

DISCUSSION AND REPLY

Extraordinary Biomass-Burning Episode and Impact Winter Triggered by the Younger Dryas Cosmic Impact ~12,800 Years Ago, Parts 1 and 2: A Discussion

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Introduction

Wolbach et al. published two papers on the Younger Dryas Impact Hypothesis (YDIH)—the paleoenvironmental effects of a purported cosmic impact at the beginning of the Younger Dryas Chronozone (YDC). Part 1 includes a selective summary of previous discussions of the YDIH but leaves out key reviews, uncritically accepts previous interpretations of purported impact, and fails to take into account abundant criticisms and contradictory data. A discussion of ice-core evidence focuses only on the beginning of the YDC rather than on a longer interval that would allow the context of claimed impact indicators to be evaluated. The exceptionalism claimed for many of the key data points is the result of exaggerations, and the graphical analyses themselves are not reproducible. Part 2 presents data from sedimentary records. The authors assume that impacts triggered widespread fires, but the evidence for such a link between extraterrestrial impacts and wildfires is weak. The presence of charcoal at the beginning of the YDC (YDB) fails to unambiguously support the hypothesis of impact-related fires because there is also a large peak at the end of the YDC. Stratigraphic markers used to argue for widespread burning, such as the Usselo soil of northwest Europe and the black mat of the southwestern United States, were shown by their original investigators to have no plausible link to an impact event. Human population decline in North America is not supported by abundant published

archaeological, geochronological, and stratigraphic evidence. Late Pleistocene megafauna extinctions varied in time for individual species across the Americas, Europe, and Asia and thus cannot be accounted for by a single impact. If there was some sort of extraterrestrial YDB-age event, it apparently had negligible terrestrial impact.

The articles by Wolbach et al. (2018a, 2018b) are part of a long series of publications that began more than a decade ago dealing with the YDIH (Firestone et al. 2006, 2007). That hypothesis has generated considerable data and debate regarding the viability of the idea that at ~12,900 cal BP (at the onset of the YDC), some sort of cosmic event (single impact, multiple impacts, and/or airbursts) affected North America, South America, western Europe, and western Asia (Wolbach et al. 2018a, p. 165). This purported event is claimed by the adherents of the YDIH to have brought on extraordinary environmental changes that “triggered an ‘impact winter’ and the subsequent YD climate episode, biomass burning, late Pleistocene megafaunal extinctions, and human cultural shifts and population declines” (Wolbach et al. 2018a, p. 165). A key criticism of the YDIH over the past decade is that the proponents do not consider, or perhaps misrepresent, the data and arguments that contradict the YDIH. The same problems that have plagued the evaluation of the YDIH are well displayed in the two articles. In this discussion we highlight these problems and alert readers to the considerable body of contradictory data.

The first article (Wolbach et al. 2018a) focuses on evidence for burning and wildfires in ice cores from

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Greenland and includes appendixes that summarize data in support of the YDIH. Part 2 (Wolbach et al. 2018b) is a discussion of terrestrial evidence, largely from North America, claimed to support the ice-core data on burning and wildfires. Our discussion focuses on the background of the debate as summarized in part 1 of Wolbach et al. (2018a, tables A1 and A3), on the data from ice cores presented in part 1, and then on the data and discussion in part 2 (Wolbach et al. 2018b), an examination of the terrestrial evidence for burning and wildfires in North America and claimed “proxy indicators” for burning and an impact.

Background of the Debate

Key issues in the YDIH debate include cratering and comet physics, dating, stratigraphy, and the interpretation of a variety of indicators claimed to be “proxies” for an impact (Wolbach et al. 2018a, appendix; Wolbach et al. 2018b; see also Boslough et al. 2012; Wittke et al. 2013b; Holliday et al. 2014; Kennett et al. 2015a). At the outset of the first of the two articles, referring to what the authors call the “Younger Dryas Boundary” (YDB; materials deposited at the beginning of the YDC), Wolbach et al. (2018a, p. 165) state, “It is not the intent of this contribution to review and discuss previous publications concerning the YDB impact proxies, and so a comprehensive bibliography is provided in table A3.” However, their table A3 is not comprehensive; it omits key critical articles and contradictory data. Few of the criticisms in those articles are seriously addressed. An annotated table including those critical articles and data is presented as our table 1.

Acknowledging and addressing critical reviews and contradictory data has continued to be a significant problem in this debate. Among the proponents, Kennett et al. (2015b) assert that claims of evidence for multiple horizons with “impact proxies” at times other than the YDB were “refuted in detail” (citing Kennett et al. 2015a; see also Bunch et al. 2012; LeCompte et al. 2012; Wittke et al. 2013b). In fact, few of the criticisms and data regarding dates and dating, stratigraphy and soils, megafauna extinctions, and Paleoindian archaeology that contradict the YDIH have been dealt with “in detail” (table 2).

Moreover, table A3 by Wolbach et al. (2018a) is organized around a trichotomy of “proponents,” “independent workers,” and “critics,” a peculiar grouping of articles that is not mutually exclusive. As far as we are aware, all of the “critics” started as independent researchers doing what scientists are supposed to do: greeting new hypotheses with skepticism and testing those hypotheses by trying to reproduce the results.

In contrast, we note that, among the “independent workers” listed, Haynes et al. (2010a, 2010b; see also Haynes 2008) were critical of the initial hypothesis and the associated data and presented their own contradictory data. Furthermore, among the independent workers, W. C. Mahaney and M. LeCompte are coauthors of “proponent” articles by Kennett et al. (2015a) and the two under scrutiny in this discussion (Wolbach et al. 2018a, 2018b).

Reliable and precise numerical age control for stratigraphic sections and associated samples is a key component of the YDIH debate. Proponents recommend “very high chronological resolution to test the hypothesis” (Kennett et al. 2008a, p. 2531). Furthermore, they argue that “only” radiocarbon dates with precisions of “<100 years, and preferably <60 years” should be used for dating the YDB layer and complain that many dates employed by others have “precisions from 200 years to >2,000 years” (Kennett et al. 2008b, p. E107). They also propose that the only valid dates are those processed with “modern techniques [e.g., XAD . . . or ultrafiltration].” Given that the debate is about whether some sort of extraterrestrial event created an environmental catastrophe at a precise moment in geologic time, we agree that accurate and high-precision dating is essential for testing the hypothesis.

Nevertheless, few of the age determinations published by YDIH proponents meet any of their own criteria. Wolbach et al. (2018a, table A1) list 23 sites as “well dated,” with no definition or discussion in the context of the source of the dates (Kennett et al. 2015a). Six of these sites listed as “well dated” are described as “low quality” by Kennett et al. (2015a, fig. 2), and another 17 exhibit standard deviations of 180 y and much more (at a 68% confidence interval) (tables 3, 4). Kennett et al. (2015a), in a discussion of dating following Bayesian “cleansing,” list only 6 of 32 YDB sites with age estimates of <100 y uncertainty (at a 68% confidence interval) (table 3). Further confusing the dating issue, Wolbach et al. (2018b, fig. 2) in a set of figures comparing platinum and soot at eight sites use four sites with “low” or “inadequate” age control (few dates or very low precision following Kennett et al. 2015a, fig. 2, and Wolbach et al. 2018a, table A1). Only three of the eight sites have standard deviations below 100 y.

In the most recent discussion of dating, the YDB is placed at $12,800 \pm 300$ BP (Kennett et al. 2015a). Firestone et al. (2007) placed the YDB at $\sim 12,900$ cal BP, not at $\sim 12,800$, as stated by Wolbach et al. (2018a, p. 165; 2018b, p. 185). Conventional ice-core layer-counting age for the beginning of the YDC or Greenland Stadial 1 (GS-1) is $12,896 \pm 4$ y before 2000 CE or

Table 1. Impact Indicators: Key References Missing from Wolbach et al. (2018a, Table A3)

Indicator, references	Comments/issues not addressed
Ir:	
Haynes et al. 2010b	High levels of Ir in modern stream alluvium at the Murray Springs site, AZ. Higher-than-background levels of Ir at, above, and below the ~12,900-cal BP level at Murray Springs; the Blackwater Draw Clovis site, NM; and the Sheaman site, WY
Magnetic microspherules: Surovell in Holliday et al. 2014 Haynes et al. 2010b Wu et al. 2013	Methods supplied by A. West; microsphere ID confirmed by A. West Abundant spheres in modern stream alluvium at Murray Springs No evidence for impact at Blackwater Draw, Gainey, Lommel, Murray Springs, Newtonville, and Sheridan Cave based on osmium content of the spheres
Meltglass: Roperch et al. 2017	Glass distributed across paleo-wetland deposits, formed by melting of partially silicified plants and/or phytoliths-rich soils. Complex mineralogical assemblage shows that presence of iron sulfides, magnetite spherules, iron droplets, or iron phosphides do not necessarily indicate hypervelocity impact event. Fire in a subsurface layer (e.g., an archaeological site) rich in organic matter may form such exotic minerals by reduction of sulfates and iron oxides.
Nanodiamonds:	
Bement et al. 2014	Nanodiamond zone ~10 cm below ^{14}C date of $11,070 \pm 60$ BP (~12,935 cal BP; contra Kennett et al. 2009a and Kinzie et al. 2014) and <3000 cal BP in upper 20 cm
Holliday et al. 2016	Large spike in nanodiamonds (recovered by J. P. Kennett) dated <10,000 BP (<11,500 cal BP)
Daulton et al. 2017	In YDB sediment no credible evidence for lonsdaleite. Cubic nanodiamonds have not been linked to impact processes. Cubic nanodiamonds reported in sediments and in carbonaceous forms within sediments without clear association with impact structures and not YDB age. Most of the reported YDB "nanodiamonds" are not diamond but controversial "n-diamond." No evidence of a spike in nanodiamond concentration at the YDB
Extinction of human populations in North America: Holliday and Meltzer 2010; Holliday et al. 2014	Well dated, stratified archaeological sites provide no indication of any sort of population decline or demographic collapse at or just after 12.9 ka
Extinction of megafauna: Holliday et al. 2014; Grayson 2016	A YD impact event would have to be disastrous enough to have affected animals ranging from horses in Alaska to ground sloths in Patagonia while leaving mammoths on such places as St. Paul and Wrangel Islands unscathed. How did such a wide range of large mammals, from musk-oxen (<i>Ovibos moschatus</i>) and elk (<i>Cervus elaphus</i>) in North America to capybaras (<i>Hydrochoerus hydrochaeris</i>) and tapirs (<i>Tapirus</i> spp.) in South America, survive such an event? A wide variety of megafauna became extinct at different times on different continents; a YD impact cannot account for that

Note. Ir = iridium; YDB = Younger Dryas Boundary; YD = Younger Dryas.

12,846 y before 1950 CE (or 12,846 BP). Modeled age ranges with standard deviations of >300 y up to 2405 y are presented for layers of claimed impact indicators at nine sites of "low quality" in terms of dating (their description in Kennett et al. 2015a, table 2). These layers are argued to represent the YDB based solely on the premise that if they could be YDB, they must be the YDB. Such circular reasoning is a common problem in the YDIH literature (table 5).

Kennett et al. (2015a), for example, following their Bayesian analyses, purport to show the contempora-

neity of radiocarbon dates from supposed impact sites. However, they do not always state (or justify) decisions about radiocarbon ages included or not in the analyses. Some of those decisions are arbitrary at best and archaeologically naïve at worst; for example, including only ages from within 40 m (Murray Springs) or 67 m (Blackwater Locality 1) of the sampling spot on the ground that ages within these distances "provide the most accurate age model" (Kennett et al. 2015a, p. E4352). Sites can have highly complex and discontinuous stratigraphy, and areas more (or less)

Table 2. YDIH Critiques and Replies

Articles and issues	Comments	Response
Pinter and Ishman (2008a) note: Varied proposals for the nature of the extra-terrestrial event “The 12.9-ka impact story . . . has struggled with the broad range of impact-related materials reported” (p. 37)	High concentrations of impact proxies at YDB (Bunch et al. 2008)	Much of this material represents micrometeorite ablation fallout, which can and should be concentrated at any depositional hiatus or in any condensed section (Pinter and Ishman 2008b) “Unusual assortment of evidence well outside criteria accepted by the impact community. . . . A common theme among the bevy of marginal impact claims is that they eschew accepted criteria in favor of new and untested markers” (Pinter and Ishman 2008b) Ir from spherule and magnetic grain separates, fully consistent with a noncatastrophic micrometeorite source (Pinter and Ishman 2008b) YDB is at base of low-energy lake deposits on top of high-energy alluvial deposits (V.T.H.) Many genera extinct or declining in numbers well before YDB; A wide variety of megafauna became extinct at different times on different continents (V.T.H.) As noted by Surovell et al. (2009, p. 18,157; SI, p. 1) and by Surovell in Holliday et al. (2014), the methods followed were supplied by A. West and microsphere ID confirmed by A. West, a leading YDIH proponent (e.g., Firestone et al. 2006, 2007; Wolbach et al. 2018a, 2018b) (V.T.H.) ^a The same problems apply to dating the YDB (V.T.H.)
Complexity of “black mat” layers	Sedimentation at Blackwater Draw was rapid (Bunch et al. 2008)	
Complexity of Late Pleistocene extinctions	Many megafauna taxa became extinct near the YD boundary (Firestone and West 2008)	
Surovell et al. (2009) provide: Data on spheres; unable to reproduce data of Firestone et al. (2007)	Correct methods not followed (LeCompte et al. 2012)	
Holliday and Meltzer (2010) note: Archaeological, geochronological, and stratigraphic data provide no evidence for a post-Clovis demographic collapse	¹⁴ C reversals and plateaus for the early YD render accurate dating of archaeological remains difficult (Kennett 2010) Calls for dating short-lived material (e.g., seeds, bone) for archaeological chronology (Kennett 2010) No comment	Rarely conducted by YDIH proponents (V.T.H.)
Pinter et al. (2011) note: None of the original purported YD impact signatures (carbon spheres and elongates, magnetic grains and magnetic spherules, byproducts of catastrophic wildfire, and nanodiamonds) have been subsequently		

corroborated by independent tests; “Throughout the arc of this hypothesis, recognized and expected impact markers were not found, leading to proposed YD impactors and impact processes that were novel, self-contradictory, rapidly changing, and sometimes defying the laws of physics” (p. 247–248)

Boslough et al. (2012) note:

Problems with impact physics; no single YDIH but several that conflict; no impact craters; no unambiguously shocked material or other features diagnostic of impact; climatological, paleontological, and archeological events “explained” by YD impact proponents are not unique, have large chronological uncertainties, are not necessarily coupled, and do not require an impact; independent researchers have been unable to reproduce reported results

Pigati et al. (2012) provide:

Multiple peaks in magnetic spheres and Ir from black mats ranging in age from 40 to 6 ka across the US Southwest and in Argentina van Hoesel et al. (2014) note:

Problematic age control; age discrepancy of up to two centuries among different YDB sites in the Usselo soil

Meltzer et al. (2014) note:

Problematic age control among 29 YDB sites; several lack any age control; others have radiometric ages that are chronologically irrelevant; nearly a dozen have ages inferred by statistically and chronologically flawed age-depth interpolations; in several sites ages directly on the supposed impact layer are older or younger than ~12.8 ky

Holliday et al. (2014) note:

No YDB crater, craters or other direct indicators of an impact

Direct age control in association with purported proxies is rare and problematic at some sites Results of physical and geochemical analyses supporting YDIH not reproducible or not unique to an impact nor to ~12.9 ky

No comment

Accept data of Pigati et al. for YDB mats but not other mats (LeCompte et al. 2012, 2013)

No comment

Critique of some methods, but not all (Kennett et al. 2015a)

No comment on numerous issues regarding integrity of site contexts and reliability of specific dates (V.T.H.)

No comment

No comment

“Evidence for multiple horizons with ‘impact proxies’ at times other than the YDB . . . ‘refuted in detail’” (Kennett et al. 2015b, p. E6723, citing Bunch et al. 2012; LeCompte et al. 2012; Wittke et al. 2013b; Kennett et al. 2015a)

No discussion of specific problematic data in any of the cited articles (see above) except critique of Surovell et al. (2009), but see above

Table 2 (*Continued*)

Articles and issues	Comments	Response
	“No interval other than the YDB layer in 23 widely separated stratigraphic profiles, spanning up to 50,000 y, contains the same broad assemblage of proxies” (Kennett et al. 2015 <i>b</i> , p. E6723)	The focus of most sampling in all studies by YDIH proponents focuses on the YDB and zones just above and below (see table 4 in this article)
Geomorphic setting (soils), of purported indicators at most sites tend to concentrate particulate matter and probably created many “YDB zones”	No comment	No reported sites with long (thousands of years), continuous records of sedimentation subjected to close-interval, continuous sampling to show that claimed impact proxies are unique to ~12.8 ky
Geomorphic, stratigraphic and fire records show no evidence of catastrophic changes at or immediately following the YDB	No comment	
Late Pleistocene extinctions varied in time and across space	No comment	
Archeological data provide no indication of population decline, demographic collapse or major adaptive shifts at YDB	Refer to optically stimulated luminescence dating of Odessa Meteor Crater (Holliday et al. 2005)	Irrelevant; dating focused on fill in the crater to provide an upper limiting date

Note. YDB = Younger Dryas Boundary; YD = Younger Dryas; SI = supplementary information; YDIH = Younger Dryas Impact Hypothesis; V.T.H. = V. T. Holliday.

^a Long involved in YDIH issue (Firestone et al. 2006, 2007), and corresponding author for Kinzie et al. (2014), Kennett et al. (2015*a*), and Wolbach et al. (2018*a*, 2018*b*); see also Dalton (2010).

Table 3. Examples of Dating Inconsistencies: Summary Dating Evaluations for 32 Younger Dryas Impact Hypothesis Sites

Dating quality ranking	Number of sites per standard deviation (68%) range ^a				Geologic context		
	<100 y	100–300 y	300–1000 y	>1000 y	Unconformity	Soil	Not indicated ^b
High	6	2	1		7	6	
Medium		5	3		5	3	
Low			4	2	6	4	
Inadequate ^b		9 sites					9 sites

Source. Kennett et al. 2015a, figure 2.

^a The totals in each cell vary slightly from the published table.

^b Nine sites are essentially devoid of direct numerical age control except for Late Holocene/modern dates on “impact markers” from Gainey (see table 6).

distant can be just as reliable in terms of providing age control of a specific surface; no site- and stratigraphy-specific justifications were provided for the selection of those distances, the net effect of which is to exclude potentially useful ages beyond those distances. There is also a continuing and troublesome problem of omitting radiocarbon ages without explanation, including ages that are said in one article to directly date the YDB but that are omitted in the next article (e.g., Abu Hureyra ages OxA-172 and UCIAMS-105429, which are in Wittke et al. 2013b but not Kennett et al. 2015a). Finally, there are the nine sites with no age control at all but that are said to date to the YDB age because they purportedly have the impact markers (Kennett et al. 2015a, supplementary information). They can be so only by traveling in a logical circle.

The focus of part 1 (Wolbach et al. 2018a) of the two articles is on data from Greenland ice cores. A significant issue here, as it is with most of the YDIH literature, is that most sampling and data are only from within and around the presumed YDB zone rather than throughout thicker, longer, or more continuous sections that would allow comparison of the relative magnitudes of “peaks” in claimed indicators at the YDB with those at other stratigraphic levels. Essentially no data to date show that increased levels of proxy impact indicators at the YDB are unique to, for instance, the post–Last Glacial Maximum (LGM) Quaternary record or, for that matter, the last glacial-interglacial cycle. At a minimum, several thousand years before and after the YDB (including the end of the YDC) must be analyzed for unusual changes in selected indicators to be claimed. Very few studies do so. Table 4 summarizes the number of samples collected at most of the key sites. Data from several studies show that claimed impact indicators are found in deposits of a wide age range (table 6). For example, nanodiamonds were misidentified and/or the data are not reproducible (Daulton et al. 2017) or there are multiple nanodiamond peaks over the past 13,000 y.

Part 2 (Wolbach et al. 2018b) of the two articles is a review of data from middle latitudes, largely in North America, for “proxy indicators” of a YD impact. A number of such indicators have been offered as a “smoking gun” of sorts for an impact: charcoal, carbon spherules, magnetic microspheres, iridium, nanodiamonds, and platinum. Few have been confirmed (tables 1, 2). More important, as indicated earlier, we do not know if these indicators are unique to the YDB within the context of either the Holocene or the late Quaternary.

Greenland Ice-Core Evidence

Wolbach and colleagues’ (2018a) analysis of the ice-core record of climate and biomass burning (in the form of oxygen isotopes and “combustion aerosols”) involves simple graphical comparisons of time series relative to one another and, in particular, to the Greenland Ice Sheet Project 2 (GISP2) platinum peak. Frequent assertions about the exceptionalism of individual data points are distributed throughout the discussion. In their figures 3 and 4, for example, they plot oxygen-isotopic ($\delta^{18}\text{O}$) and ammonium-ion (NH_4^+) values from the GISP2 (Mayewski et al. 1993; Stuiver and Grootes, 2000) and North Greenland Ice Core Project (NGRIP) ice-core records (Steffenson et al. 2008; Fischer et al. 2015). They focus on the (apparently) exceptionally large peak (relative to the rest of that part of the record that appears in the figures) in NH_4 corresponding to the GISP2 platinum peak, and the (apparently) coincident changes in oxygen-isotope values. As is the case with other lines of evidence, they focus on a narrow time window around the beginning of the YDC, which adds to the sense of exceptionalism they claim. We have been unable to reproduce those figures using readily available data sets and following their approach (Wolbach et al. 2018a, p. 167) for reconciling the differing chronologies (or “time scales”) used in the original data publications (by putting them all on

Table 4. Examples of Dating Inconsistencies: “Well-Dated YDB Site” of Wolbach et al. (2018a, table A1) with Dating and Sampling Information

Site	Quality rank ^a	Mean	68% SD	Total samples collected and analyzed	Samples at or near claimed YDC zone
Aalsterhut ^b	High	12,780	35	3?	?
Abu Hureya	High	12,825	55	6	3
Arlington Canyon	High	12,805	55	27	27 ^c
Barber Creek ^d	Med	12,865	535	3	3
Big Eddy ^d	High	12,770	85	5	1
Blackville	Low	12,820	1080	11 ^e	1
Blackwater Draw	Med	12,775	365	15	1
Bull Creek	High	12,840	75	34	1 ^f
Daisy Cave	High	12,730	320	4	2
Indian Creek	Med	12,750	425	Unpublished ^g	
Lake Cuitzeo	Low	12,850	570	16	5
Lake Hind	Med ^h	12,745	180	8	1
Lindenmeier	Med	12,775	180	4 ^e	1
Lingen	Med ^h	12,735	85	10	1
Lommel	Med ⁱ	12,735	790	9	2
Melrose	Low	12,255	2405	5	2
Mucuñuque ^j	Low	12,845	630	No data available	
Murray Springs	Med	12,750	235	10 ^e	1
Ommen	Low	12,750	560	7	1
Parangueo Lake	... ^k	12,843	228	No data available ^l	
Santa Maria	Med	12,785	295	2	1
Sheridan Cave	High	12,840	120	9	1
Stara Jimka	... ^k	12,805	70	No data available ^m	
Talega	Med	12,860	150	9	3
Topper	Med	12,785	185	6	1

Source. Dating and sampling information from Bunch et al. (2012); Wittke et al. (2013b); Bement et al. (2014); Kinzie et al. (2014); Kennett et al. (2015a).

Note. YDB = Younger Dryas Boundary; SD = standard deviation; YDC = Younger Dryas Chronozone; Med = medium.

^a Rank from Kennett et al. (2015a, fig. 2).

^b Number of samples for possible impact indicators not clear.

^c Twenty-seven samples were collected from a zone ~4 m thick (Kennett et al. 2008a). That zone yielded 15 radio-carbon dates accepted by the authors (their fig. 5 and table 5). They are out of stratigraphic order but span 13,470 to 12,830 cal BP. The nine basal samples yielded carbon spherules and that zone was identified as the YDB, based on accepted dates ranging from 13,090 to 12,780 cal BP. Four other older dates are rejected because of the “old wood effect” without explanation (Kennett et al. 2008a, p. 2538). The sediments above are also dated “to between 13 and 12.9 ka” (Kennett et al. 2008a, p. 2539) but contained no spherules. No samples were collected from below the level identified as the YDB.

^d Not listed by Wolbach et al. (2018a, table A1). At Big Eddy, purported YDB impact proxies are from a zone 8 cm thick in soil Bt horizon; pedogenic processes likely mixed particulate material, negating dating precision.

^e Samples from YDB are on a disconformity (see table 5): At Blackville lower five samples immediately below claimed YDB level are from Miocene deposits; at Lindenmeier the dark YDC soil is on erosion slope; at Murray Springs the samples from YDC “black mat” rest on disconformity.

^f Kennett et al. (2009a, 2015a) report a nanodiamond spike from the same level as a date of ~11,070 (~12,960 cal) but in a more comprehensive study of the full section, Bement et al. (2014) report a nanodiamond spike below the date and show that the YDB zone is on top of a dated soil; the dating is on organic carbon from a soil that formed for an unknown period of time. Therefore the ND zone could be significantly older than the dated surface.

^g Indian Creek. Nanodiamonds “reported independently in conference presentations” (Kinzie et al. 2014, p. 478).

^h Listed as “High Quality” by Kennett et al. (2015a) in their fig. 2 but listed under “Medium Quality” in text (p. 4349).

ⁱ Listed as “Low Quality” by Kennett et al. (2015a) in their fig. 2 but listed under “Medium Quality” in text (p. 4350).

^j References in Kennett et al. (2015a, “Mahaney et al. 2008, 2010”) provide no data on number or location of samples nor claimed impact indicators. Mn-encrusted zone is confused with “black mats” of Haynes (2008), which are not Mn encrusted. All dates are for peat layer below.

^k Not listed by Kennett et al. (2015a).

^l Identified as a “well dated YDB site” by Wolbach et al. (2018a), table A1, but cited reference (“Domínguez-Vásquez 2012”) is miscited and contains no data on the YDB.

^m Stara Jimka reference in Wolbach et al. (2018a, table A1, “Mentlik et al. 2010”) contains no data or discussion related to the YDB or an impact.

Table 5. Circular Reasoning

Site, context	References
YDB context:	
Gainey:	
"The same Gainey layer includes the onset of the YD at $\approx 12,800$ cal BP and is not modern in age. Thus, on the basis of available evidence, these young radiocarbon dates do not accurately reflect the age of the inferred YDB layers at these sites."	Kinzie et al. 2014, p. 481
Basic premise: because purported impact proxies might be of Clovis age, they must be of YDB age. There is no documented "onset" of the YD at this site, simply an assertion. The Clovis/Gainey layer at the site is not directly dated; the stratigraphic relationship of the purported impact markers to the artifact zone is not described. The archaeologist who excavated the site is clear and emphatic that the site has no contextual integrity. Late Holocene/modern dates were determined directly from purported impact markers by an impact proponent (R. B. Firestone [Firestone 2009]) and from samples supplied by an impact proponent (A. West [Boslough et al. 2012]).	Simons et al. 1984; Simons 1997; Firestone 2009; Boslough et al. 2012; Holliday et al. 2014; Meltzer et al. 2014
Chobot:	
"The Clovis points may be reworked . . . but that is inconsistent with the closely associated YDB proxy peaks, which have never been found outside the YDB in similar quantities."	Wittke et al. 2013a, p. E3900
Basic premise: because purported impact proxies might be of Clovis age, they must be of YDB age. There is no Clovis layer at the site based on field observations at the site and in the area. Purported impact proxies are in apparent proximity to Clovis artifacts, but the artifacts are near the surface and subject to dating contamination and likely out of place.	Ives and Froese 2013
Chobot and Gainey:	
"Inadequately dated."	Wolbach et al. 2018a, table A1
"Firestone (2009) presented several possibilities to explain these age discrepancies, and the most likely is the effects of bioturbation."	Kinzie et al. 2014, p. 481
"The ages of these two sites remain poorly constrained. Nevertheless, 18 of the 24 sites with the same YDB markers are well dated, suggesting that the YDB layer is correctly identified at Gainey and Chobot."	
Basic premise: because purported impact proxies might be of Clovis age they must be of YDB age. The sites are effectively undated and there is no way to know with any accuracy or precision the age of the layer of purported impact markers beyond the direct dating of carbon spherules from Gainey, which shows that they are late Holocene/modern (see above).	
Melrose ^a :	
Spherules and magnetic grains are impact indicators and therefore define the YDB.	Wu et al. 2013
Basic premise: there should be an increased concentration of assumed impact markers at the YDB; therefore, those markers define the location of the YDB.	
A single OSL date of $11,701 \pm 1846$ confirmed model for position of YDB	Kinzie et al. 2014, app. B, p. 10
Basic premise: because the YDB is within the modeled age range of 3692 y, the samples must be from the YDB.	

Table 5 (*Continued*)

Site, context	References
Newtonville: "There is no direct date on the YDB layer. . . . Wu et al. (2013) concluded that the bottom of the dark layer is the YDB." YDB is inferred with no argument or case made for the dating. Basic premise: because purported impact proxies might be of YDB age, they must be of YDB age.	Kinzie et al. 2014, app. B, p. 10 Wu et al. 2013, SI, fig. S1B
Big Eddy: "The YDB layer from 327 to 335 cmbs dates close to 12.8 ka, consistent with the age of the YDB at other sites." Basic premise: because purported impact proxies might be of YDB age, they must be of YDB age.	Wittke et al. 2013<i>b</i>, SD, p. 5
Chobot, Gainey, Kangerlussuaq, Kimbel Bay, Morley, Mt. Viso, Newtonville, Paw Paw Cove, Watcombe:^b Dating inadequate for "robust Bayesian analysis." "Evidence indicates that all nine are YDB sites. Each contains one or more proxies. . . . On the other hand, there are few to no proxies above and below the YDB layer [in a narrow range of sampling, V.T.H.]. . . . A YDB age for the proxy-rich layers is supported by biostratigraphy, archaeostratigraphy, climatology, and/or palynology. Because these nine sites contain the same abundance peaks in proxies that are found at well-dated YDB sites, we have proposed that they are of YDB age."^c Basic premise: peak in abundance of purported impact markers must be of YDB age.	Kennett et al. 2015<i>a</i>, SD, p. 34
Mucuñuque: YDB inferred from older radiocarbon dates below and black Mn-encrusted zone correlated with YDC "black mat" of Haynes (2008). Basic premise: because it is black and <13.3 ka, it must be a YDB layer. "Black mats" are not Mn-encrusted, and none are reported with associated Mn (Haynes 2008). Glacial deposit above Mn layer "appears to be contemporaneous with" (Mahaney et al. 2010, p. 48) the YDC but produced no numerical age control.	Haynes 2008; Mahaney et al. 2010
Sampling contexts: dating soils and unconformities: Blackville: "The sediment sequence is represented by eolian and alluvial sediments composed of variable loamy to silty red clays down to an apparent unconformity at 190 cm below surface (cmbs). Below this there is massive, variegated red clay, interpreted as a paleosol predating bay rim formation (Miocene marine clay >1 million years old)," i.e., the purported YDB sample zone rests directly on the unconformity (figure S4D).	Bunch et al. 2012, p. E1905
Bull Creek: Kennett et al. report a nanodiamond spike from the same level as a date of ~11,070 (~12,960 cal), but in a more comprehensive study of the full section, Bement et al. document a nanodiamond spike below the date and show that the YDB zone is on top of a dated soil; the dating is on organic carbon from a soil that formed for an unknown period of time (see table 4). Therefore, the ND zone could be significantly older than the dated surface.	Kennett et al. 2009<i>a</i>, 2015<i>b</i>; Bement et al. 2014

Table 5 (*Continued*)

Site, context	References
Murray Springs: Sampling reported by Firestone et al. (2006, 2007) was along Tr22 which has no archaeological remains or radiocarbon dates (Haynes and Huckell 2007; C. V. Haynes, pers. comm., November 2013). Sampling section discussed by Wittke et al. not specified nor dated so likely Tr22. The black mat at Tr22 sample section is compressed and mixed and covers a disconformity on top of unit D. The age of the surface of unit D has not been determined, but based on the age of units F1 and E, it must have been exposed for at least several hundred years if not thousands of years before the Clovis occupation (i.e., it is a disconformity).	Firestone et al. 2006, 2007, 2010a, 2010b; Wittke et al. 2013b; Kinzie et al. 2014; Kennett et al. 2015a; Wolbach et al. 2018a
Lindenmeier: Samples from base of “black mat” (stratum D) at contact with loess (stratum C). This contact is a disconformity represented by a soil (Holliday 2016). At the sampling section (Kinzie et al. 2014, app. B, fig. B5B) the contact is also on the slope of the paleo-valley (Holliday 2016, figs. 7.2, 7.8) and is erosional. The contact could represent up to 1000 ¹⁴ C years.	Kinzie et al. 2014; Kennett et al. 2015a; Wolbach et al. 2018a
Watcombe Bottom, UK: Preece et al. (1994) described the soil below the sample zone as being formed from poorly stratified chalk muds and rubble produced by frost-shattering and solifluction (gradual mass wasting).	Kinzie et al. 2014; Kennett et al. 2015a; Wolbach et al. 2018a

Note. YDB = Younger Dryas Boundary; SI = supplementary information; SD = supplementary data; Tr22 = Trench 22; V.T.H. = V. T. Holliday.

^a Melrose: samples from three depths spanning 14 cm out of a total section of 43 cm identified as the YDB by Kinzie et al. (2014, app. D, table D4).

^b Only one sample was analyzed from Paw Paw; three from Newtonville

^c The only archaeology is from Gainey and Chobot (both shallow sites and heavily mixed); position of Clovis artifacts estimated at Paw Paw. The only “climatology” is gross glacial-to-postglacial stratigraphy at Morley, Newtonville, and Mt. Viso. Paleoenvironmental details available only from Watcombe. The only direct dating is on carbon spherules from Gainey, which are late Holocene/modern (see entry on this table).

the “GICC05” time scale, expressed as “years BP1950”; Rasmussen et al. 2008; Seierstad et al. 2014), and we note that the superlatives they attach to individual data points are exaggerations.

Ice-Core Figures. The necessary data for attempting to reproduce figures from Wolbach et al. (2018a) are contained in four text or spreadsheet files that can be readily downloaded (table 7). The NGRIP data were published using the GICC05 time scale, and no modification or adjustment is necessary (except for subtracting 50 y to place GICC05 “b2k” ages relative to 1950 CE). The GISP2 NH₄ data can be placed on the GICC05 time scale using the information in the Seierstad et al. (2014) supplemental file, which also provides the GISP2 and NGRIP $\delta^{18}\text{O}$ data on the GICC05 time scale. No interpolation or rescaling of ages or data values is required in any case.

To compare Wolbach and colleagues’ (2018a) figures 3 and 4 as published, with actual data, we extracted the bitmaps of the figures from the PDF version of the article and rendered the white areas of

the bitmaps transparent. No other manipulation of the figures was done other than rescaling to fit the page. By plotting the published data “under” the gray-scale bitmap, differences can be easily noted where the published data (in color) show through. Figure 1 shows the long time-series plots of panels A and B in figures 3 and 4 from Wolbach et al. (2018a). The $\delta^{18}\text{O}$ plots match quite well (within the limitations of this graphical comparison approach), which supports the validity of this sort of comparison, and argues that—at least for the long time-series plots—the $\delta^{18}\text{O}$ data are indeed plotted correctly. The NH₄ data as plotted by Wolbach et al. (2018a), however, have evidently been smoothed. Although the authors allude to the use of lowess-style smoothing, they state that the data “are typically presented in both raw and smoothed formats” (p. 167–168). Neither the text nor figure captions mention any smoothing of the NH₄ data. The NH₄ values increase in magnitude in the Holocene, relative to earlier, and this has generally been ascribed to warming relative to earlier times (Power

Table 6. Purported Impact Proxies in Non-YDB Contexts

Site	Proxies and context	References
Lubbock Lake, TX	Samples from lake beds less than ~11,500 BP (~10,000 cal BP) show a spike in nanodiamonds and carbon spherules (identified as impact spherules by YDB proponent J. Kennett [Holliday et al. 2016])	Holliday et al. 2016
USA and Argentina	Multiple peaks in magnetic spheres and Ir from “black mats” across the US Southwest and in Argentina ranging in age from 40 to 6 ka (these data for the YDB mats but not the other mats were selectively accepted by LeCompte et al. 2012, 2013)	Pigati et al. 2012
Arlington Canyon, CA; Squires Ridge, NC; Barber Creek, NC; Pen Point, SC; Topper, SC; Johns Bay, SC	Multiple Pt peaks are documented just before the YDB and in the Holocene	Moore et al. 2017
Gainey, MI	Carbon spherules, claimed to be YDB impact proxies, were directly dated by a key YDB impact proponent (R. B. Firestone) and supplied by another proponent (A. West [Boslough et al. 2012]) to critics (M. Boslough and V. Holliday); results showed that the “YDB” spherules are very young (see table 5)	Firestone 2009; Boslough et al. 2012
Bull Creek, OK	A terminal Pleistocene-Holocene stratigraphic sequence yielded a nanodiamond spike 10 cm below the dated YDB (contra Kennett et al. 2009a) and throughout deposits <3000 BP in upper 20 cm of the section (see tables 3, 4, 5)	Bement et al. 2014

Note. YDB = Younger Dryas Boundary.

et al. 2008; Danianu et al. 2012; Fischer et al. 2015), particularly in the northern extratropics, and not to “anthropogenic burning” (which none of these articles claim). Wolbach et al. (2018a, p. 170) state, “The NGRIP ice interval from 120,000 to 5000 cal BP displays only one anomalously high peak in NH_4 (fig. 4), and this is contemporaneous with the GISP Pt [platinum] anomaly.” The NGRIP NH_4 record (Fischer et al. 2015) extends only to 10,226 cal BP, but the inclusion of 1500 y of Holocene values in the smoothed NGRIP NH_4 time series tends to exaggerate the apparent size of the “Pt/YD Onset” peak in their figure, as also happens in the GISP2 smoothed series. At the same time, the smoothing attenuates the many earlier peaks visible in both NH_4 records (fig. 1, in red). Wolbach et al. (2018a) clearly refer to individual data values in the long time series: “The GISP2 NH_4 peak that coincides with the Pt anomaly is not the highest recorded, but is greater than 99.96% of 26,535 measured NH_4 values” (p. 169) and “there is an NH_4 peak [in the NGRIP record] that is higher than 99.5% of all NH_4 values before the YD onset” (p. 170). However, the smoothed time series do not allow the reader to judge the veracity of those statements, and indeed, the unsmoothed data show frequent peaks that rival the magnitude of those that occurred during the last glacial-interglacial transition.

Figure 2 shows our attempt to reproduce figures 3C and 4C in Wolbach et al. (2018a), which examine the $\delta^{18}\text{O}$ and NH_4 data over the interval between ca. 13 ka and 12.6 ka. The approach followed by Wolbach et al. (2018a) in these panels was to display the data at high temporal resolution, labeling key points or events, and noting their relationship to one another and to the GISP2 “Pt anomaly,” which the authors assign to the interval from 12,836 to 12,815 BP on the GICC05 time scale (e.g., years BP1950). Figure 2A shows the GISP2 NH_4 data (Mayewski et al. 1993) plotted in red using the GICC05 chronology (Seierstad et al. 2014), and it can be easily seen that a difference exists between the same data as plotted (in black) in figure 3C in Wolbach et al. (2018a). The offset between the two series is not linear—there is no way to simply shift or re-scale the X-axis of the plotted data to match that in the figure of Wolbach et al. (2018a). The GISP2 bidecadal $\delta^{18}\text{O}$ data (from the supplemental material file that accompanies Rasmussen et al. 2014 and Seierstad et al. 2014, in blue) also differ both in timing and magnitude from that in figure 3C in Wolbach et al. (2018a). Close inspection reveals that there are actually two distinct X-axes in Wolbach and colleagues’ (2018a) figure 3C and that their $\delta^{18}\text{O}$ data (which they ascribe to Stuiver et al. 1995) are plotted relative to the top axis. Because all of the data come from the

Table 7. Ice-Core Data Sources, Variables, and Treatments

Figures and elements	Data sources, variables used, and data treatments
Figs. 3A–3C:	
GISP2 NH ₄ ⁺ :	
Source URL	ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/greenland/summit/gisp2/chem/iond.txt
Y-variable	"NH4_pbb" (col. 4)
GICC05 chronology	https://ars.els-cdn.com/content/image/1-s2.0-S027737911400434X-mm2.xlsx (table 7)
X-variable	$((\text{"Top Age" [years b2k GICC05]} + \text{"Bottom Age" [years b2k GICC05]}) / 2) - 50 = \text{"Mid Age" [years BP1950 GICC05]}$
Treatment	The Y- and X-variables were aligned using "DEPTH Top" (Y-variable) and "Top depth GISP2" (X-variable), placing the data on the GICC05 years b2k time scale. Fifty years were subtracted to place the data on the GICC05 years BP1950 time scale.
References	Data: Mayewski et al. 1997; chronology: Rasmussen et al. 2014; Seierstad et al. 2014
GISP2 $\delta^{18}\text{O}$:	
Source URL	https://ars.els-cdn.com/content/image/1-s2.0-S027737911400434X-mm2.xlsx (tables 3, 4)
Y-variable	" $\delta^{18}\text{O}$ GISP2"
X-variable	"Age (years b2k)" [GICC05] – 50 = "Age" [years BP1950 GICC05]
Treatment	Both variables were provided on the GICC05 years b2k time scale. Fifty years were subtracted to place the data on the GICC05 years BP1950 time scale.
References	Original data: Stuiver et al. 1995; chronology: Rasmussen et al. 2014; Seierstad et al. 2014
Figs. 4A, 4B:	
NGRIP NH ₄ ⁺ :	
Source URL	https://media.nature.com/original/nature-assets/ngeo/journal/v8/n9/extref/ngeo2495-s3.xlsx
Y-variable	"NH4source_ng/m3"
X-variable	"GICC05age_yrBP" [years BP1950 GICC05]
Treatment	Both variables were provided on the GICC05 years BP1950 time scale. No further adjustment was made.
Reference	Data and chronology: Fischer et al. 2015
NGRIP $\delta^{18}\text{O}$:	
Data source	https://ars.els-cdn.com/content/image/1-s2.0-S027737911400434X-mm2.xlsx (tables 3, 4)
Y-variable	" $\delta^{18}\text{O}$ NGRIP"
X-variable	"Age (years b2k)" [GICC05] – 50 = "Age" [years BP1950 GICC05]
Treatment	Both variables were provided on the GICC05 years b2k time scale. Fifty years were subtracted to place the data on the GICC05 years BP1950 time scale.
References	Original data: NGRIP Members 2004; chronology: Rasmussen et al. 2014; Seierstad et al. 2014
Fig. 4C:	
NGRIP NH ₄ ⁺ :	
Source URL	https://media.nature.com/original/nature-assets/ngeo/journal/v8/n9/extref/ngeo2495-s3.xlsx
Y-variable	"NH4source_ng/m3"
X-variable	"GICC05age_yrBP" [years BP1950 GICC05]
Treatment	Both variables were provided on the GICC05 years BP1950 time scale. No further adjustment was made.
Reference	Data and chronology: Fischer et al. 2015
NGRIP $\delta^{18}\text{O}$:	
Source URL	http://science.sciencemag.org/content/suppl/2008/06/19/1157707.DC1
Y-variable	" $\delta^{18}\text{O}$ (per mill)"
X-variable	"Age (yr)" [years b2k GICC05] – 50 = "Age" [years BP1950 GICC05]
Treatment	Both variables were provided on the GICC05 years b2k time scale. Fifty years were subtracted to place the data on the GICC05 years BP1950 time scale.
Reference	Data and chronology: Steffensen et al. 2008

Source. Figures are from Wolbach et al. (2018a), figures 3 and 4.

Note. The GICC05 chronology (Rasmussen et al. 2014; Seierstad et al. 2014) can also be downloaded from http://www.iceandclimate.nbi.ku.dk/data/GICC05modelxt_GRIP_and_GISP2_and_resampled_data_series_Seierstad_et_al._2014_version_10Dec2014-2.xlsx. The original GISP2 bidecadal $\delta^{18}\text{O}$ are available at: <https://www1.ncdc.noaa.gov/pub/data/paleo/icecore/greenland/summit/gisp2/isotopes/d18o20y.txt>. Low-resolution GRIP ion data: <ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/greenland/summit/grip/chem/gripion.txt>. NGRIP = North Greenland Ice Core Project.

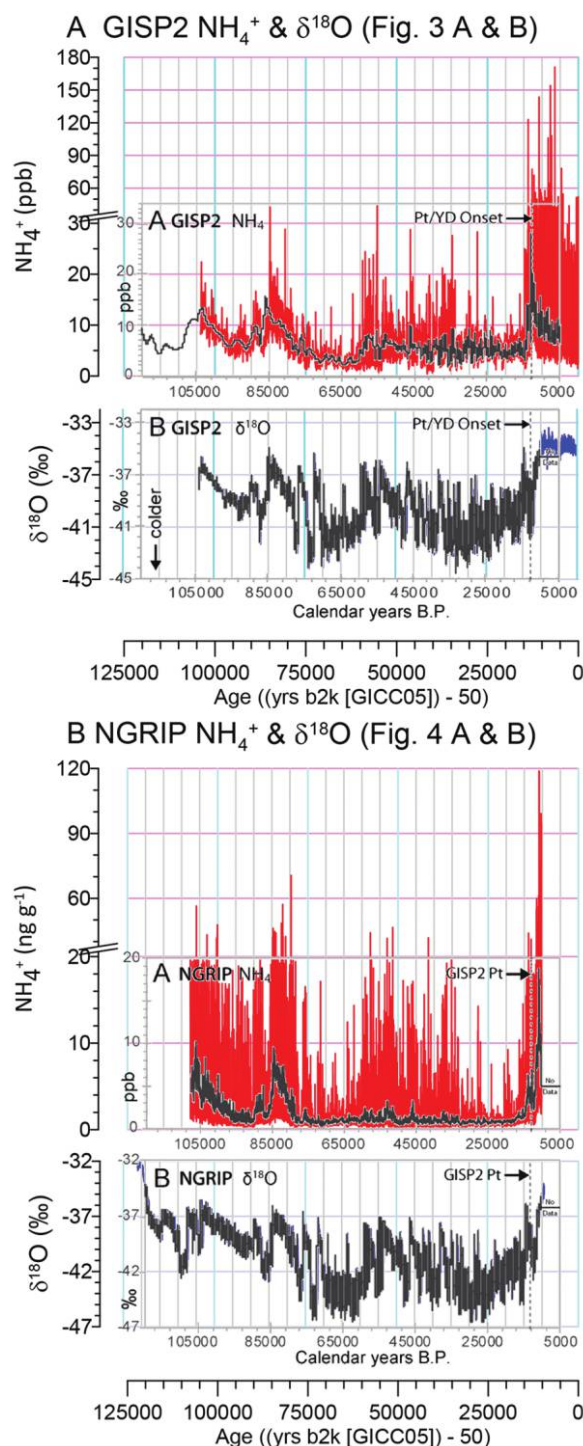


Figure 1. Reconstruction of figures 3A and 3B (GISP2 data) [A] and figures 4A and 4B (NGRIP data; B) of Wolbach et al. (2018a). Panels A and B combine parts of the bitmap version of the published figures (in black and gray), with actual NH_4^+ (red) and $\delta^{18}\text{O}$ (blue) observations from the data sources listed in table 8. Where colors are visible, there is disagreement between the two. The grid of light-colored lines was used to register our plots to the images of Wolbach et al. (2018a).

same core, even if measured at differing depths or times, there should be no reason to employ more than one age axis.

Wolbach and colleagues' (2018a) figure 4C also differs from the actual data (fig. 2B, left). The NGRIP NH_4^+ plot of the data is offset from the plot in Wolbach et al. (2018a) by about 10 y. This may be a simple graphical aberration because it can be observed that the GISP2 Pt anomaly interval is also offset by about 10 y in their figure. The annual values of $\delta^{18}\text{O}$, from Steffensen et al. (2008; in blue), differ more substantially, by about 50 y. If the age axes for NH_4^+ and $\delta^{18}\text{O}$ are shifted by 10 and 50 y, respectively, then the plots can be reconciled (fig. 2B, right). We can speculate that in the case of the annual $\delta^{18}\text{O}$ data, ages that were thought to be on the GICC05 b2k scale were adjusted by 50 y to place them on the GICC05 years BP1950 scale when they already were on the latter scale. Consequently, the $\delta^{18}\text{O}$ point they note and label with a plus sign, and which on their figure plots in the middle of the GISP2 Pt anomaly interval (with a value of -42.59‰), actually has a GICC05 age of 12,863 cal BP (outside of the Pt anomaly interval), whereas $\delta^{18}\text{O}$ values within the GISP2 Pt anomaly interval are not particularly "cold" or rapidly changing (ranging from -38.9 to -40.4‰). Our attempt to reproduce their figures 3 and 4 (figs. 1, 2) failed because of undisclosed data-analysis steps taken by Wolbach et al. (2018a), misregistration of individual time series, and unexplained shifts in the age axes of the plotted data and reveals that the ice-core records in fact provide little support for their hypothesis.

Exaggerated Claims and Other Issues. Wolbach et al. (2018a) make a number of assertions (e.g., numbers of data points, ranks of peak values, magnitudes of changes, rates of changes) that are unsupported by data or are simply exaggerated (table 8; see also table 7). This list of claims is not exhaustive; we focused on the discussion of the GISP2 and NGRIP ice cores because those records are continuous over most of the last glacial-interglacial cycle and are of much higher resolution than the GRIP records.

The ice-core NH_4^+ data also raise an "apples and oranges" issue. The GISP2 data (Mayewski et al. 1997) are NH_4^+ concentrations in the ice, whereas those from NGRIP (Fischer et al. 2015) are thought to represent NH_4^+ concentrations in the atmosphere at the "source," namely, the location of the fires "upstream" of Greenland. Those values consist of the concentrations of NH_4^+ in the ice, adjusted first for wet- and dry-depositional processes over the ice sheet and then to reflect atmospheric transport, which, by using present-day atmospheric circulation data, implicitly assumes that the North American ice sheets had no impact on atmospheric circulation. Leaving aside the appropriateness

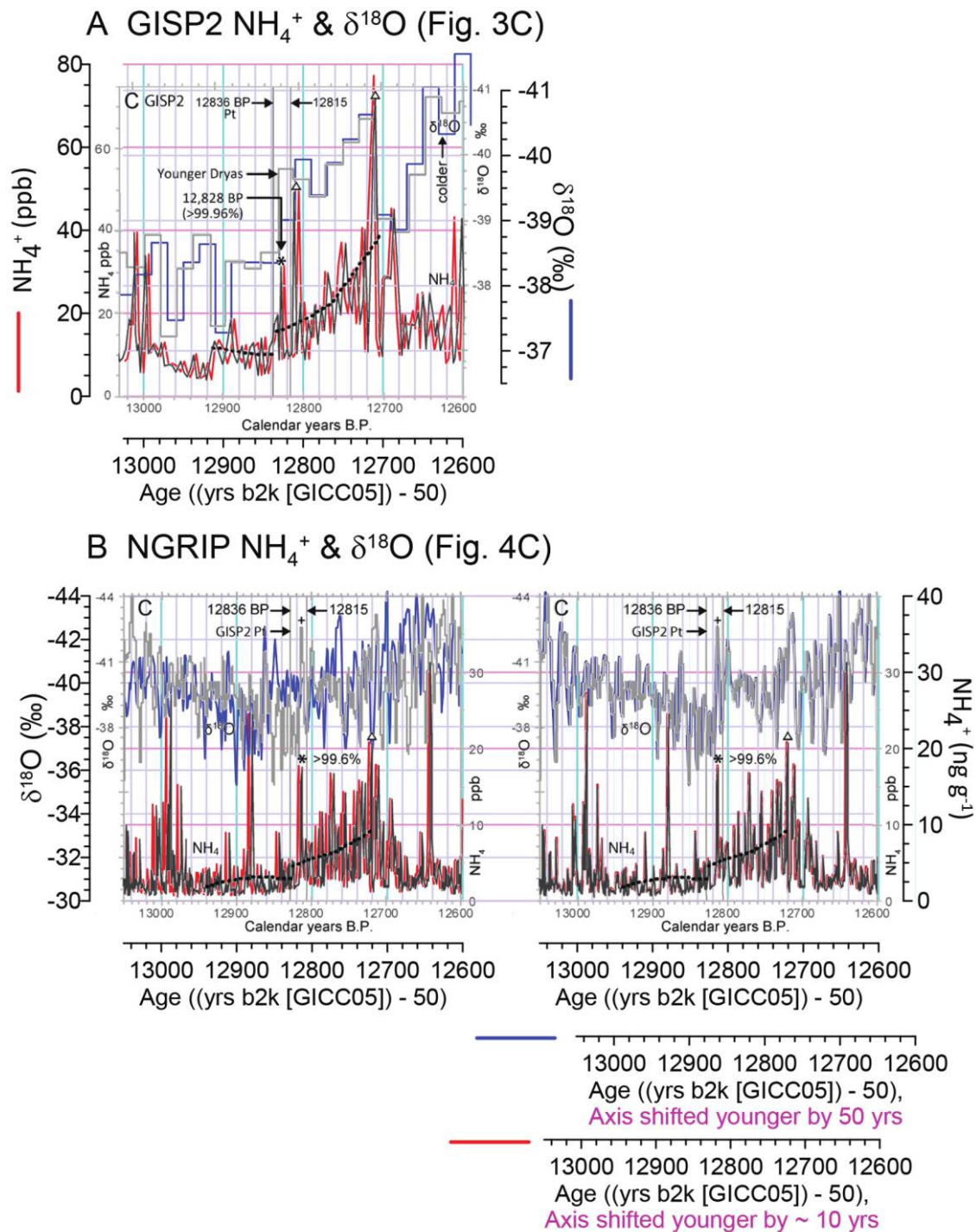


Figure 2. Reconstruction of figure 3C (GISP2 data; A) and figure 4C (NGRIP data; B) from Wolbach et al. (2018a). Panel B, right, shows that the plot of the actual data can be reconciled with Wolbach and colleagues' (2018a) figure 4C only if the age axes for NH_4^+ and $\delta^{18}\text{O}$ values are shifted "younger" (to the right) by 10 and 50 y, respectively. As in figure 1, the light-colored lines were used to register our plots to the images of Wolbach et al. (2018a).

Table 8. Greenland Ice-Core Data Claims and Exaggerations

Wolbach et al. 2018a	Data	Source ^a
"This record for NH ₄ , a biomass-burning proxy, displays one of the highest peaks in the 120,000-y record in an interval dating to 12,830-12,282 cal BP {1712.3-1712.3 m" (p. 169)	The sample (31.4 ppm) at that depth in the GISP2 core has an age of 12,825 to 12,823 BP and is the 120th largest value in the record.	1
"The GISP2 NH ₄ peak that coincides with the Pt [platinum] anomaly . . . is greater than 99.96% of 26,535 measured NH ₄ values, making it a standout in the entire pre-Holocene record" (p. 169)	There are only 12,188 values in the file gisp2_iond.txt (Mayewski et al. 1997) and only 10,709 with GICC05 age assignments.	1
"NH ₄ values marked with triangles are the two highest within the 120,000-y record" (p. 169, fig. 3 caption)	The two values are 77.3 ppb (at 12,711.5 BP) and 49.6 ppb (at 12805.5 BP), the 8th and 25th largest values in the record.	1
"Most of this shift [in GISP2 $\delta^{18}\text{O}$ values] occurs across a single ice sample from ~1713.40 to ~1711.69 m, dating to 12,855-12,814 cal BP" (p. 170)	There is no sample with those depths in the Stuiver et al. (1995) data set. There are samples at depths of 1712.29 and 1711.64 (equivalent to 12,880 to 12,860 BP) that show a change in $\delta^{18}\text{O}$ values of -1.28 between them, the 35th largest decrease in that record.	2
"[Fischer et al. 2015] identified a single high NH ₄ peak that begins at the YD onset, reflecting the largest biomass-burning episode from North American sources in the entire record" (p. 170)	It is not clear what Wolbach et al. are referring to. Overall, the single largest NH ₄ peak (118.88 ng g ⁻¹) occurred at 10,881.5 BP. Before the Holocene, the single largest NH ₄ peak (70.5 ng g ⁻¹) occurred at 79,640 BP.	3
"The NGRIP ice interval from 120,000 to 5000 cal BP displays only one anomalously high peak in NH ₄ (fig. 4A), and this is contemporaneous with the GISP2 Pt anomaly. . . . This NH ₄ peak occurs within a 3-cm interval centered on 1524.75 m, dating to 12,819 cal BP" (p. 170)	A sample at a depth of 1524.746 m (12,791.5 BP) has a value of 2.57 ng n ⁻¹ and is the 16,379th largest observation in the record. A sample at the age of 12,819.5 (at a depth of 1525.605 m) has value of 5.23 ng g ⁻¹ , and is the 6930th largest observation in the record.	3

^a Source 1: data from Mayewski et al. (1997), <ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/greenland/summit/gisp2/chem/iond.txt>; chronology from Rasmussen et al. (2014) and Seierstad et al. (2014), <https://ars.els-cdn.com/content/image/1-s2.0-S027737911400434X-mmc2.xlsx> (table 7). Source 2: data from Stuiver et al. (1995), <https://www1.ncdc.noaa.gov/pub/data/paleo/icecore/greenland/summit/gisp2/isotopes/d18o20y.txt>; chronology from Rasmussen et al. (2014) and Seierstad et al. (2014), as for source 1. Source 3: data and chronology from Fischer et al. (2015), <https://media.nature.com/original/nature-assets/ngeo/journal/v8/n9/extref/ngeo2495-s3.xlsx>.

of that assumption, the "source" data wind up having a longer-tailed distribution than the "ice" data and thus display more prominent peaks.

Differences in the figures and in the specific superlatives associated with individual data points could be accommodated within age or analytical uncertainties, but those uncertainties are not considered, and individual data-point values and ages are taken at face value. Wolbach et al. (2018a) argue that the closeness in time of particular data points to the GISP2 Pt anomaly or to commonly accepted ages for the beginning of the YDC (i.e., the start of GS-1) attaches some level of exceptionalism to those points, making the beginning of the YD unique in terms of biomass burning or climate change. Wolbach et al. (2018a, p. 170) assert that Fischer and colleagues "identified a single large NH₄ peak that begins at the YD onset, reflecting the largest biomass-burning episode from North American sources in the entire record." Fischer et al. (2015) make no such claim but instead note that a fire-peak-frequency index they developed "indicates a strong direct response of fire recurrence to rapid warmings,

which seems to be most pronounced at the *onset* of the BA and at the *end* of the YD" (emphasis added). When the time window for examining the ice-core biomass-burning indicators is expanded, then the beginning of the YDC appears to be not particularly remarkable.

Biomass Burning

Wolbach and colleagues' (2018a) attempt to make a case for burning at the YDB based in part on the assumption that an impact would trigger widespread fires, but the evidence for a link between extraterrestrial impacts and wildfires is weak (Jones and Lim 2000). The idea of a global fire following the K/Pg impact is widespread in the literature and is used as corroborative evidence for a YD impact (e.g., Wolbach et al. 2018a, p. 166, appendix, and references therein). Scott et al. (2000b), however, studied the terrestrial site nearest the K/Pg impact crater and saw no evidence of major fire, although fire was common both before and after the impact. Additional research

on the K/Pg impact and fire show that a global fire was unlikely if not impossible (Belcher et al. 2003, 2005, 2009, 2015; Harvey et al. 2008; Belcher 2009).

Likewise, the Tunguska impact is cited as having started a fire (Bunch et al. 2012; Wolbach et al. 2018a, p. 166), but an investigation based on contemporary reports, research articles, and websites provided no firm evidence of major wildfires (Jones and Lim 2000). Of particular significance, contemporary photos show downed trees but no charring.

There is no clear evidence of any large fires connected to an impact at the beginning of the YD, in large part because no impact site is known or has been unambiguously dated, and thus the location of implied impact-related wildfires is poorly defined. The way fires ignite and spread (Scott et al. 2014; Belcher et al. 2015) means that such an event, if it occurred, would be unlikely to have caused all the vegetation within hundreds or thousands of kilometers to combust (wet, live fuels are difficult to combust). Usually most of the vegetation does not burn or is only charred (Scott 2010), and no evidence of extensive log jams or postfire erosion in the majority of identified localities exists. Nevertheless, the lack of such expected evidence is misrepresented or ignored. In pine forests, for example, which often have a fire return interval of less than 50 y (Scott et al. 2014), dating with a precision of ± 100 y could reflect the occurrence of several fires decades apart.

Fire Indicators. In the original article on the YD impact, Firestone et al. (2007) state that carbon spherules exhibit “no evidence of seed-like morphology or cellular plant structure, as in charcoal” (p. 16,018). However, these properties do not define charcoal (Whitlock and Larsen 2001; Enache and Cumming 2006; Conedera et al. 2009; Scott 2010), and many plant, animal, and fungal materials may be preserved as charcoal (Scott et al. 2000a; Scott 2010). In addition, Firestone et al. (2007, p. 16,018) state that “we recovered them from one of four modern fires . . . confirming that they can be produced by intense heat in high-stand wildfires.” However, no hypothesized process or evidence is provided showing how they may be formed. In fact, such spherules are commonly found in sediments and have been identified previously as fungal sclerotia that are widespread and have no relationship with intense heat (Scott et al. 2010, 2017). Equally, the claim that such spherules contain nanodiamonds has been shown to be mistaken (Daulton et al. 2017) and is, importantly, not evidence of a wildfire.

Significant methodological problems arise in the charcoal samples described in Wolbach et al. (2018b, appendix). At Arlington Canyon, California, Wolbach et al. (2018b, p. 189, fig. 2; following claims by

Wittke et al. 2013b and Kennett et al. 2009b) claim a peak but without samples from below the peak (thus making the identification of “peak” impossible) and a horizon when only a single set of vertical samples are shown (against the interpreted layer rather than real position in the section) where there are considerable lateral facies changes and no evidence of a layer or horizon (Hardiman et al. 2016; Scott et al. 2017; fig. 3; appendix). Furthermore, comparisons in terms of weight are made, which is inappropriate when using samples from different lithologies. Even a small lateral movement of the sampled sediments would have provided a different result given that the charcoal occurs predominantly in lenses within these facies.

There are significant problems in the recording and interpretation of black mats and charcoal occurrence at many of the sites and in the identification and interpretation of charcoal, carbonaceous spherules, and carbon elongates (Scott et al. 2010, 2017). In many cases, horizontal units are claimed where such layers do not exist. At Arlington Canyon in Santa Rosa Island, the so-called YD impact layer does not exist. Only a single stick section was examined in a complex fluvial system (Scott et al. 2017). No samples were obtained from below the claimed layer. The dark layer or black mat has been misnamed and is not laterally continuous. They claim this to be “a discrete layer that is contemporary with, and similar to, the organic-rich sedimentary layers described by Haynes across North America” (Kennett et al. 2009b, p. 12,624), but this is not the case. In addition, charcoal occurs throughout the sedimentary sequences in many parts of the canyon sections (Hardiman et al. 2016). At site III, at least 17 charcoal layers span 14,500 to 12,710 cal BP, but charcoal lenses elsewhere on the island document fire activity as early as ~29,000 cal BP (Scott et al. 2010, 2017; Hardiman et al. 2016). Fire frequency diminished with time but continued into the Holocene.

All of the recording and interpretation of charcoal data (fig. 3) seem to contradict our current understanding of the nature of wildfire and the taphonomy of charcoal (Scott 2010, 2018; Scott et al. 2014, 2017). That is, what a wildfire leaves on the ground immediately after a burn can be different from what we eventually see in a stratigraphic section. In the geologic record, we see the effects of “fire taphonomy” (Scott 2010).

Wolbach et al. (2018b, appendix) argue that massive wildfires occurred at the YDB, based on a variety of charcoal data and analyses. The analysis, presentation, and interpretation of such data are problematic in a number of ways. First, figure A8 purportedly shows the “locations of 129 lake cores exhibiting

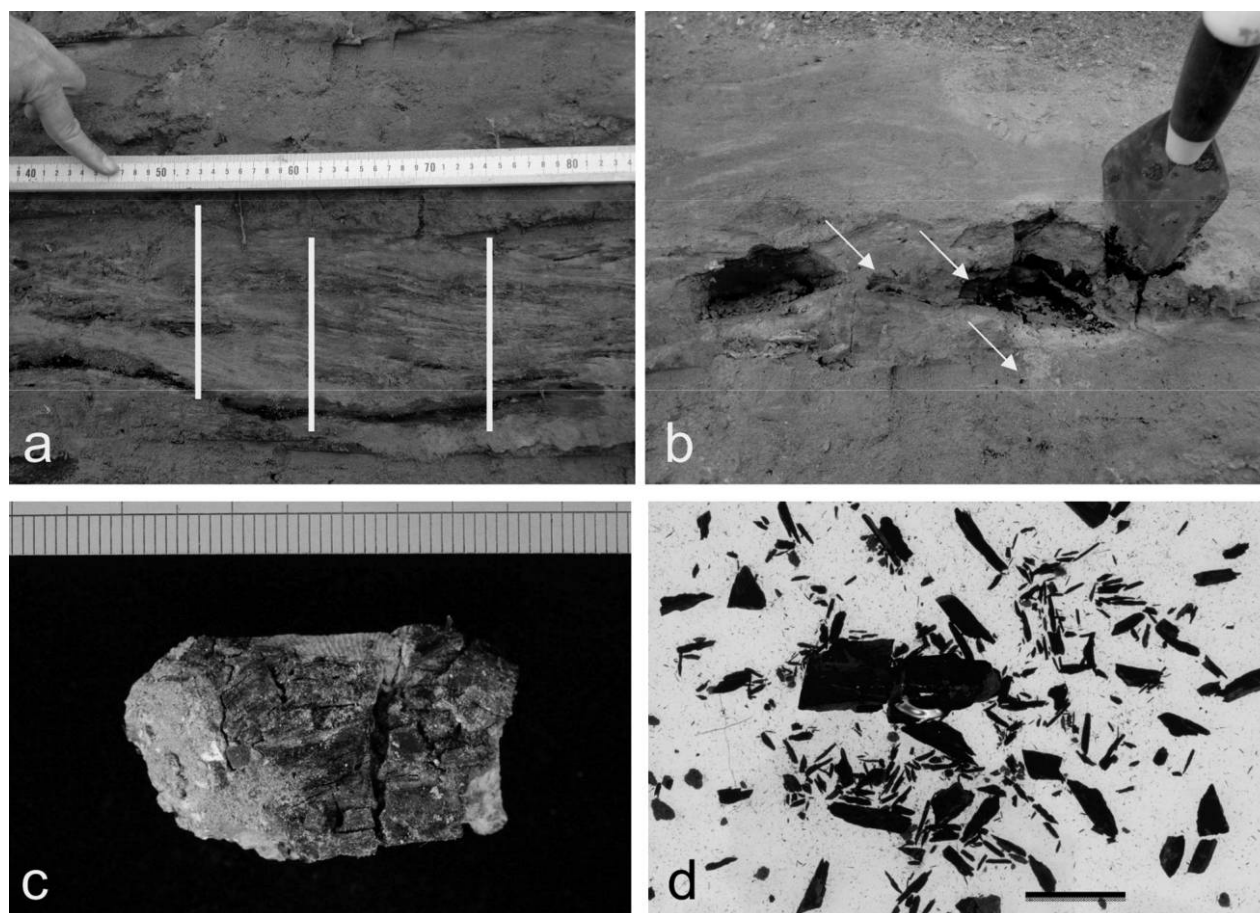


Figure 3. Sediments and carbonaceous fossils from locality III in Arlington Canyon (Scott et al. 2010, 2017), which is also locality as AC003 of Kennett et al. (2008a, 2009a, 2009b) and Wittke et al. (2013b). *A*, Typical distribution of charcoal in the mid sandy layers in the section. Note that the charcoal is strongly related to sedimentary structures and not evenly distributed. Samples taken from each of the three lines would give quantitatively different results. The basal, thicker lens yielded radiocarbon sample SRI 10-56 (Scott et al. 2017), dated $11,095 \pm 30$ cal BP (12,830–13,070 cal BP). *B*, Close-up of the thicker charcoal zone at the bottom of *A*, illustrating the range of charcoal sizes (arrows) from very small <1-mm fragments to pieces >1 cm in fine sands. *C*, A single large charcoal fragment that breaks into many different-sized pieces. *D*, Specimen shown in *C* that was gently sieved in water through a 125- μ m sieve. One piece can break into many hundreds of fragments, making the counting of charcoal fragments meaningless in this context. A color version of this figure is available online.

charcoal records that span the YD onset. Purple circles represent marine sites with charcoal and/or soot spanning the YD onset." The figure, however, shows all publicly available charcoal records with samples spanning the YDC (i.e., sediment was collected and dated to the time interval around the YD) from the Global Charcoal Database. (The Global Charcoal Database [GCDv03_Marlon_et_al_2015.mdb], ver. 3, used by Wolbach et al. [2018b, app.] is not attributed to its source publication [Marlon et al. 2016], which was published at the time the database was made public and before the articles by Wolbach et al. were submitted; regardless of whether this was a conscious omission, it deviates from common practice in scientific publication.) However, the mere ex-

istence of charcoal in a record dated to a time of interest does not mean the site was burning at that time. Every known charcoal record from North America has some charcoal in every sample at every depth. Very rarely, and only in the tropics, have sediment cores been found that contain no charcoal. Therefore, implying that the existence of charcoal in sediments dated to the YDB supports the hypothesis of widespread fires during that time is completely unfounded.

A second problem with the charcoal data analysis is the selection of "clear examples" in figure A10 (Wolbach et al. 2018b). The issue is the absence of an explanation for the criteria used to pick these examples. Marlon et al. (2009), in contrast, graphed all the data that were publicly available at the time.

They explicitly presented alternative selection criteria for assessing whether a particular record showed a peak in burning during the beginning or end (or beginning and end) of the YDC specifically because the choice of selection criteria could have a large influence on whether or not a peak was identified. The results of the transparent analysis presented in Marlon et al. (2009) were a broad peak at the beginning of the YD and a larger peak at the end of the YDC. In addition, frequent, widespread fires at many other times were observed, especially after the YDC because fuel availability increased in the Holocene. The transparency of the methods description in Marlon et al. (2009) is illustrated by the ability of Wolbach et al. (2018b) to reproduce the figure. In contrast, it would not be possible to reproduce the results from Wolbach et al. (2018b) given their current explanation.

As is the case with other analyses in their articles, the attempt of Wolbach et al. (2018b) to elaborate on the analysis in Marlon et al. (2009) focuses on a narrow time window at the beginning of the YDC. This approach misses the large increases in charcoal accompanying the abrupt warming at the beginning of the Bølling-Allerød chronozone (Greenland Interstadial 1 [GI-1], 14,642 BP) and end of the YDC (11,653 BP). Interestingly, in the analyses of both Wolbach et al. (2018b) and Marlon et al. (2009), the increase in charcoal influx begins about 400 y before the beginning of the YDC, contemporaneously with the warming from the middle of the cold substage of GI-1b to the warmer stage GI-1a (Rasmussen et al. 2014). The magnitude of the $\delta^{18}\text{O}$ changes in the GISP2 and NGRIP ice-core records from GI-1a to GI-1b are exceeded only by those at the beginning of the Bølling-Allerød chronozone and end of the YDC, raising the possibility that the increase in charcoal influx that Wolbach et al. (2018b) attribute to the YDIH is actually an instance of the canonical response of biomass burning to abrupt warming (Daniau et al. 2010; Fischer et al. 2015).

Finally, mistakenly conflating the existence of charcoal in YDB-age sediment cores with evidence for large synchronous wildfires is remarkable. Unlike discontinuous sediment profiles commonly used in terrestrial geological and archaeological studies, lake-sediment records capture continuous environmental changes, allowing comparisons between different times to be made easily. Indeed, comparisons to other time periods with similar conditions are integral to any claims of unusual activity. Encountering such errors alongside methodological descriptions that lack basic details essential to interpreting the results invites strong skepticism not only of this specific claim but of the other claims based on the charcoal data analyses more broadly and of the results as a whole.

As the saying goes, once is chance, twice is coincidence, the third time is a pattern.

The record from Linsley Pond (Wolbach et al. 2018b, fig. A11) shows charcoal concentrations rather than influx. Concentrations are not a reliable indicator of burning because sedimentation rates vary over time (see Marlon et al. 2016). What appears to be a peak in concentration can, in reality, reflect flat, rising, or declining charcoal accumulation rates (CHARs), and vice versa. As a result, the conclusion that “the presence of a significant YDB charcoal peak at this site with no corresponding soot peak suggests that soot was once present but was either carried away or not preserved” (Wolbach et al. 2018b, appendix, p. 12) has another possible interpretation. The lack of a soot peak is actually consistent with the lack of a charcoal peak because no unusual burning occurred. We will not know until the data are analyzed properly. Even if there were burning (as suggested by the CHAR reconstructed from black carbon), it was not an unusual amount of burning, as it is comparable to the burning at the end of the YDC (and with so many other records in North America).

Usselo Soil. In a specific example of charcoal claimed to be linked to a YDB-age impact, Wolbach et al. (2018b, p. 190) argue that the charcoal in the Usselo soil, a widespread stratigraphic marker in northwest Europe, is evidence of biomass burning. They follow the assertions of Firestone et al. (2007) and Wittke et al. (2013b) and claim support from Kaiser et al. (2009). However, the geomorphologists and soil stratigraphers who were the principal investigators of the Usselo soil, including Kaiser, clearly demonstrate that the soil is just that: a zone of pedogenic weathering including accumulation of organic matter such as charcoal over time (van Geel et al. 1989; Hoek 1997; Kaiser et al. 2009; van Hoesel et al. 2012, 2014). Hoek (1997) and Kaiser et al. (2009) show that the age of the charcoal spans ~1400 ^{14}C years, consistent with pedogenesis over time. Based on the dating and the evidence for pedogenesis, van Hoesel et al. (2012, p. 7651), van der Hammen and van Geel (2008, p. 360), and Kaiser et al. (2009) all reject the claim that the Usselo soil is a rapidly deposited YDB “event” layer.

Black Mat. Wolbach et al. (2018b, p. 195) note that “the YD onset is marked by a widely distributed deposition of black mat layers across North America” and describe black mats as “sedimentary layers” (p. 188–189). But black mats are much more complex geologic entities, as is clearly explained by Haynes (2008) and clearly shown in his data tables (and as elaborated by Meltzer and Holliday 2010 and Holliday et al. 2014). Wolbach et al. (2018b, p. 195) assert, “The presence of these organic-rich sediments is

consistent with an abrupt episode of large-scale biotic degradation that resulted from YD climate change and a major increase in biomass burning." They simply repeat an unsupported assertion from the original YDIH proposal and completely misstate the work of Haynes (2008). Evidence for burning is mentioned nowhere in his work. Subsequently, Haynes et al. (2010a, p. 4014) noted, "Over the past four decades the lead author has chemically pretreated hundreds of black mat samples for multifracton ^{14}C dating. . . . Very few YD-age black mats were found to contain adequate charcoal." More broadly, deposits similar to the "black mats" of Haynes are documented in sediments both older than and younger than the YDB (Holliday 1995; Quade et al. 1998; Pigati et al. 2012).

Megafauna Extinctions and Human Population Decline

Wolbach et al. (2018b) resurrect, without dealing with abundant contradictory data, fully discredited notions of megafauna extinctions and archaeology as proxy indicators of a YDB catastrophe. Indeed, in their table A3, they list no critics of the notion that extinctions and purported human population declines serve as proxies of the impact. Furthermore, in the initial presentation of the YDIH (Firestone et al. 2006, 2007), those purported phenomena were "explained" by the hypothesis but here and in other contexts seem to be offered as evidence of an impact. They cannot be both.

Wolbach et al. (2018b, p. 200) state, "One focus of this article is to explore whether the megafaunal extinctions were synchronous with the YDB impact event, increased biomass burning, YD climate change, and human population declines. . . . See tables A1 and A2 for previously published studies of the following three standout YDB sites," which are Blackwater Draw, Murray Springs, and Sheridan Cave. Given that the extinction debate tends to focus on a minimum of one continent (e.g., North America) but was a worldwide phenomenon, three sites have little to offer beyond being simply data points. What is telling is the table of "proxies" in support of the YDIH (Wolbach et al. 2018b, table 1), which uses sites tabulated by Haynes (2008) in a discussion of "black mats." In their table, Wolbach and colleagues list 73 of 97 sites as having extinct fauna. Among the extinct fauna included in this tabulation is bison (as the sole extinct mammal at 29 of 97 sites), indicating a significant lack of understanding of late Pleistocene extinctions. As is well documented in the literature and has long been known (e.g., Martin and Wright 1967), bison sur-

vived the extinction and thus have no bearing on the YDB impact debate other than to confound it.

More generally, Wolbach et al. (2018b; following Firestone et al. 2007) repeatedly assert or imply that the extinction of late Pleistocene fauna was synchronous at ~12,900 cal BP. This is a gross oversimplification and a fundamental misstatement of a complex issue that is well documented in the extinction literature (e.g., Barnosky et al. 2004; Grayson 2007, 2016; Gill et al. 2009; Faith 2014; Meltzer 2015; Stuart 2015). Late Pleistocene vertebrate extinctions took place across the Americas, Europe, and Asia and were complex, time-transgressive, and geographically far-reaching (Grayson in Holliday et al. 2014; Stuart 2015). YDIH proponents have invoked a YDB-age cataclysm to explain the extinctions but have never attempted a coherent argument outlining how an impact at ~12,900 cal BP could explain what is known about the extinctions in time and space.

Long at the heart of the extinction debate is the question of why some species were wiped out but not others (e.g., bison; see, e.g., Meltzer 2015). More germane to the YDIH is the evidence in North America and on other continents of extinction of some species before 12,900 cal BP but not others and the evidence for declining mammal populations preceding the YDB (e.g., Gill et al. 2009; Grayson 2016). In North America, only 17 of the 37 genera of mammals lasted to between 13,000 and 11,500 cal BP (Grayson 2016, p. 177, based on his table 4.2). Another five genera have last appearance dates of >24,000 cal BP, and 13 genera have no reliable radiocarbon control. "Megafaunal populations collapsed from 14,800 to 13,700 years ago, well before the final extinctions" (Gill et al. 2009, p. 1100). These data clearly contradict the assertion that some specific event wiped out a specific subset of mammals across North America at ~12,900 cal BP. The timing of extinctions around the rest of the world was more varied in both time and space (Barnosky et al. 2004; Stuart 2015).

The notion that the YDB ended the "Clovis culture" and was linked to "the decline in other paleo-human populations across the Northern Hemisphere" (Wolbach et al. 2018b, p. 196) has been a component of the YDIH canon, like the extinction issue, since the initial publications on the YDIH. Firestone et al. (2006, p. 113) claim, for example, that Paleoindian sites in the southeastern United States are "well-dated" and provide evidence of a population decline just after the Clovis occupation. Those assertions are not true. Numerical-age control or even basic stratigraphic relations for Paleoindian archaeological sequences in the Southeast are almost nonexistent (Anderson et al. 2011, p. 572; Miller and Gingerich 2013; Miller et al. 2013), although the work

of Anderson et al. (2011) is listed in the “proponent” category in table A3 of Wolbach et al. (2018a).

No data based on dated regional records of in situ archaeological materials have been offered as evidence of a population decline. Echoing Kennett and West (2008), Wolbach et al. (2018b, p. 200) argue that the absence of a post-Clovis occupation at the Murray Springs site in Arizona is evidence of a population decline. Never mentioned or addressed by Wolbach and colleagues or any of the YDIH proponents are data and arguments (Holliday and Meltzer 2010; Holliday et al. 2014) that clearly dispense with the idea of a population decline or occupation hiatus based on abundant field and radiometric data. In a sample of 156 buried, dated Paleoindian sites from Clovis through late Paleoindian times, more than two-thirds (105), from all time periods, are single-occupation sites (Holliday and Meltzer 2010)—that is, Paleoindian foragers typically did not repeatedly occupy the same site. The absence of subsequent occupations at Clovis sites, just like the absence of subsequent occupations at Folsom or other Paleoindian sites, is meaningless beyond archaeological issues of land-use choices.

Likewise, there are no mysterious gaps in post-Clovis occupations. In discussing the Blackwater Draw site, Wolbach et al. (2018b, p. 200) refer to “the last known bones of mammoths killed by Clovis hunters, who then abandoned the site for hundreds of years,” suggesting a “human population decline.” This strange myth of a lengthy occupation hiatus was put forward by Firestone et al. (2006, p. 73) and Kennett and West (2008). A cursory examination of the abundant literature on this famous site quickly dispels the notion. No stratigraphic or chronologic data exist to indicate a post-Clovis population decline.

A consistent problem in many of the arguments in support of the YDIH, going back to the book by Firestone et al. (2006), is failure to consult or understand dating, stratigraphy, and soils at sites investigated by others (e.g., Bull Creek, Murray Springs, Blackwater Draw, Chobot, Gainey, Topper, Lindenmeier, Usselo soils). Likewise, there is a persistent failure to consider the voluminous data on Paleoindian archaeology and the extinction debate. YDIH proponents present few arguments to counter the work and interpretations of others regarding all of these sites and issues.

Fundamental Problems and Questions

Is an exceptional explanation for the YD climate reversal (YDCR) necessary? The answer would be yes, if any of a number of conditions were met: (1) uniqueness of climate reversals during the most recent gla-

cial termination; (2) absence of alternative explanations for the climate reversal; (3) failure of a particular explanation to account for concurrent paleoenvironmental changes; or (4) uniqueness in the responses of those environmental systems and processes thought to have direct dependence on some exotic agency. As to the first condition, climate reversals are recurring features of glacial-interglacial transitions (e.g., Broecker et al. 2010; Capron et al. 2014; Martrat et al. 2014; Govin et al. 2015; Menviel et al. 2018). The YDCR is unique because it is within the range of radiocarbon and ice-core annual layer-counting dating and is recorded by high-resolution paleoenvironmental indicators that simply do not extend back to previous glacial transitions.

As to the second condition, the most common explanation for the origin of the YDCR remains the impact of a large meltwater pulse from the rapid drainage of Lake Agassiz to the North Atlantic, which would plausibly reduce the strength of the Atlantic Meridional Overturning Circulation and initiate cooling in the North Atlantic and adjacent regions. Leydet et al. (2018) demonstrate the existence of an ice-free path to the North Atlantic at the right time and with appropriate geochemical signals in sediments derived from the Mackenzie, St. Lawrence, and Mississippi River drainages. As with the notion of human population decline (Holliday and Meltzer 2010, p. 575), the YDIH solves a problem that does not exist.

There are other candidate explanations. More than a century ago in the pages of this journal, T. C. Chamberlin (1897, 1899) demonstrated the utility of the method of multiple working hypotheses (Chamberlin 1890) for guarding against confirmation bias. For example, an alternative explanation for the YDCR that seems exceptional at first glance is the climatic effect of the Laacher See volcanic eruption at $12,880 \pm 40$ BP (Baldini et al. 2018). Like the YDIH, an external (to the climate system) event is proposed as a trigger for the YDCR (and note this eruption could also account for some of the proposed impact evidence). What makes this explanation unexceptional is that, unlike comet impacts, the frequency of volcanic eruptions sufficient for producing YD-like reversals is such that “at least one high-latitude M6 eruption likely occurred during most deglacial intervals” (Baldini et al., p. 982). Their discussion provides an illustrative example of the consideration of multiple hypotheses (including the YDIH) in practice.

The third condition pointing to an exceptional explanation for the YDCR would hold if alternative explanations failed to account for the full range of paleoenvironmental changes that occurred during the YDC or if the alternative explanations had no mechanistic basis. Until recently, for example, climate-model

experiments had difficulty in accounting for some well-documented components of environmental change during the YDC, such as the evidence for warmer-than-present summers in Europe. This issue too seems to be diminishing in importance, as climate models (and the appropriate experimental designs) have increased in both resolution and sophistication (Renssen et al. 2018; Schenk et al. 2018).

The last condition that would require an exceptional or special explanation for the YD is illustrated by the relationship between biomass-burning indicators and climate over the 26 Greenland Stadial/Interstadial variations over the last glacial cycle. If the beginning of the YDC really was marked by exceptional peaks in biomass burning indicators, whereas all other times of cooling equivalent to that at the beginning of the YDC were not, then a case could be made for something exotic happening at the beginning of the YDC. Instead, high-resolution ice-core records (Fischer et al. 2015; Schüpbach et al. 2018) and low-resolution charcoal records (Daniau et al. 2010) converge in providing evidence for increases in fire accompanying times of abrupt warming and low levels of biomass burning during cool intervals.

Completely missing in Wolbach et al. (2018*a*, 2018*b*) and in other publications supporting the YDIH is discussion of changes to the landscape besides purported massive wildfires. The instant and cataclysmic alterations of climate, flora, and fauna that are hypothesized should manifest themselves in paleobiological, geomorphologic, and stratigraphic records; however, they do not. The literature on YDC (and preceding and superseding) conditions in unglaciated North America south of the continental ice

sheets is extensive (e.g., Orme 2002; Easterbrook 2003; Gillespie et al. 2004; Straus and Goebel, 2011; Bousman and Vierra 2012; Eren 2012; Holliday and Miller 2013). The landscape of North America from the post-LGM terminal Pleistocene into the early Holocene underwent rapid reorganization because of warming and related climate changes; melting of glaciers; rise in sea level; and changes in alluvial, eolian, and lacustrine geomorphic systems and in plant and animal communities. However, the magnitude, direction, and pace of change in each of these systems varied in time across the continent. Most purported evidence for a YDB disaster is at only the particulate and molecular scales. With the exception of some fauna, field records provide no evidence whatsoever of continent-wide catastrophic changes at ~12,900 cal BP.

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