Chronological evidence fails to support claim of an isochronous widespread layer of cosmic impact indicators dated to 12,800 years ago

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According to the Younger Dryas Impact Hypothesis (YDIH), ∼12,800 calendar years before present, North America experienced an extraterrestrial impact that triggered the Younger Dryas and devastated human populations and biotic communities on this continent and elsewhere. This supposed event is reportedly marked by multiple impact indicators, but critics have challenged this evidence, and considerable controversy now surrounds the YDIH. Proponents of the YDIH state that a key test of the hypothesis is whether those indicators are isochronous and securely dated to the Younger Dryas onset. They are not. We have examined the age basis of the supposed Younger Dryas boundary layer at the 29 sites and regions in North and South America, Europe, and the Middle East in which proponents report its occurrence. Several of the sites 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, and in several the ages directly on the supposed impact layer are older or younger than ∼12,800 calendar years ago. Only 3 of the 29 sites fall within the temporal window of the YD onset as defined by YDIH proponents. The YDIH fails the critical chronological test of an isochronous event at the YD onset, which, coupled with the many published concerns about the extraterrestrial origin of the purported impact markers, renders the YDIH unsupported. There is no reason or compelling evidence to accept the claim that a cosmic impact occurred ∼12,800 y ago and caused the Younger Dryas.

Clovis | black mat | chronology | Pleistocene extinctions

The Younger Dryas Impact Hypothesis (YDIH) proposes that at 12,800 ± 150 (or 12,900 ± 100) calendar years before present (cal B.P.), North America experienced an extraterrestrial event variously described as an impact (or impacts), airburst (or airbursts), or some combination thereof (1, 2). [In earlier publications, 12,900 ± 100 calendar years before present was identified as the age of the YDB, based on the IntCal04 radiocarbon calibration curve. YDIH proponents subsequently changed the YDB date after introduction of IntCal09. Such a change is fully appropriate, given the refinements in the calibration (IntCal09 has now been superseded by IntCal13, but we do not use the latter to insure analytical comparability [*Methods*]). In discussions of specific sites we use the same calibration curve as the original work. Where relevant, radiocarbon ages are presented both as ^{14}C years B.P. and in calibrated years (cal B.P.).] This event is claimed to have been so significant that it abruptly triggered the global onset of the Younger Dryas (YD), a millennium-long cooling episode that interrupted the warming that had been taking place as the Pleistocene came to an end and in North America ostensibly ignited continent-wide wildfires, caused the extinction of several dozen genera of Pleistocene mammals, and led to the termination of the Clovis culture (ref. 2, p. 16021), the earliest archaeologically well-documented group occupying the continent. First introduced in a popular book in 2006 (1) and soon thereafter to the scientific community (2), YDIH proponents have offered geological and geochemical evidence of an extraterrestrial impact from localities in and outside of North America (3–11). Independent investigators have provided support as well (12, 13).

According to YDIH proponents, that cosmic event is marked in terrestrial deposits by magnetic grains with iridium, magnetic microspherules, charcoal, soot, carbon spherules, glass-like carbon containing nanodiamonds, and fullerenes with extraterrestrial helium (cf. refs. 14–15). High concentrations of these indicators are said to be found in "a thin, sedimentary layer (usually <5 cm)" that they label the Younger Dryas boundary (YDB) layer (ref. 2, p. 16,017). The YDB is reportedly capped at some sites by a carbon-rich layer likened to the black mat previously identified by Haynes (16). The YDB is said to represent the extraterrestrial impact, and the black mat is said to represent subsequent impact-related processes "such as climate change and biomass burning" (ref. 2, p. 16,019). YDIH proponents claim that the supposed YDB layer is securely dated to a 300-y span centered on 12,800 cal B.P. (or a 200-y span centered on 12,900 cal B.P. depending on the calibration used).

From the outset the YDIH has been highly controversial. The reproducibility, reliability, and validity of the impact indicators have been challenged, not least because many of these may be terrestrial in origin (possibly volcanic, organic, or detrital) and have been found in deposits younger and older than the YD (14, 15, 17–27). Others have questioned the physics of the supposed impact and whether it could or did have consequences for Late Pleistocene environments, animals, and people (26, 28–32).

One key test of the YDIH, however, has been largely lacking: whether the supposed YDB layer securely dates to the Younger Dryas onset (27, 33). Knowing its precise age and demonstrating that it is isochronous across sites that reportedly extend from

Significance

A key element underpinning the controversial hypothesis of a widely destructive extraterrestrial impact at the onset of the Younger Dryas is the claim that 29 sites across four continents yield impact indicators all dated to 12,800 ± 150 years ago. This claim can be rejected: only three of those sites are dated to this window of time. At the remainder, the supposed impact markers are undated or significantly older or younger than 12,800 years ago. Either there were many more impacts than supposed, including one as recently as 5 centuries ago, or, far more likely, these are not extraterrestrial impact markers.

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North America to South America and Europe (Table 1) are critical to the claim this was an instantaneous event. YDIH proponents themselves recognize this: “The apparent suddenness of the event that occurred at the onset of the YD requires investigations of very high chronological resolution to test the hypothesis.” Accordingly, they recommend “analysis of existing stratigraphic and chronological datasets, removing erroneous radiocarbon dates that have large error margins…or other problems” (ref. 34, p. 2531). We provide just such an analysis here.

We systematically examined the chronologies of the supposed YDB layer at the 29 sites asserted in multiple sources (2, 3, 5–11) to have evidence of a cosmic impact; our efforts included cross-checking original sources used by YDIH proponents. We find that the supposed YDB layer dates to the onset of the Younger Dryas at only 3 of those 29 sites. The remainder, many with radiocarbon and/or luminescence ages, fail to provide reliable or valid chronological control for the supposed impact indicators. [The luminescence ages include optically stimulated luminescence (OSL) ages and (at Gainey site) thermoluminescence ages (TL). These are equivalent to calibrated radiocarbon ages and denoted here as years B.P. With luminescence ages, present refers to calendar years before the year of measurement, not before 1950 as with radiocarbon years. At the time scale under discussion, that difference is inconsequential.]

Results

A graphic summary of our analyses and results is shown as a flowchart (Fig. 1) which sorts sites by the availability of radiometric/numeric ages, then the type of age control (if available) on the supposed YDB layer, and finally whether that age control is secure. The discussion that follows is organized according to Fig. 1. Because chronological data and circumstances vary by site, each is discussed individually. Further details on the sites and our analyses are provided in *SI Appendix*.

We begin with the three sites that lack absolute age control (Fig. 1, group 1a). Impact indicators at the Chobot site (Alberta) are said to be consistent with an age of 12,800 cal B.P. based on their occurrence “beneath a carbon-rich black mat/layer” and above a zone “containing abundant Clovis points and artifacts” (ref. 10, SI p. 7). However, the black mat is “simply the surface leaf litter,” and only three Clovis points—none in stratigraphic context—have been found (35). More telling, Chobot is a stratigraphically mixed near-surface site where the majority of diagnostic artifacts are younger than Clovis by thousands of years. Even if it were the case that Clovis projectile points were sufficiently restricted in time to date a site to within 200–300 y of the YD onset, and they are not (30, 36), their ambiguous context at Chobot provides no age control.

The Morley site (Alberta) is a drumlin formed beneath the Cordilleran ice sheet that “appears to be” ∼13.0k years old (ref. 2, SI table 2). However, its age is based on its supposed chronological correlation with drumlins ∼2,600 km away near Lake Ontario (5) and which were formed by a separate continental ice sheet (the Laurentide). No effort was made nor was evidence provided to show that these drumlins half a continent apart were precisely contemporaneous (which is highly unlikely), let alone that they demonstrate that the Morley drumlin dates to ±150 y of the YD onset.

Table 1. Sites reportedly dated to the onset of the Younger Dryas and yielding impact markers

Site	Basis for age estimation (^{14}C calibration used)*	Fig. 1 group	Ref(s).
Abu Hureyra, Syria	^{14}C ages (IntCal 04)	3a	3, 10
Arlington Canyon, CA	^{14}C ages (IntCal09)	3a	8, 10, 34
Barber Creek, NC	OSL and ^{14}C ages (IntCal09)	3a	3, 10
Big Eddy, MO	^{14}C ages (IntCal04)	3b	3, 10
Blackville, SC	OSL ages	3a	3, 10
Blackwater Draw, NM	^{14}C ages (IntCal04)	3a	1, 3, 5, 9, 10–11
Bull Creek, OK	^{14}C ages (IntCal09)	3c	7, 63–64
Carolina Bays, NC and SC	OSL ages	2a	1, 2, 5
Chobot, Alberta, Canada	No radiometric control	1a	2–3, 5, 10
Daisy Cave, CA	^{14}C ages (IntCal04)	3d	2, 5
Gainey, MI	TL and ^{14}C ages (IntCal09)	2a	2–5, 10–11
Kangerlussuaq, Greenland	O-isotope curve and dust stratigraphy	2a	13, 41
Kimbel Bay, NC	OSL and ^{14}C ages (IntCal09)	3a	3, 10
Lake Cuitzeo, Mexico	^{14}C ages (IntCal04)	3a	3, 6, 10
Lake Hind, Manitoba, Canada	^{14}C ages (IntCal04)	3d	2, 7, 10
Lingen, Germany	^{14}C ages (IntCal09)	2a	3, 10
Lommell, Belgium	^{14}C ages (IntCal04 in 2; IntCal09? in others)	3c	2–3, 5, 10–11
Melrose, PA	OSL ages	3a	3, 10–11
Morley, Alberta, Canada	No radiometric control	1a	2, 10
MUM7B, Venezuela	^{14}C ages (IntCal04)	2a	12
Murray Springs, AZ	^{14}C ages (IntCal04)	3a	1–3, 7, 10–11
Newtonville, NJ	OSL age	2a	11
Ommen, Netherlands	^{14}C ages (IntCal09?)	3c	3, 10
Paw Paw Cove, MD	No radiometric control	1a	9
Playa Basins, NM and TX	^{14}C ages (IntCal04)	2a	1, 4
Sheridan Cave, OH	^{14}C ages (IntCal04)	2a	3, 10–11
Talega, CA	^{14}C ages (IntCal09)	3a	3, 10
Topper, SC	OSL and ^{14}C ages (IntCal09)	3a	2–3, 9–10
Wally’s Beach, Alberta, Canada	^{14}C ages (IntCal04)	2a	2, 5

With IntCal04 the Younger Dryas onset is put at 12.9 ± 0.1 kcal B.P.; it is 12.8 ± 0.15 kcal B.P. using IntCal09.

*The calibration curve used (whether IntCal04 or IntCal09) and program to derive the calibrated ages (whether CALIB, OxCal, CalPal, etc.) are only occasionally specified in the sources. We were not able to otherwise identify the calibration by replication; hence, the identification of the calibration that was used is based on the best available evidence, such as when a paper appeared relative to the available calibration.

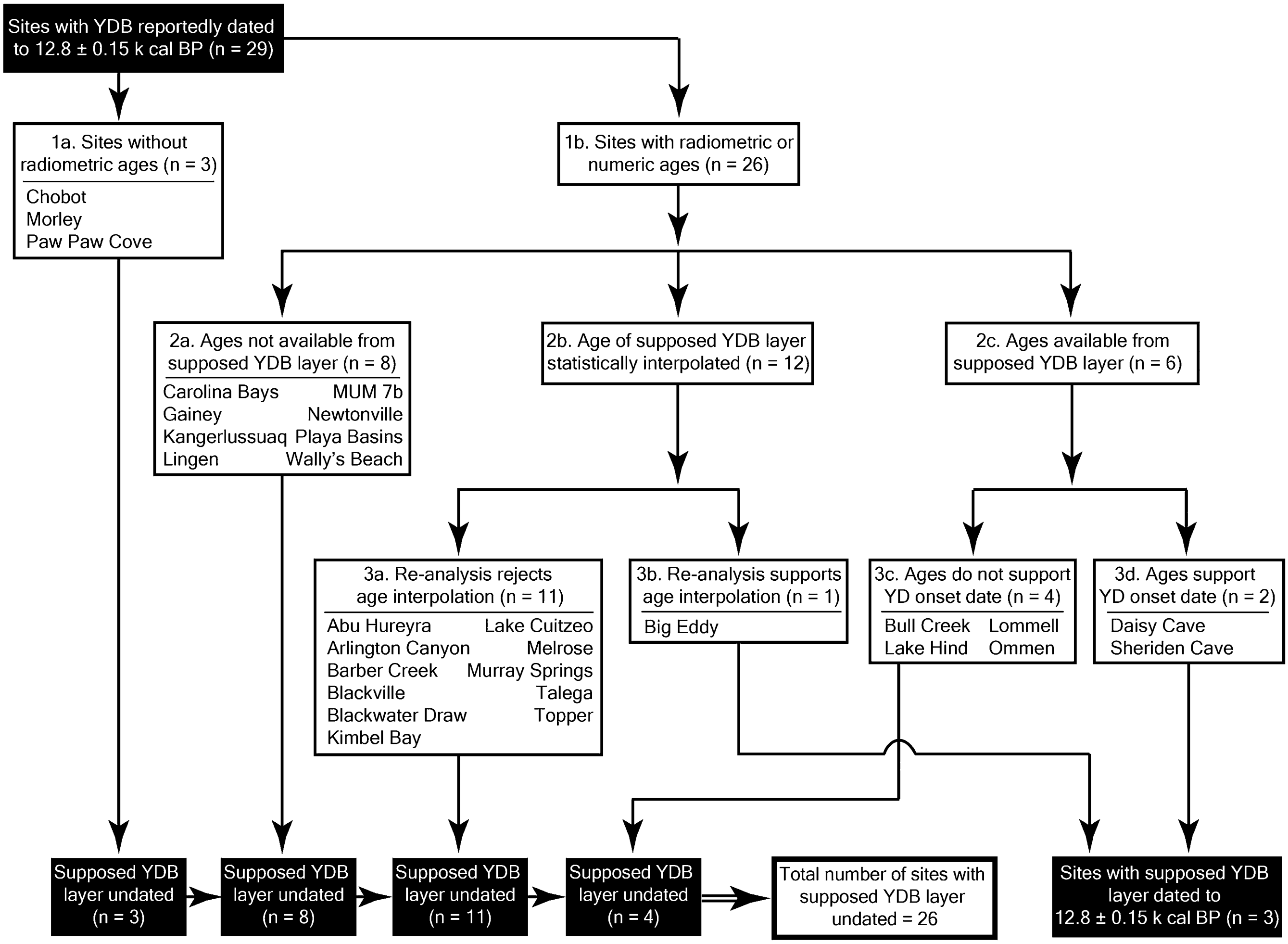

Fig. 1. Flowchart showing the 29 sites reported to have impact markers dated to the onset of the Younger Dryas. The sites are sorted by the availability of radiometric/numeric ages and then grouped according to the type of age control (if any) on the supposed YDB layer. The bottom level provides the aggregate results of the analysis reported here.

At Paw Paw Cove (Maryland), LeCompte et al. "obtained a sample from a stratigraphic section represented by Darrin Lowery, the principal site archaeologist, as most likely to contain YDB proxies, based on his knowledge of the site" (ref. 9, E2961). Their inferred YDB layer contained Clovis artifacts atop a highly eroded paleosol and buried by a layer of loess. However, Lowery indicates that the section is undated, and "given the evidence for a deflation event…the horizontal integrity of the Clovis occupation at Paw Paw Cove was…compromised." Lowery makes a similar statement regarding its relative stratigraphic position: "The Clovis-age stone artifacts at Paw Paw Cove also seem to represent a cultural lag deposit, which was subsequently buried by loess" (ref. 37, p. 57). There is no layer at Paw Paw Cove known to date to the Younger Dryas onset.

The remainder of the sites ($n = 26$) have radiometric or other potential numeric ages, yet in only a very few can those ages be used to determine the date of a supposed YDB layer.

At eight of those sites (Fig. 1, group 2a) the available ages are unrelated to the supposed YDB layer. Firestone et al. (1) initially suggested that the Carolina Bays dated to 12,900 y B.P. based on an OSL age of 11,400 ± 6,100 y B.P. that they obtained and two OSL ages of ~11,300 and ~12,630 y B.P. that they attributed to Ivester et al. (38). Firestone et al. (2) subsequently admitted that the ages of the Carolina Bays vary but then suggested that because sediment from 15 Carolina Bays contained supposed impact markers and because such impact markers occur only in the supposed YDB layer and were "identical to those found elsewhere in the YDB layers that date to 12.9 ka," the supposed YDB layer in the Carolina Bays must be the same age (ref. 2, p. 16019). Such circular reasoning assumes what it ought to demonstrate and fails to date the supposed YDB layer in the Carolina Bays.

Gainey (Michigan) is a near-surface plowed site with badly mixed deposits (39), yet is reported by Wittke et al. to contain a discrete YDB layer at 30 cm below surface that corresponds to an OSL age of 12,360 ± 1,240 y B.P. from that same approximate depth (10). In fact, there are two ages from Gainey (the other is 11,420 ± 400 y B.P.); both are TL dates (not OSL dates) on burned chert artifacts (40). However, those artifacts were not piece plotted (39), and given the extensive stratigraphic mixing at the site, it is impossible to know their position relative to the supposed YDB layer. Although the older of the two ages overlaps with the Younger Dryas onset, its very large uncertainty provides no temporal resolution. Perhaps most telling, direct dating of carbon spherules from Gainey—its supposed impact indicators—yielded ages of −135 ± 15 ^{14}C years B.P. (ref. 4, table 3) and 207 ± 87 ^{14}C years B.P. (17). This makes Gainey one of the few sites where the YDB is directly dated, although to sometime after the 16th century A.D., not the Younger Dryas onset.

Kurbatov et al. (41) report YDB-age impact markers (nanodiamonds) on the thinned western margin of the Greenland ice sheet near Kangerlussuaq. Age control of a "potential postglacial peak" of nanodiamonds found below dusty ice (suspected to be from an "episode of cooling that may represent the YD") was based on dust stratigraphy and δ^{18}O values reported to "generally correspond to the distinctive sequence of warming/cooling episodes" of the terminal Pleistocene recognized in the deep ice cores of central Greenland (ref. 41, p. 751 and fig. 5). However, they admit that their samples were "taken at relatively coarse resolution," and because their locality is at the thin margins of the ice sheet, they recognize "more precise dating and more detailed geochemical time-series measurements are needed" (ref. 41, p. 757). Until then, the reported nanodiamond peak cannot be securely ascribed to the YD onset.

The Lingen (Germany), Lommell (Belgium), and Ommen (The Netherlands) sites are grouped in discussion by YDIH proponents because each has an exposure of the Usselo soil, a widespread buried soil formed in eolian cover sand across northern Europe. The Usselo soil at these sites is reported to contain an abundance of charcoal marking widespread biomass burning and a variety of impact indicators (5) (one source, however, states that impact indicators "peak *beneath* the Usselo layer [which is] the European analog to the black mat" [ref. 10, pp. 40–41]). The Usselo soil at Lingen, Lommell, and Ommen is placed at the Younger Dryas onset "based on [its] known regional age" (ref. 10, SI pp. 11–12). The cited regional age is a single radiocarbon date of 10,950 ± 50 ^{14}C years B.P. [1 sigma range: 12,896–12,715 cal B.P. (IntCal09)] from the Usselo type site in The Netherlands (42).

Relying on that single age is problematic: the Usselo soil is not an event specific to a narrow window of time but was formed over ~1,400 radiocarbon years as a result of pedogenic processes that began well before and continued into the Younger Dryas (43, 44). Charcoal within the Usselo layer, as van Hoesel et al. (45) demonstrate at Aalsterhut, can even postdate the Younger Dryas onset by 200 y. Thus, the single age for the soil at the type site cannot be applied uncritically to other otherwise undated sites. To demonstrate that the supposed YDB layer at Lingen was deposited at the YD onset requires direct dating (46), but no such dates are available. There is an age of 11,310 ± 60 ^{14}C years B.P. [1 sigma range:13,261–13,138 cal B.P. (IntCal09)] from a sample obtained 9 cm below the supposed YDB layer, but that only indicates that the layers above it are younger, not how much younger. Hence, the age of Lingen's purported impact markers is unknown (Lommell and Ommen have dates on the supposed YDB layer and are discussed with group 3c sites).

Mahaney et al. (12) report the occurrence of a black mat at MUM7B (Venezuela) with impact indicators. Although MUM7B has several radiocarbon dates, none are from the black mat (47). The youngest predates 13,200 cal B.P., and all are from ~18–25 cm deeper in the section. The only basis for the inference that the MUM7B black mat is "well within the YD window" is that it appears "coeval with 'black mat' sites in North America" (ref. 47, p. 53). However, not all black mats are the same age: some predate the Younger Dryas period by several thousand years, and others formed through the Holocene and are thousands of years younger (21, 30, 48). The MUM7B black mat cannot be dated to the YD onset on this chronologically indefinite basis.

The Newtonville (New Jersey) site is a sand pit in which two sand layers are exposed; the upper is described as a black mat (11). Two 10-cm–thick samples for impact indicators were collected: one immediately above and the other immediately below the boundary separating the sand layers. A single OSL age of 16,800 ± 1,700 y B.P. was obtained from the lower layer; there is no age control on the upper layer (11). The inferred YDB layer is at the base of the supposed black mat. Given the thickness of the samples, the lack of bracketing ages, and the fact that the older underlying layer yielded more magnetic microspherules/kilogram than the presumed YDB layer (ref. 11, SI p. 1), the most that can be concluded is that Newtonville remains undated and may even provide evidence of supposed impact indicators occurring well before the YD onset.

The playa basins of the Great Plains are presented as features "blown out of the soft earth by flying debris" from an impact, their age supposedly "consistent with the date of the [YD] Event" (ref. 1, pp. 217–218). However, the geological origins and age of the playas as originally reported by Holliday et al. (49) were misstated by Firestone et al. (ref. 1, pp. 216–217): these are not impact features or YD in age. In fact, the original investigation and more recent work (50) shows that most playa basins formed >14,000 cal B.P. (some even earlier) and are thus substantially older than the Younger Dryas. Moreover, at least one of these playas contained a Clovis mammoth bone bed (51, 52), but it should not, given the claim (1) that the supposed playa-producing YD impact is said to postdate Clovis.

The last group 2a site is Wally's Beach (Alberta), said to yield impact markers in sediment from the skull of an extinct horse. A radiocarbon age of 10,980 ± 80 ^{14}C yrs B.P. [12,966 ± 61 cal B.P. (ref. 2, table 2)] is used to date the markers. Not mentioned, however, is that this radiocarbon age was from an extinct musk ox at Wally's Beach (53). The fossil yielding the supposed impact markers was not dated, nor is there is evidence to suggest that the fossils from Wally's Beach are all of the same age: in fact, a horse fossil at this same site yielded an age of 11,330 ± 70 ^{14}C yrs B.P. (53), predating the Younger Dryas onset by several centuries. Most important, the fossil bone date may be irrelevant: the critical yet unknown age is when sediment filled the cranium. That would depend on when the carcass decomposed and its skull cavity opened, which could have occurred more than once over the next ~10,000 y as the skull was swept clean of sediment and refilled. The supposed YDB markers at Wally's Beach are undated.

There are a dozen sites (Fig. 1, group 2b) for which radiometric ages are available and for which various regression models (linear, logarithmic, and polynomial) were used by YDIH proponents to derive an age–depth model for a stratigraphic section and thus interpolate the depth and age of the supposed YDB layer (3, 6, 10). We have reanalyzed those data and find that the chronological results at all but one of the sites (Big Eddy, as further discussed in the next section) are neither reliable nor valid.

The ages for the supposed YDB layer at the 11 sites in Fig. 1, group 3a, are discussed as a group because overlapping subsets of them share four significant flaws with their age–depth regression data and analyses: ages are omitted from the models without explanation or justification; depth measures are arbitrary; the regression results cannot be replicated even using the same age–depth data and in most cases are statistically insignificant; and, perhaps most critically, the statistical uncertainty that necessarily accompanies all radiometric dates (luminescence ages have at least 10% error) is altogether ignored. We discuss each of these flaws and their consequences in turn.

First, a review of the original reports for 7 of these 11 sites reveals that radiometric ages closely bracketing and at some sites directly on the supposed YDB layer were omitted from the age–depth analysis by YDIH proponents without explanation or justification (this is also true of other sites not in this group, as noted below in regard to Sheriden Cave). [This tally does not include ages for which explanations are provided for the omission, such as the Arlington Canyon dates thought to be unreliable as a result of the old wood effect (34).] Those sites with ages omitted without explanation are Abu Hureyra (n = 3 omitted ^{14}C ages), Arlington Canyon (n = 4 ^{14}C ages), Barber Creek [n = 10 ages (4 OSL and 6 ^{14}C)], Blackwater Draw (n = 16 ^{14}C ages), Murray Springs (n = 41 ^{14}C ages), Talega (n = ~4 ^{14}C ages), and Topper (n = 7 OSL ages). These arbitrary omissions, particularly in cases such as Blackwater Draw and Murray Springs where only 5 and 7 radiocarbon ages were used out of the 21 and 48 available (respectively) on the relevant strata, renders any age–depth calculations questionable, if not invalid.

Second, at four of the sites—Abu Hureyra, Blackwater Draw, Murray Springs, and Topper (Table 2)—the samples examined for supposed impact indicators were collected at places that were tens; scores; or in two cases, Blackwater Draw and Murray Springs, hundreds of meters from where the samples yielding the dates were obtained. At Blackwater Draw, for example, which has complex and topographically highly variable stratigraphy, the supposed impact markers were collected no closer than ~60 m from four of the radiocarbon ages used and ~175 m distant from the fifth. At Murray Springs, the radiocarbon dates were obtained from seven different locations ~120–250 m distant and at varying elevations from where the supposed impact markers were obtained. Age–depth analysis assumes that depths have been precisely measured and are on the same vertical scale. Ideally, all samples for dating and examination for supposed impact indicators should come from the same stratigraphic column; less than ideal but arguably still acceptable would be where the site stratigraphy is relatively level and uniform, making samples from multiple locations more or less on the same scale. These sites fail to meet either criterion.

At Abu Hureyra, Blackwater Draw, Murray Springs, and Topper, spatially scattered ages, although varying in absolute elevation and distance from one another, were reportedly integrated by Wittke et al. onto a common absolute vertical scale (ref. 10, SI pp. 7 and 14). The manner in which the integration was done is not specified, nor is it apparent that it can be justified given the topographic and stratigraphic complexity of these sites. This renders the scale of these interpolations entirely arbitrary and with it their statistical results. Indeed, if the arbitrarily assigned depth is changed by as little as ~10 cm, the result from the age–depth regression can vary by multiple centuries (as is the case with Abu Hureyra).

Third, the regression results presented or implied but not shown are largely irreproducible at virtually all of these sites (Tables 2 and 3), even using the same data and methods [as best as those data and methods can be inferred because methods and in some cases data are not specified, especially in Wittke et al. (10)]. In our regression replications, we use the same ages YDIH proponents use (and correspondingly omit the same ages they omit) and also use their radiocarbon calibration results. We present the results of regression models to predict the depth of deposits that date to the YD onset (i.e., depth is the dependent variable; Table 2) and of models to predict the age of layers identified as having YDB impact markers (i.e., age is the dependent variable; Table 3). We do this in part because it is often unclear which of these two approaches was taken in the original analyses of YDIH proponents and in part because the results of each approach are relevant in some cases.

There are a few sites in this group for which we are able to replicate the originally interpolated depths for YDB-age deposits or at least come close (Table 2): our results for Blackwater Draw, Melrose, Murray Springs, and Topper are within 3 cm or less of previously reported depths for the proposed YDB layers. Our results for other sites, however, vary substantially, including differences on the order of tens of cm for Abu Hureyra (depending on which of two different depths provided for the supposed YDB layer at this site is used) and Arlington Canyon. Two other sites warrant brief comment.

At Lake Cuitzeo (Mexico), Israde-Alcántara et al. applied a fifth-order polynomial regression to derive a depth for YDB-age sediments; they state that this regression provides a result of ~270–290 cm below surface (6). However, when the equation they provide is solved ($y = -5\text{E}{-}07x^5 + 6\text{E}{-}05x^4 - .0025x^3 + .0366x^2 - .0108x + .512$; solved for $x = 12.9$ kcal B.P.), the predicted depth of the YDB is actually 258 cm below surface, at least 12 cm above their reported depth. Further, using their same data (6), our fifth-order polynomial regression returned a different equation ($y = -6\text{E}{-}20x^5 + 8\text{E}{-}15x^4 - 3\text{E}{-}10x^3 + 6\text{E}{-}06x^2 - 0.0205x + 93.278$; solved for $x = 12{,}900$ cal B.P.) that puts YDB-age deposits at a depth of 259.33 cm below surface, also well above the depth presumed to mark the YD onset (see also ref. 33).

At Talega (California), the age–depth model produced by second-order polynomial regression reportedly supports an age of 12,800 cal B.P. for a supposed YDB layer at 15 m below surface (10). However, multiple attempts to reproduce a second-order polynomial age–depth model resembling the one shown in

Table 2. Calibration, sampling, and age–depth model information for sites in Fig. 1, group 3a, with results of attempts to replicate proposed depths of YDB-age deposits

Site	Originally reported ^{14}C calibration*	Radiometric ages from ~same column as samples for impact markers?†	Regression method used in original YDB depth calculation	Depth of proposed YDB layer originally reported (midpoint)	Recalculated predicted depth of YDB-age deposits	Depth difference (column 6 minus column 5)
Abu Hureyra‡	IntCal04	No, depth scale arbitrary	Linear	284.29 masl	284.63 masl	34 cm
				284.70 masl	284.63 masl	−7 cm
Arlington Canyon	IntCal09	Yes	Linear	500.50 cmbs	441.14 cmbs	−59.36 cm
Barber Creek	n/a – OSL	Yes	Second-order polynomial	100 cmbs	109.47 cmbs	9.47 cm
Blackville	n/a – OSL	Yes	Linear	183 cmbs	174.67 cmbs	−8.33 cm
Blackwater Draw	IntCal04	No, depth scale arbitrary	Logarithmic	1,237.56 masl	1,237.59 masl	3 cm
Kimbel Bay	IntCal09	Yes	Logarithmic	358 cmbs	353.56 cmbs	−4.44 cm
Lake Cuitzeo	IntCal04	Yes	Fifth-order polynomial	282 cmbs	259.33 cmbs	−22.67 cm
Melrose	n/a – OSL	Yes	Linear	21 cmbs	22.02 cmbs	1.02 cm
Murray Springs	IntCal04	No, depth scale arbitrary	Second-order polynomial	246 cmbs	246.88 cmbs	0.88 cm
Talega	IntCal09	Yes	Second-order polynomial	14.85–15.15 mbs (15 mbs)	−33.05 mbs	−48 m
Topper	n/a – OSL	No, depth scale arbitrary	Second-order polynomial	57.5–62.5 cmbs (60 cmbs)	58.63 cmbs	−1.37 cm

*The date of 12,900 cal B.P. is used for calculation purposes in column 6 for those sites with radiocarbon ages originally calibrated using IntCal04 or where only OSL dates are available but YDB was estimated as 12,900 cal B.P. (e.g., Melrose); for all other sites, 12,800 cal B.P. is used for calculation purposes in column 6.

†Yes indicates that ^{14}C and/or OSL samples come from the same vertical column as was sampled for impact markers, or from sufficiently close by that they are on the same scale of absolute depth. No indicates that ^{14}C and OSL samples are from parts of the site other than where samples were collected for impact markers and are not on the same absolute depth scale.

‡Two different depths are provided for the supposed YDB layer at Abu Hureyra: as layer 445 at depth of 284.70 masl (ref. 3, SI p. 2) and 284.29 masl (ref. 10, SI table S1). Our recalculated predicted depth of YDB-age deposits is compared with each of these depths.

Table 3. Results of attempts to replicate ages of proposed YDB layers for sites in Fig. 1, group 3a

Site	Age of YDB originally reported	Predicted age of proposed YDB layer, unweighted	Age difference (column 3 minus column 2)	Predicted age of proposed YDB layer, weighted	Age difference (column 5 minus column 2)
Abu Hureyra*	12,900	13,082	182	13,044	144
		12,658	−242	12,763	−137
Arlington Canyon	12,800	13,106	306	13,108	308
Barber Creek	12,800	12,100	−700	12,100	−700
Blackville	12,800	12,960	160	12,960	160
Blackwater Draw	12,900	12,860	−40	12,866	−34
Kimbel Bay	12,800	18,106	5,306	12,094	−706
Lake Cuitzeo	12,900	19,725	6,825	15,916	3,016
Melrose†	12,900	12,300	−600	–	–
Murray Springs	12,900	12,847	−53	12,809	−91
Talega	12,800	13,030	230	13,030	230
Topper	12,800	11,773	−1,027	11,098	−1,702

*Ages given for Abu Hureyra are for the reported 284.29 m and 284.70 m depths of the supposed YDB layer.

†A weighted model is not possible for Melrose because one of the data points is the ground surface, not a date with an error term.

Wittke et al. (ref. 10, SI fig. 14) using several different statistical and graphing software packages produced a very different curve, one that results in the absurd predicted depth of −33 m below surface for YDB-age sediments: that is, their YDB layer is predicted to occur 33 m above ground. This is due largely to the fact that any age–depth model using the Talega dates used by Wittke et al. involves extrapolation beyond the actual age data.

More broadly, there are serious problems in using a second-order polynomial equation for an age–depth model (as also applied by YDIH proponents at Barber Creek, Murray Springs, and Topper). As Parnell et al. (54) point out, dates should get older with depth; however, a second-order polynomial equation is the equation for a parabola, which must reverse direction at some point. The use of a second-order polynomial equation in age/depth modeling amounts to assuming that at some point in a chronological sequence the law of superposition will be inverted and dates will begin to get younger with increasing depth. The use of such an equation illustrates that YDIH proponents are not following curve-fitting best practices, which require a theoretical or mechanistic rationale for the model chosen (55), but instead are simply applying an equation that seems to connect the dots on a scatterplot.

Inferences about the ages of supposed YDB layers are unsupported by replication in more cases than not, as shown in Table 3 where column 3 presents results obtained through our best attempt to reproduce the results in Bunch et al. (3), Israde-Alcantara et al. (6), and Wittke et al. (10). Many of the predicted ages we obtained for proposed YDB layers vary greatly from the time span of the YD onset (either 12,800–13,000 or 12,650–12,950 cal B.P., as appropriate).

It is also important to observe (Table 4) that many of the regression models for these sites are not statistically significant (at a 0.05 alpha level; regression coefficients, P values, and r^2 values are in *SI Appendix*, Table S19). Regression significance is given virtually no attention in the prior YDIH analyses, and indeed, it appears to be infrequently considered in paleoenvironmental age–depth modeling in general. However, a statistically insignificant regression-based age–depth model is one that cannot have real power for inferring age from depth or vice versa. Of course, statistical significance alone is not a sufficient criterion for a strong age–depth model: a model may be statistically significant but subject to other geological or sampling factors that render it problematic. However, it is a necessary one: even an age–depth model that is geologically sound will provide a poor basis for age interpolation if the sample size of dates is small and/or if the relationship between age and depth is weak, precluding statistical significance.

Finally, all radiocarbon and OSL ages are statistical estimates accompanied by a SD marking their uncertainty. These error terms cannot be ignored (54). However, they were ignored in Bunch et al. (3), Israde-Alcántara et al. (6), and Wittke et al. (10), who ran their regression analyses using a single point such as the median calibrated age. Had SDs for all ages been constant, the effect of ignoring them would not have had significant statistical consequences, because standard regression analysis assumes a constant SD (54). However, the age uncertainties at all these sites are highly variable: at Blackwater Draw, for example, the statistical uncertainties on the five radiocarbon ages used by Wittke et al. (10) range from ±90 to ±920 radiocarbon years (*SI Appendix*, Table S9). At sites where radiocarbon and OSL ages are used the span is even greater: at Kimbel Bay, age uncertainties range from ±15 radiocarbon years to ±2,940 y for OSL dates (*SI Appendix*, Table S10). Ages with different uncertainties cannot be given the same statistical weight (56) and yet were in analyses of all the sites in this group.

Moreover calibrated ages, unlike radiocarbon ages, often have wide, asymmetrical, and multimodal calendar age uncertainties, and thus, using only the median or mean calibrated age is not as robust as using the full calibrated probability distribution (57). Because regression techniques, as Blaauw observes, "often assume symmetrical/normally distributed errors" (ref. 57, p. 513), it is highly problematic to assume symmetry and reduce ages to a single point (54, 57–59).

One approach to account for variability in dating error in regression-based age–depth models would be to use weighted regression, in which the influence of a data point (^{14}C age) upon a regression equation is weighted by its SD (55, 60). Weighted regression is still not ideal for developing age–depth models, in part because it does not take the asymmetry of the probability distributions into account (for other problems, see 54, 61; for an alternative approach, see the discussion of Big Eddy in the next group). However, it is more appropriate than unweighted regression in that dates with large uncertainty will not inordinately bias the result. Table 3, column 5, presents the predicted ages of the supposed YDB layers using the same data and methods as were used in deriving the results shown in column 3, except that regressions weighted by dating error are used. Using these more appropriate regression-derived results, 9 of the 11 sites in this group have predicted ages for the supposed YDB that fall outside the YD onset time span: Abu Hureyra, Arlington Canyon, Barber Creek, Blackville, Kimbel Bay, Lake Cuitzeo, Melrose, Talega, and Topper. That is, using the exact same data and regression model types as used by YDIH proponents, but with

Table 4. Summary of results of statistical replication for sites in Fig. 1, group 3a

Weighted regression is statistically significant at α = 0.05?	Predicted age of proposed YDB layer from weighted regression falls within YDB interval? No	Yes
No	Arlington Canyon Barber Creek Blackville Lake Cuitzeo Melrose Talega Topper	Murray Springs
Yes	Abu Hureyra Kimble Bay	Blackwater Draw

dating errors taken into account, only two sites—Blackwater Draw and Murray Springs—have age estimates for the supposed YDB layer that fall within the YDB target interval.

Weighted regression models yield significant results in only three cases: Abu Hureyra, Blackwater Draw, and Kimbel Bay. Abu Hureyra and Kimbel Bay, as noted, have predicted ages for their proposed YDB layers that fall outside of the YDB interval, and given the statistical significance for the regression models at these sites (*SI Appendix*, Table S19), it can be concluded these layers do not date to the YD onset. This leaves only Blackwater Draw with statistical support for the proposition that the supposed YDB layer dates to the YDB onset (again, using just the data and regression model types as YDIH proponents). However, Blackwater Draw is subject to the more serious problem, already mentioned, that its age–depth model is based on limited data and an entirely opaque, arbitrary depth scale and thus can be rejected.

The dating and statistical flaws that undermine the age/depth interpolations of the sites in the prior group also apply to Big Eddy, the sole site in the next group (Fig. 1, group 3b). Here too the statistical analysis failed to take into account uncertainties associated with radiocarbon ages, radiocarbon samples were incorporated from multiple locations across the site at distances as much as 36 m from where the samples for impact indicators were obtained, and relevant ages (n = 4) were omitted without explanation [three of those are on soil carbon (62), making their exclusion not unjustifiable]. However, Big Eddy is an alluvial section with relatively uniform and nearly level stratigraphy, so it is possible to place samples from across the site on a common depth scale. In this case our reanalysis replicated the prior logarithmic regression: we recalculated a depth of 330.23 cm below surface for the proposed YDB layer, within 0.77 cm of the prior estimate (331 cm below surface), and an uncertainty-weighted estimated age of 12,952 cal years B.P. that matches the unweighted predicted age (12,939 cal years B.P.) and falls within the window of stipulated YD onset age (12,900 ± 100) (*SI Appendix*, Table S19).

Nonetheless, the Big Eddy chronology is not altogether secure. The radiocarbon ages on the proposed YDB layer (327–335 cm below surface) span ~1,700 radiocarbon years, and only one slightly intersects the temporal window of the YD onset (at 2 SDs). More striking, the sampled layers above and below the supposed YDB all yielded YD onset ages (*SI Appendix*, Table S6). Wittke et al. admit that there is a problem "accurately dating individual layers. . .because some charcoal fragments have clearly moved up and down within the sequence, and some older charcoal may have been introduced by flood-induced redeposition from sources upstream" (ref. 10, SI p. 5). That raises the question of whether the YD onset occurred earlier (or later) than the deposition of the supposed YDB layer.

That may be the case. The Big Eddy sequence was reanalyzed using MCAge Depth (63), one of a suite of programs (54, 57, 61) that uses a Monte Carlo algorithm to predict the age of different stratigraphic levels based on calibrated radiometric dates and their uncertainties and that can account for variation in sedimentation rate and detect ages that fall outside statistical confidence intervals. That analysis showed that all Big Eddy layers from depths of 320–348 cm below surface have ages that fall within the span of 12,900 ± 100 cal B.P., and when upper and lower confidence intervals are taken into account, all layers from 316 to 355 cm below surface date to that temporal span (*SI Appendix*, Table S7). Thus, although the supposed YDB layer at Big Eddy dates to the YD onset, it is also reasonable to expect that the layers above and below it should not be the same age. If they are, then they should have impact indicators as well. They do not (ref. 10, SI table S3).

The remaining six sites have ages directly on the supposed YDB layer. However, at four of those sites (Fig. 1, group 3c) the ages do not support the chronological claim that the layer dates to the YD onset. At Bull Creek (Oklahoma), Kennett et al. (7) reported high levels of nanodiamonds associated with a radiocarbon date of ~13,000 ± 100 cal B.P. The date has little accuracy as a moment in time, however, because it was derived from organic acids from a 9-cm–thick sediment sample obtained in the middle of the A horizon of a buried soil (64). In a subsequent paper based partly on resampling of the section, Bement et al. (65) show that the nanodiamond peak is from a sample 5 cm thick collected below the zone that yielded the radiocarbon date. The nanodiamond zone therefore predates the YDB. Furthermore, an additional nanodiamond spike occurs in Late Holocene to modern sediments at Bull Creek (65) indicating, as Bement et al. note, that nanodiamonds are not unique to the YD onset.

At Lake Hind (Manitoba) the directly dated supposed YDB layer postdates the YD onset. Firestone et al. (2) provide a radiocarbon age of 10,610 ± 25 ^{14}C years B.P. for the YDB layer, which they calibrate as 12,755 ± 87 cal B.P. That calibration cannot be replicated (IntCal04, available to Firestone et al., returns a cal age range of 12,757–12,661 cal B.P. at 1 SD). However, even at two SDs that age, whether calibrated with IntCal04 [12,791–12,617 cal B.P. (96% of the area under the curve) and 12,442–12,416 cal B.P. (4%)] or IntCal09 (12,662–12,538 cal B.P.), the supposed YDB layer at Lake Hind falls largely outside of and younger than the temporal window of the YD onset.

Finally, the ages of the supposed YDB layers at Lommel (Belgium) and Ommen (Netherlands) are partly based on the age of the Usselo soil at the type site, the limited relevance of which we have already discussed. However, at both Lommel and Ommen, there are also radiocarbon ages directly on charcoal from the supposed YDB layers, yet in both instances those ages of 13,433–13,245 cal B.P. and 13,360–13,259 cal B.P. (11,480 ± 100 ^{14}C years B.P. and 11,440 ± 35 ^{14}C years B.P., respectively, showing 1 SD range with IntCal09) are older by many centuries than the stipulated onset of the Younger Dryas. Wittke et al. therefore suggest that van Geel et al.'s (42) date of 10,950 ± 50 ^{14}C years B.P. (which they calibrate as both "12.86 ± 0.07 cal ka" and "12.9 ± 0.03 cal ka") is relevant to Lommel, asserting that it comes "from nearby at the same site" (ref. 10, SI p. 12). That is incorrect. van Geel et al. (42) obtained that age from the Usselo type locality, ~160 km from Lommel. The radiocarbon ages directly on the supposed YDB layer at Lommel and Ommen falsify the assertion this layer is "consistent with an age of ≈12.8 ka" and instead reinforce our earlier point that the Usselo soil represents more than a millennium of relative landscape stability and attendant soil development (43, 44). Charcoal and supposed impact markers could date throughout that age range; hence, the claimed YD onset age for these sites is not supported.

There are only two sites (Fig. 1, group 3d) in which the supposed YDB layer appears to coincide with the YD onset, but even the evidence from these sites is not straightforward. Daisy Cave (California) is a multicomponent archaeological site on the northeast coast of San Miguel Island (66). Firestone et al. (2) report impact markers from Stratum I, described as a dark brown cave soil, from which a radiocarbon age of 11,180 ± 130 ^{14}C years B.P. was obtained on a small carbonized twig fragment by Erlandson et al. (67). The calibrated age of 13,219–12,913 cal B.P. [at 1 sigma (IntCal09)] overlaps with the temporal window of 12,800 ± 150 cal B.P. The sampled stratum yielded several purported impact markers, although in relatively trace amounts in comparison with other localities (ref. 10, SI figs. 16 and 17). Firestone et al. (2) indicate that additional samples other than the one from Stratum I were obtained and analyzed, yet no information is provided on the stratum (strata) in which those occur or their absolute ages, making the significance of this claim unclear.

Sheriden Cave (Ohio) has two radiocarbon dates [not three (cf. ref. 10)] directly on a charcoal lens reported to contain impact indicators (68). Those two ages average 10,920 ± 50 ^{14}C years B.P. [12,869–12,695 cal B.P. (IntCal09)]. However, that charcoal lens is at least ∼450 cal years younger than Stratum 5a in which it occurs and likewise younger than overlying Stratum 5b (*SI Appendix*). In fact, the charcoal lens/supposed YDB layer is chronologically aligned most closely with Stratum 5c, which rests atop Stratum 5b (68). Complicating the chronology still further, eight radiocarbon ages at Sheriden Cave fall within the temporal window of 12,800 ± 150 cal B.P., and they come from the charcoal lens in Stratum 5a, at the Stratum 5a/5b contact, in Stratum 5b, and especially in Stratum 5c. This begs the question of why supposed YD impact indicators are only found in a charcoal lens embedded within much older deposits and not in the other layers that actually date to the YD onset.

Discussion

It is evident that the claim of a widespread isochronous event at the YD onset is not supported, nor is there the "very high chronological resolution" YDIH proponents themselves agree is critical to accepting evidence of this reputedly sudden event (ref. 34, p. 2531).We even relaxed one of their criteria, namely that "only ^{14}C dates with measurement precisions <100 years, and preferably <60 years, should be used" in assessing the supposed impact chronology and its potential effects (69). Had we applied it, we would have had to discard all luminescence ages and almost 60% of all radiocarbon ages used by YDIH proponents. Doing so would have instantly removed all radiometric age control from 11 sites and left 8 more with only a single age that in no case dates to the YD onset, meaning that 19 of their 26 sites with radiometric ages (group 1b) would become essentially free-floating chronologically.

As is, only 3 of all 29 sites offered in support of the YDIH apparently date to the YD onset. However, two of these are problematic: at Big Eddy and Sheriden Cave the supposed YDB layer has the required age, but its age is inconsistent with the ages of the layers that encompass it. The third site (Daisy Cave) seems to have been dropped from the corpus of evidence since being published in ref. 2.

A large part of the failure of these localities to meet the chronological standard YDIH proponents themselves set is likely due to the nature of the sites. By design, many (although not all) were "Clovis and equivalent-age sites [selected] because of their long-established archeological and paleontological significance, and, hence, most are well documented and dated by previous researchers" (ref. 2, p. 16017). However, such sites are poor settings in which to spot what might be trace evidence of an evanescent event: they had surfaces exposed for unknown and possibly long periods (after all, people and animals were living on those surfaces), they rarely provide a record of continuous sedimentation, and they frequently have complex depositional and erosional histories. That the chronological details and complexities of these sites were ignored in the omission of dates and the unexplained and unjustifiable integration of ages across significant distances only further weakens the case for the YDIH.

A far better setting to resolve the age and contents of a supposed YDB layer would be in a lake or an ice core where there was more or less continuous deposition and thus a surface on which impact indicators are more likely to have been buried quickly and quietly (in a depositional sense). These more stable settings are less likely than archaeological sites to have hiatuses or changes in accumulation rates (57) and thus have greater potential to yield a discrete and readily identifiable layer. Ideally, Telford et al. observe, such a layer would be directly dated "with dates immediately, but unambiguously, above and below the event horizon," thereby obviating the need for age–depth models (ref. 59, p. 5). However, even if that is not possible, such cores are more likely to yield sequential and nonoverlapping ages (although there are exceptions, as at Lake Cuitzeo), making it possible to construct reliable age–depth models without recourse to long-distance integration and with the level of precision YDIH proponents rightly demand. In the event of rapid sedimentation it will be far easier to spot where a supposed YDB layer occurs and, equally important, where it does not (or should not), because the assumption of monotonicity holds [that deeper sediments must be older (54)], as it does not for the sections at sites like Arlington Canyon and Big Eddy.

At the same time, it is necessary to test portions of cores that are not expected to yield impact indicators. It may be that "YDB markers are typically present in abundances that are substantially above background" (ref. 3, E1903), but that assertion has been largely self-fulfilling. In many of the sites studied, only sediments immediately adjacent to the supposed YDB layer were examined for impact indicators, as at Barber Creek, where just three samples, each 2.5 cm thick surrounding the boundary presumed to mark the YD, were examined in a 3.15-m–deep section. This procedure effectively ensures that no earlier or later strata with impact indicators will be encountered. The significance of the abundance of indicators in the supposed YDB zone will not become clear until the measured background includes more than just the strata thought to be YD in age, especially because it is now apparent that supposed impact markers are not exclusive to that specific geological moment (19, 21, 65).

Because these goals are readily accomplished in lake cores, it is relevant to observe that there are many thousands of lakes in the Great Lakes region where the supposed impact/airburst is said to have occurred. If there is evidence of a YD impact, it ought to be found in cores from those lakes with sediments that span the period from the Late Wisconsin to the present. It should be noted, however, that an examination of extant lake sediment cores from the Great Lakes region, as well as other North American lake cores, failed to yield indications of the massive burning predicted by the YDIH (31).

Unless and until the supposed YDB layer is more securely linked to the Younger Dryas onset, these results can only amplify concerns regarding the problematic physics of the presumed impact, the questionable origin and lack of reproducibility of its supposed markers, and the doubts about its purported biotic consequences (14, 15, 17–28, 30–33). For now, there is no reason or evidence to accept the claim of an extraterrestrial impact at the start or as a cause of the Younger Dryas.

Methods

Where we replicated regression analyses (sites in Fig. 1, groups 3a and 3b), we used the calibration specified in the original analyses by YDIH proponents [IntCal04 or IntCal09 (70, 71)] rather than the currently available calibration (IntCal13) to ensure comparability. All other calibrations in the text were run using the relevant version of the CALIB Radiocarbon Calibration Program (CALIB 5 or CALIB 6) except in the case of the Big Eddy weighted regression analysis, which used the OxCal calibration program to derive the 1-SD error terms necessary for that particular analysis.

The method(s) by which the original age/depth interpolations were conducted was routinely left unspecified by the original authors, although in most cases it appears to have been done using Microsoft Excel relying on a single point estimate for each radiocarbon age. However, no single value can completely describe the probability distribution of a calibrated date, and therefore, using just a single point estimate—whether a median, midpoint, or weighted mean—fails to account for uncertainties in the age estimate and thus leads to questionable regression results (57–59).

Our reanalysis included using Excel for exploratory purposes, but because Excel cannot perform the types of analyses that take dating error into account, we also used two additional analytical programs. First, in attempting to replicate the age/depth models YDIH proponents have used, we used GraphPad Prism (version 6.03 for Windows; GraphPad Software). This is a statistical and graphing software package whose capabilities include both weighted and unweighted regressions for linear and a variety of nonlinear models. The data that we used in these replicated analyses came from ref. 10, table S1, and are shown in *SI Appendix*, Table S17, which provides for each the type of date (^{14}C or OSL), the laboratory number, the radiocarbon age and its associated error (^{14}C SD), and the calibrated age (Cal B.P.) and its associated error (Cal SD).

In attempting to replicate age/depth model results for each of the sites in Fig. 1, groups 3a and 3b, we conducted three regression analyses: (*i*) an unweighted regression with age as the independent variable (IV) and depth as the dependent variable (DV), (*ii*) an unweighted regression with depth as the IV and age as the DV, and (*iii*) a weighted regression with depth as the IV and age as the DV. As noted above, calibrated dates were used in all regressions, and in the weighted regressions, data points were weighted by the inverse of the variance of the calibrated dating error (i.e., Cal SD^{-2}) (60).

The purpose of our regression analyses was solely to evaluate whether the data and methods used by YDIH proponents actually support the conclusions that they draw from age/depth models. For this reason, we did not use additional data in our replication analyses that we knew were available from certain sites, nor did we use alternate regression model types (e.g., logarithmic instead of second-order polynomial), even when there was reason to think that other types of models were more appropriate. For selected sites, however, when it was clear data were amenable, we went beyond the age/depth models of YDIH proponents and used additional data and, most important, a method more appropriate than regression to further evaluate the age of supposed YBD layers.

Although regressions analyses can be weighted by radiocarbon dating error expressed as a SD, such a SD is a symmetric encapsulation of an irregular and sometimes-complex multimodal probability distribution (54, 57). Moreover, weighted regression cannot readily account for dating uncertainties associated with undated depths or with age outliers. To better treat such issues, we modeled age/depth chronologies using the MCAge Depth program for sites that had reliable depth data (63, 72). MCAge Depth is one of a suite of programs (see also refs. 54, 57) that uses a Monte Carlo algorithm for repeated random sampling of the probability distributions to generate confidence intervals for the age/depth curve that incorporate the probabilistic nature of the calibrated ^{14}C ages, variation in sedimentation rate, and varying uncertainties dependent on the distance of the layer for which an age is sought from the layers for which ages are available; this program also makes it possible to identify and remove outliers (ages that are outside the 99% confidence interval). In conducting the MCAge Depth analyses, we again used the calibration version specified in the original analyses and calibrated ages using CALIB, which generates the uncertainty distribution files required by the MCAge Depth program.

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