., high Ti) from many sites across North America cannot be explained at this time, but the YDB abundance of microspherules and magnetic grains most likely resulted from the influx of ejecta from an unidentified, unusually Ti-rich, terrestrial source region and/or from a new and unknown type of impactor.

Carbon-Rich Markers. At Murray Springs, Haynes (37) first reported the presence of glass-like or "vitreous" carbon in the black mat. In addition, he chemically analyzed the black mat layer, concluding that it most likely resulted from the decomposition of charred wood and/or a prolonged algal bloom, both of which could result from event-related processes (e.g., climate change and biomass burning). Some black mats have no algal component, only charcoal. The widespread peaks of charcoal in or near the YDB, and their association with soot and polycyclic aromatic hydrocarbons at specific sites, provide strong evidence for extensive wildfires. We propose that glass-like carbon, carbon spherules, and nanodiamonds were produced in the YDB by high temperatures resulting from the impact and associated biomass burning.

Ir Anomaly. Ir concentrations in sediments and ocean cores are high for many accepted impact events, such as for the K/T and Chesapeake Bay (≈36 Ma) (38). However, Ir values in the YDB bulk sediment are lower than at many K/T sites (e.g., 9.1 ppb at Gubbio, Italy) (12), suggesting much less Ir in the YD impactor. The evidence indicates an Ir anomaly in both the YDB bulk sediment and the magnetic fraction; however, for Ir in the bulk sediment, the level of uncertainty remains high (±50–90%), in contrast to the magnetic fraction, where values have higher certainty (up to ±10%), and are, therefore, more compelling. In 169 measurements at 14 sites up to ≈9,200 km apart, Ir was detected only in the YDB sediments, YDB magnetic fraction, and the black mat. Ir never was detected above or below these layers, lessening concerns about the high uncertainties, while providing strong evidence that Ir concentrations are above background in the YDB or black mat. The relatively low Ir and Ni peaks associated with the YDB are more

GEOPHYSICS

consistent with the generally proposed composition of comets and inconsistent with the high-Ir content typical of most stony, nickel–iron, or chondritic meteorites.

Alternately, Ir peaks are found at major geologic boundary layers with no confirmed impacts, and at least some of those Ir concentrations may have resulted from volcanism. However, no major North American volcanic episode is known at 12.9 ka, and, according to Koeberl (39), such events produce Ir abundances of <0.5 ppb, much less than we find in the YDB. Therefore, the high concentrations of Ir do not appear to be of volcanic origin.

We also considered microbial concentration from Ir-rich adjacent sediment, such as occurred in experiments by Dyer *et al.* (40), who cultured microbes in Ir-rich igneous rocks and meteoritic material. However, at all sites analyzed, non-YDB sediment levels of Ir are very low (<0.1 ppb and possibly <0.02 ppb) and are insufficient to account for Ir levels up to 5,000× crustal abundance. Given the association of high Ir with a suite of other event-related markers, an ET connection is more plausible.

Ice Core Evidence. Large increases in Ir and Pt occurred during the Younger Dryas as recorded in the GRIP (Greenland) ice core by Gabrielli *et al.* (41), who attributed these increases to increased cosmic input. Although sample resolution in the ice core was too low to permit us to specifically link the onset of these increased fluxes with the timing of the YD event, the evidence is consistent with the YD event.

As evidence for biomass burning, Mayewski *et al.* (42, 43) reported large ammonium and nitrate spikes in the Greenland GISP2 ice core at the onset of the YD. These GISP2 data are consistent with strong geochemical evidence in the GRIP ice core for massive biomass burning at the YD onset, especially a major ammonium spike, in association with peaks in nitrate, nitrite, formate, oxalate, and acetate (44). Altogether, the YD onset was one of the most robust intervals of biomass burning inferred from the Greenland ice cores, although the source of this burning signal must have been far more remote than sources today, because much of the modern forested Arctic region was then covered by ice. The cause of this biomass burning is consistent with the YD event.

Radioactive Elements. Some megafaunal bones in the YDB are highly radioactive relative to other stratigraphic intervals, as occurred for some bones at the K/T boundary (see SI Figs. 13 and 14). In addition, high concentrations of U and Th were found in the YDB sediment at six of six Clovis-age sites analyzed and in four of four Bays with a paleosol, just as were found in the impact layers at Chesapeake Bay (38) and the K/T (see SI Fig. 15) (45). Because the heavy minerals, zircon, monazite, and garnet, along with Ti-rich minerals, such as titanite, ilmenite, and rutile, sometimes contain high concentrations of U and Th, we investigated whether lag deposits of those minerals might be the source of high radioactivity. We conclude that lag deposits may explain the high YDB radioactivity at some sites but not at others. Ilmenite, rutile, and titanite are possible carriers given that they comprise up to ≈2% of all sediments, but zircon, monazite, and garnet are unlikely, because they represent <0.1% each (see SI Figs. 16 and 17). The elevated levels of U and Th may result from multiple processes related to the impacts/airbursts, including formation of lag deposits, as well as the dispersal of ejecta from the impactor and/or the target area.

Nature of the Event. The evidence points to an ET event with continent-wide effects, especially biomass burning, but the size, density, and composition of the impactor are poorly understood. Even so, current data suggest that this impactor was very different from well studied iron, stony, or chondritic impactors (e.g., at the K/T boundary). The evidence is more consistent with an impactor that was carbon-rich, nickel–iron-poor, and therefore, most likely a comet. Although the current geologic and geochemical evidence is insufficient to fully understand impact dynamics, we can offer speculation for future work.

Toon *et al.* (46) suggest that an impact capable of continent-wide damage requires energy of 10^7 megatons, equivalent to an impact by a >4-km-wide comet (figure 1 in ref. 46). Although an impactor that size typically leaves an obvious large crater, no such late Pleistocene crater has been identified. The lack of a crater may be due to prior fragmentation of a large impactor, thereby producing multiple airbursts or craters. Hypervelocity oblique impact experiments (P.H.S., unpublished data) indicate that a low-impedance surface layer, such as an ice sheet, can markedly reduce modification of the underlying substrate if the layer is equal to the projectile's diameter. These results suggest that if multiple 2-km objects struck the 2-km-thick Laurentide Ice Sheet at <30°, they may have left negligible traces after deglaciation. Thus, lasting evidence may have been limited to enigmatic depressions or disturbances in the Canadian Shield (e.g., under the Great Lakes or Hudson Bay), while producing marginal or no shock effects and dispersing fine debris composed of the impactor, ice-sheet detritus, and the underlying crust.

Toon *et al.* (46) also noted 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 that is equivalent to a ground impact of 10^9 megatons (figure 5 in ref. 46). Such airbursts effectively couple the impactor's kinetic energy with the atmosphere or surface (47, 48), producing devastating blast waves well above hurricane force ($70\ m \cdot s^{-1}$) (46). In 1908, at Tunguska, Siberia, a object <150 m in diameter, either a carbonaceous asteroid or a small, burned-out comet, produced a <15-megaton airburst with an intense fireball (10^7 °C) that scorched ≈200 km^2 of trees and leveled ≈2,000 km^2 of forest yet produced no crater or shock metamorphism (49). A debris shower from a heavily fragmented comet (11) 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, but again possibly, without typical cratering.

Environmental Effects. The YD event would have created a devastating, high-temperature shock wave with extreme overpressure, followed by underpressure, resulting in intense winds traveling across North America at hundreds of kilometers per hour, accompanied by powerful, impact-generated vortices (50–52). In addition, whether single or multiple objects collided with Earth, a hot fireball would have immersed the region near the impacts and would have been accentuated if the impact angles were oblique (46, 53). For comparison, Svetsov (48) calculated that a Tunguska-sized airburst would immerse the ground with a radiation flux severe enough to ignite 200 km^2 of forest within seconds. Thus, multiple, larger airbursts would have ignited many thousands of square kilometers. At greater distances, the reentry of high-speed, superheated ejecta would have induced extreme wildfires (53), which would have decimated forests and grasslands, destroying the food supplies of herbivores and producing charcoal, soot, toxic fumes, and ash. The number of ET airbursts or impacts necessary to induce the continent-wide environmental collapse at 12.9 ka is unknown.

Climate. A number of impact-related effects most likely contributed to the abrupt, major cooling at the onset of the YD and its maintenance for >1,000 years. Cooling mechanisms operating on shorter time scales may have included (*i*) ozone depletion, causing shifts in atmospheric systems in response to cooling, with the side-effect of allowing increased deadly UV radiation to reach survivors on the surface (46); (*ii*) atmospheric injection of nitrogen compounds (NO_x), sulfates, dust, soot, and other toxic chemicals from the impact and widespread wildfires (46), all of which may have led to cooling by blockage of sunlight, with the side-effect of diminished photosynthesis for plants and increased chemical toxicity for animals and plants (46); and (*iii*) injection of large amounts of water vapor and ice into the upper atmosphere to form persistent cloudiness and noctilucent clouds, leading to reduced sunlight and surface cooling (46). Although these cooling mechanisms tend to be short-lived, they can trigger longer-term consequences through feedback mechanisms. For example, noctilucent clouds can reduce solar insolation at high latitudes, increasing snow accumulation and causing further cooling in a feedback loop. The largest potential effect would have been impact-related partial destabilization and/or melting of the ice sheet. In the short term, this would have suddenly released meltwater and rafts of icebergs into the North Atlantic and Arctic Oceans, lowering surface-ocean salinity with consequent surface cooling. The longer-term cooling effects largely would have resulted from the consequent weakening of thermohaline circulation in the northern Atlantic (54), sustaining YD cooling for >1,000 years until the feedback mechanisms restored ocean circulation.

Clovis and Megafauna. The impact-related effects would have been devastating for animals and plants. For humans, major adaptive shifts are evident at 12.9 ka, along with an inferred population decline, as subsistence strategies changed because of dramatic ecological change and the extinction, reduction, and displacement of key prey species (55, 56). Many sites indicate that both Clovis people and extinct megafauna were present immediately before the YD event, but, except in rare cases, neither appears in the geologic record afterward. At Murray Springs, butchered, still-articulated mammoth bones, Clovis tools, and a hearth were found buried directly beneath the black mat, indicating that it buried them rapidly (37). YDB markers, including Ir at 51 ppb, occur inside an extinct horse skull at the Wally's Beach Clovis kill-site (57), again suggesting rapid burial following the YD event. It is likely that some now-extinct animals survived in protected niches, only later to become extinct because of insufficient food resources, overhunting, climate change, disease, flooding, and other effects, all triggered or amplified by the YD event.

Conclusions

Our primary aim is to present evidence supporting the YD impact event, a major ET collision over North America at 12.9 ka, which contributed to the YD cooling, the massive extinction of the North American fauna, and major adaptations and population declines among PaleoAmericans. The unique, carbon-rich, YDB layer, coupled with a distinct assemblage of impact tracers, implies isochroneity of the YDB datum layer and thus highlights its utility for correlation and dating of the North American late Pleistocene. These associations, if confirmed, offer the most complete and recent geological record for an ET impact and its effects, such as global climate change and faunal extinction. This evidence also would represent a record of a major ET event having serious, widespread consequences for anatomically modern humans.

Methods

Elemental analyses were performed by using prompt gamma-ray activation analysis, neutron activation analysis, and inductively coupled plasma MS. Microspherules, glass-like carbon, and carbon spherules were analyzed by SEM/x-ray fluorescence. These methods are very standard and discussed further in *SI Text*, "Methods."

We thank C. V. Haynes, Jr., and J. Ballenger (University of Arizona, Tucson, AZ), B. Kooyman and colleagues (University of Calgary, Calgary, BC, Canada), B. Childress and J. Pike-Childress (Bureau of Land Management, Phoenix, AZ), M. Boyd and colleagues (Lakehead University, Thunder Bay, ON, Canada), A. Huston, (Channel Islands National Park, Ventura, CA), J. Johnson (Santa Barbara Museum of Natural History, Santa Barbara, CA), M. Waters and A. Rodriguez (University of North Carolina, Chapel Hill), D. Kimbel (Restoration Systems, LLC), and W. Newell (Restoration Systems, LLC) for providing/collecting samples and/or for access to sites; M. Gifford for help with inductively coupled plasma MS analyses; Henry Wright (University of Michigan, Ann Arbor, MI) and Denise Henry and Terrence Rettig (National Science Foundation, Arlington, VA) for early help and encouragement; J. Talbot (K/T GeoServices, Argyle, TX), B. Cannon (Cannon Microprobe, Seattle, WA), C. J. Eastoe (University of Arizona), J. Edwards (Process NMR Associates, Danbury, CT), E. Hoffman (Activation Laboratories, Ancaster, ON, Canada), J. Feathers and J. Johnson (University of Washington, Seattle, WA), S. Simpson (Becquerel Laboratories, Mississauga, ON, Canada), Philippe Claeys (Vrije Universiteit Brussel, Brussels, Belgium), and J. Southon (University of California, Irvine, CA) for their careful analyses of samples. This work was supported, in part, by U.S. Department of Energy Contract DE-AC02-05CH11231 and National Science Foundation Grants 9986999, OCD-0244201, and ATM-0713769.

1. Taylor R, Haynes CV, Jr, Stuiver M (1996) *Antiquity* 70:515–525.
2. Haynes, CV, Jr (2005) in *Paleoamerican Origins: Beyond Clovis*, eds Bonnichsen R, Lepper BT, Stanford D, Waters MR (Texas A&M Univ Press, College Station, TX), pp 113–132.
3. Grayson D, Meltzer D (2003) *J Arch Sci* 30:585–593.
4. Haynes CV (1998) *Mammoth Trumpet* 13(2):2–6.
5. Mosimann J, Martin P (1975) *Am Scientist* 63:304–313.
6. Guthrie R (2006) *Science* 441:207–209.
7. Grayson D, Meltzer D (2003) *J Arch Sci* 30:585–593.
8. MacPhee R, Marx P (1997) in *Natural Change and Human Impact in Madagascar,* eds Goodman S, Patterson B (Smithsonian Inst Press, Washington, DC), pp 169–217.
9. LaViolette P (1987) *Earth, Moon, Planets* 37:241–286.
10. Brakenridge G (1981) *Icarus* 46:81–93.
11. Clube V, Napier W (1984) *Mon Not R Astronom Soc* 211:953–968.
12. Alvarez L, Alvarez W, Asaro F, Michel H (1980) *Science* 208:1095–1108.
13. Becker L, Poreda RJ, Basu AR, Pope KO, Harrison TM, Nicholson C, Lasky R (2004) *Science* 304:1469–1476.
14. Firestone RB, Topping W (2001) *Mammoth Trumpet* 16(9):1–5.
15. Firestone RB, West A, Warwick-Smith S (2006) *Cycle of Cosmic Catastrophes* (Bear, Rochester, VT), pp 19–35.
16. Lougheed MS (1966) *Ohio J Sci* 66:274–283.
17. Bi D (1993) *Meteoritics* 29:88–93.
18. Alley RB (2000) *Quat Sci Revs* 19:213–226.
19. Goodyear AC (2006) *Curr Res Pleistocene*, 23:100–101.
20. Melton FA, Schriever W (1933) *J Geol* 41:52–56.
21. Prouty WF (1952) *Bull GSA* 63:167–224.
22. Frey DJ (1955) *Ecology* 36(4):762–763.
23. Anders E, Grevesse N (1989) *Geochim Cosmo Acta* 53:197–214.
24. McDonough W, Sun S (1995) *Chem Geol* 120:223–253.
25. Rudnick R, Gao R (2003) *Treatise on Geochemistry,* eds Holland H, Turekian K (Elsevier, Oxford, UK), Vol 3, pp 1–64.
26. Wolbach WS, Lewis RS, Anders E (1985) *Science* 230:167–170.
27. Kroto H (1988) *Science* 242:1139–1145.
28. Venkatesan MI, Dahl J (1989) *Nature* 338:57–60.
29. Gilmour I, Russell SS, Arden JW, Lee MR, Franchi IA, Pillinger CT (1992) *Science* 258:1624–1626.
30. Becker L, Poreda RJ, Bunch TE (2000) *Proc Natl Acad Sci USA* 97:2979–2983.
31. Haynes CV, Jr (1995) *Geoarchaeology* 10(5):317–388.
32. Haynes CV, Jr, Stanford DJ, Jodry M, Dickenson J, Montgomery JL, Shelley PH, Rovner I, Agogino GA (1999) *Geoarchaeology* 14(5):455–470.
33. Simonson B, Glass B (2004) *Annu Rev Earth Planet Sci* 32:329–361.
34. Iyer SD, Prasad MS, Gupta SM, Charan SN, Mukherjee AD (1997) *J Volcanol Geotherm Res* 78:209–220.
35. Wright F, Hodge P, Allen R (1966) *Smithson Astrophys Obs Spec Rep* 228:1–9.
36. Pan K-L, Overstreet WC, Robinson K, Hubert AE, Crenshaw GL (1980) *USGS Professional Publications* 1135:3–22.
37. Haynes CV, Jr (2007) in *Murray Springs: A Clovis Site with Multiple Activity Areas in the San Pedro Valley, Arizona*, eds Haynes CV, Jr, Huckell BB (Univ of Arizona Press, Tucson, AZ), pp 240–249.
38. Bodiselitsch B, Montanari A, Koeberl C, Coccioni R (2004) *Earth Planet Sci Lett* 223:283–302.
39. Huber H, Koeberl C, Egger H (2003) *Geochem J* 37:123–134.
40. Dyer BD, Lyalikova NN, Murray DP, Doyle M, Kolesov GM, Krumbein WE (1989) *Geology* 17(11):1036–1039.
41. Gabrielli P, Barbante C, Plane JM, Varga A, Hong S, Cozzi G, Gaspari V, Planchon FA, Cairns W, Ferrari C, *et al.* (2004) *Nature* 432:1011–1014.
42. Mayewski PA, Meeker LD, Whitlow SI, Twickler MS, Morrison MG, Alley RB, Bloomfield P, Taylor K (1993) *Science* 261:195–197.
43. Mayewski PA, Meeker LD, Twickler MS, Whitlow SI, Yang Q, Lyons WB, Prentice M (1997) *J Geophys Res* 102:26345–26366.
44. Legrand M, De Angelis M (1995) *J Geophys Res* 100:1445–1462.
45. Martinez-Ruiz F, Ortega-Huertas M, Palomo I (1999) *Terra Nova* 11:290–296.
46. Toon OB, Tukco RP, Covey C, Zahnle K, Morrison D (1997) *Rev Geophys* 35:41–78.
47. Schultz PH, Gault DE (1985) *J Geophys Res* 90:3701–3732.
48. Svetsov VV (2002) *Palaeogeogr Palaeoclim Palaeoecol* 185:403–405.
49. Wasson JT (2003) *Astrobiology* 3:163–179.
50. Schultz PH (1992) *J Geophys Res* 97:16183–16248.
51. Barnouin-Jha O, Schultz PH (1996) *J Geophys Res* 101:21099–21115.
52. Wrobel K, Schultz PH, Crawford D (2006) *Meteorit Planet Sci* 41:1539–1550.
53. Schultz PH, D'Hondt S (1996) *Geology* 24:963–967.
54. Broecker WS (2006) *Science* 312:1146–1148.
55. Anderson DG, Faught MK (2000) *Antiquity* 74:507–513.
56. Bamforth DB (2002) *J World Prehistory* 16(1):55–98.
57. Kooyman B, Newman ME, Cluney C, Lobb M, Tolman S, McNeil P, Hills LV (2001) *Am Antiquity* 66:686–691.
58. Boyd M, Running G, Havholm K (2003) *Geoarchaeology* 18:583–607.

GEOPHYSICS