

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

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Introduction

New hypotheses with major multidisciplinary implications, such as the Younger Dryas airburst/impact hypothesis, appropriately face intense testing, and we respect that. However, such criticisms must be based on facts. Instead, many of the assertions made in the discussion by Holliday and coauthors

are inaccurate. In this article, we present rebuttals of the most significant of their inaccurate assertions but decline to address unfounded opinions. Most of the following discussion deals with the implications of the Younger Dryas Boundary (YDB) layer, including evidence supporting extensive YDB burning and its proposed age, identification, and context within the chronological record. Other issues include the association of biomass burning with impact-related proxies, megafaunal extinctions, and human

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population declines. Holliday and coauthors dispute whether impacts, in general, can even cause biomass burning, a long-settled question. These issues are presented mostly in order of appearance with direct quotations from the discussion by Holliday and coauthors in boldface type within quotation marks. Emphasis has been added to some of their statements, as noted.

Holliday et al.'s Introduction

“The presence of charcoal at the beginning of the YDC [Younger Dryas Chronozone] (YDB) fails to unambiguously support the hypothesis of impact-related fires because there is also a large peak at the end of the YDC.” This is a spurious argument. When multiple wildfires occur, the cause of each must be considered separately because biomass burning results from multiple causes. Lightning and humans trigger most wildfires, but that does not mean a meteorite impact cannot cause them too.

Holliday et al. (2020) reject the YDB wildfire hypothesis based on the fact that there are larger charcoal peaks exhibited elsewhere in the record. However, there is no requirement that an impact-related fire must be the largest in any record. Furthermore, there is evidence that there may be less charcoal than normal in an impact-related fire because such fires tend to destroy charcoal (Robertson et al. 2013), making them appear less intense than they actually were.

We agree that the presence of charcoal in the YDB sediments is not sufficient by itself to show causation. Nevertheless, the charcoal evidence presented in Wolbach et al. (2018a, 2018b) indicates a significant peak at the Younger Dryas (YD) onset, when many rapid changes occurred simultaneously across a large geographic area, coeval with deposition of impact-related proxies. These proxies include aciniform carbon (soot), glass-like carbon, carbon spherules, nanodiamonds, polycyclic aromatic hydrocarbons, high-temperature magnetic spherules, meltglass, platinum, iridium, nickel, cobalt, ammonium, nitrate, oxalate, acetate, and chromate (Wolbach et al. 2018a, 2018b, and references therein). This correlation suggests but does not prove a cause-and-effect relationship between the wildfires and the YDB impact event. On the other hand, there is also a large charcoal peak at the termination of the YD that is not associated with any similar impact-related proxies. We maintain that the widespread increases in wildfires at the onset and termination of the YDB had different causes, which has no bearing on the validity of the impact hypothesis.

Holliday et al. (2020) also claimed in their abstract that “the exceptionalism claimed for many

of the key data points is the result of exaggerations.” This is a puzzling claim because we report peaks in charcoal and biomass-burning proxies that are in the 99th percentile by size. Surely that percentile is exceptional enough.

“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.” This is mostly false. The claim is correct for the platinum data acquired by independent researchers (Petaev et al. 2013) but is incorrect for indicators of biomass-burning markers, including ammonium, nitrate, acetate, formate, and oxalate. For those markers, Wolbach et al. (2018a) present well-dated evidence spanning up to ~120,000 y for the Greenland Ice Sheet Project 2 (GISP2), Greenland Ice Core Project (GRIP), and North Greenland Ice Core Project (NGRIP) ice cores.

Background of the Debate

“[T]heir table A3 is not comprehensive; it omits key critical articles and contradictory data.” There is no requirement for either scientific critics or proponents of any hypothesis to cite every paper ever published. Even so, we omitted no papers that are essential to the theme of biomass burning. Moreover, we were reasonable in citing ~44 references of publications by critics and/or independent researchers (Wolbach et al. 2018a, 2018b).

“In the most recent discussion of dating, the YDB is placed at 12,800 ± 300 BP (Kennett et al. 2015a). Firestone et al. (2007) placed the YDB at ~12,900 cal BP, not at ~12,800, as stated by Wolbach et al. (2018a, p. 165; 2018b, p. 185).” Holliday et al. offer this as a criticism, but they should not need to be reminded of continual changes in the radiocarbon calibration curves by others. Our table A7 (Wolbach et al. 2018b) shows that the radiocarbon date of 10,900 ± 100 ¹⁴C y BP calibrates with the IntCal13 calibration curve to 12,819 cal BP (mean age), whereas a previous calibration curve, IntCal98, calibrates the same date of 10,900 ± 100 ¹⁴C y BP to an age of 12,936 cal BP, a difference of 117 y. It is important to note that the actual radiocarbon date (10,900 ± 100 ¹⁴C y BP) for the YDB impact event has remained the same in all YDB publications, whereas the calibrated age has been revised multiple times by an independent, international body.

With respect to “nine sites of ‘low quality’ in terms of dating,” “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 [Younger Dryas Impact Hypothesis] literature.” (emphasis added). This is a false

claim. Kennett et al. (2015) wrote, “Nine other proxy-rich sites currently lack sufficient dating for robust Bayesian analysis. Even so, the stratigraphic context of a proxy-rich layer or samples at these sites *supports a YDB age*” (p. E4351; emphasis added) and later, they wrote that “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” (app., p. 34; emphasis added). Contrary to the assertion of Holliday et al. (2020), Kennett et al. simply used marker layers for stratigraphic correlation and never claimed that these definitely are YDB sites. Instead, they proposed that the observed impact-related proxies may date to the YD onset.

“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.” This is inaccurate. Impact-related proxies have been found in sediment samples from 23 Bayesian-dated sites in nine countries on three continents, as reported by Kennett et al. (2015; table 1). The average age ranges from ~18,640 cal BP in the Last Glacial Maximum through the entire YD episode to 7,837 cal BP into the early Holocene, an average span of ~11,000 y. The age of the oldest profile is >48,000 y. Coeval peaks in the suite of impact-related proxies have never been found outside the YDB and adjacent

strata in any of those records. Furthermore, biomass-burning proxies have been investigated extensively in three Greenland ice cores spanning the past ~120,000 y. The result is that YDB peaks in ice-core concentrations of ammonium, nitrate, oxalate, acetate, and formate are greater than or equal to ~99% of all other peaks elsewhere in the ice cores, and in some cases, the peaks are the largest in the entire ice record, confirming that these peaks are extraordinary.

“[N]anodiamonds were misidentified and/or the data are not reproducible (Daulton et al. 2017).” This statement is both false and misleading. Holliday et al. (2020) neglected to cite an independent study by Tian et al. (2011), who wrote, “Our findings confirm . . . the existence of diamond nanoparticles also in this European YDB layer. No such particles are found in the overlying silt and clay or in the underlying fine sands” (p. 40). There is another problem with the results of Daulton et al. (2017). Those authors claim to have analyzed samples from the YDB layer provided by Pinter et al. (2011). However, figures 3 and 4 of Pinter et al. reveal that not a single sample was acquired from 12,800-y-old strata, and instead, samples were acquired up to thousands of years younger and older, completely missing the YDB-age layer. This oversight explains the reported absence of YDB nanodiamonds that had been previously

Table 1. Age Span of Sedimentary Profiles from 23 Younger Dryas Boundary Sites (Kennett et al. 2015)

Site	Location	Oldest age	Youngest age
Aalsterhut	Netherlands	12,690	12,815
Abu Hureyra	Syria	11,360	12,970
Arlington Canyon	California, USA	12,630	12,835
Barber Creek	North Carolina, USA	9770	14,995
Big Eddy	Missouri, USA	11,235	14,705
Blackville	South Carolina, USA	600	19,620
Blackwater Draw	New Mexico, USA	8115	14,980
Bull Creek	Oklahoma, USA	7110	12,890
Daisy Cave	California, USA	2360	14,105
Indian Creek	Montana, USA	7690	13,290
Lake Cuitzeo	Mexico	835	47,245
Lake Hind	Manitoba, Canada	2730	48,565
Lindenmeier	Colorado, USA	9965	14,970
Lingen	Germany	12,330	13,605
Lommel	Belgium	11,660	15,390
Melrose	Pennsylvania, USA	1640	24,075
Mucunuque	Venezuela	12,845	14,000
Murray Springs	Arizona, USA	5515	26,890
Ommen	Netherlands	10,395	13,990
Santa Maira	Spain	5330	17,405
Sheridan Cave	Ohio, USA	9845	14,555
Talega	California, USA	10,335	19,530
Topper	South Carolina, USA	3255	15,305
Average		7837	18,640
Maximum range		600	48,565

documented (Kinzie et al. 2014) using six different types of electron microscopy.

Holliday et al. (2020) also claim that Bement et al. (2014) found a “nanodiamond zone ~10 cm below ^{14}C date of $11,070 \pm \text{cal } 60 \text{ BP}$.” (table 1). Here, Holliday et al. misrepresent the results of Bement et al. (2014), the independent site investigators, incorrectly implying that those nanodiamonds were found below the YDB layer. To the contrary, Bement et al. (2014) referred to Kennett et al. (2009) and wrote that “the earlier report of an abundance spike of nds [nanodiamonds] in the Bull Creek I Younger Dryas boundary soil is confirmed” (p. 1726; emphasis added).

Greenland Ice-Core Evidence

“In their figures 3 and 4 . . . 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. . . . 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.” (emphasis added). This claim is false. Figures 3A and 4A in Wolbach et al. (2018a) show biomass-burning data representing ~120,000 y of ice-core records. Figures 3B and 4B simply show close-up views of a portion of the entire core.

Wolbach et al. (2018a, p. 169) state, “Nearly a dozen earlier NH_4 peaks are higher than that of the YD onset, as are several younger peaks that are likely related to increases in anthropogenic biomass burning (Cooke 1998; Power et al. 2008).” Holliday et al. (2020) claim these peaks are not due “to ‘anthropogenic burning’ (which none of these articles claim).” This claim is inaccurate, even though two coauthors of Holliday et al. (2020) are also coauthors of Power et al. (2008), who referred to end-Pleistocene/Holocene anthropogenic influences on wildfires multiple times. For example, they wrote about (1) “a mid-to-late Holocene interval when . . . human influences on fire regimes became important” (emphasis added); (2) “human populations were increasing in the Americas and may have locally contributed to the changing incidence of fire” (emphasis added); and (3) “the possible role of anthropogenic fire for forest clearing [emphasis added] may have contributed to increased fire at sites in southern Europe” (p. 900). Cooke (1998) wrote, “A sudden increase in particulate charcoal at Lake La Yeguada (Panama) after ca. 11,000 BP suggests that humans began to burn fires [emphasis added] in oak-*Ilex*-magnolia forests at this time” (p. 185). Daniau et al. (2010), who also share a coauthor with Holliday et al., wrote, “The interactions between climate, vegetation and

fire regimes are complex, and can be *difficult to disentangle* [emphasis added] under modern conditions when fire regimes are influenced by human activities” (p. 2918). This difficulty in interpreting the record supports our position (Wolbach et al. 2018a) that Holocene NH_4 peaks must be discounted when evaluating older records. In any event, large Holocene peaks in biomass burning are irrelevant to the issue of large impact-related fires at the YD onset.

“Wolbach et al. (2018a, p. 170) assert that Fischer and colleagues ‘identified a single large NH_4 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.” This statement is false. In figures 2c, 3c, and 4c of Fischer et al. (2015), those authors plotted running averages of the concentrations of NH_4 in two ice cores, NGRIP and GRIP. Their figure 4c displays very large peaks in NH_4 concentrations at the YD onset for both cores within the interval of the past 10,000 to 20,000 y. Compared with the running averages for NH_4 in figures 2c and 3c of Fischer et al., the peaks at the YD onset are more than twice as large as any other peak within the past 10,000 to 100,000 y.

Fischer et al. (2015) also discuss peak fire frequency (peaks per 201 y) and show that fire frequency was low at the YD onset. Holliday et al. use that to claim that no unusual impact fires occurred. However, that logic is seriously flawed. Any 201-y interval may contain hundreds of fires or only a few. Either way, the number of nonimpact fires is irrelevant to the question of whether nearly simultaneous impact fires also occurred in that interval.

Biomass Burning

“[T]he evidence for a link between extraterrestrial impacts and wildfires is weak. . . . The idea of a global fire following the K/Pg impact is widespread in the literature. . . . Scott et al. [2000], 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.” This position is not widely accepted, as Holliday et al. (2020) acknowledge. Robertson et al. (2013) discussed the claim of those arguing against a wildfire-impact connection at the K/T boundary and wrote that the critics’ “assertions either are incorrect or have alternate explanations that are consistent with global firestorms.” Multiple researchers have analyzed more than a dozen marine cores globally, confirming the global nature of soot distribution due to biomass burning at the K/Pg boundary (Wolbach 1990; Wolbach et al. 1990, 2003; Krueger et al. 1994). Durda and

Kring (2004) calculated that conflagration on a continental scale may be initiated by ejecta that was thrown from an impact crater at least 85 km in diameter. The continental/global conflagration studied by them is caused by ejecta from a large impact falling back on Earth. In the case of an encounter with comet fragments, the incoming material has a lower mass but enters at a substantially higher speed (30 km/s), and thermal radiation generated by it may ignite 5%–10% of the Earth's biomass (Napier 2010), consistent with our calculations (Wolbach et al. 2018a, 2018b).

“Likewise, the Tunguska impact is cited as having started a fire . . . but an investigation based on contemporary reports, research articles, and websites provided no firm evidence of major wildfires.” This statement is highly inaccurate. Intense fires caused by the Tunguska impact event were described by eyewitnesses. Jenniskens et al. (2019) reported that nearly 30 people were within the radius of the airburst that felled >80 million trees. At least three of those were killed by the concussion, and many more were burned by the impact fires. One eyewitness told investigators that 200 reindeer burned in the fires and that “the explosion was very strong, the deer tore up, the chum [lodge] was carried away, people were unconscious. Many deer died. Strong fires started on the taiga. The sky was red for a few days” (Jenniskens et al. 2019, p. 11). Jenniskens et al. (2019, p. 5) further wrote that “fires were also started in a spotty pattern over a larger area, out to about 10–15 km from the epicenter.” Florenskiy (1965) wrote, “The 1908 fire spread rapidly through the treetops of the meteorite area, before a wind moving at a speed of 6 to 10 m/sec. . . . The fire lasted for at least five days. . . . The trunks of live trees did not burn during the fire; only needles and small twigs were scorched” (p. 13). Contrary to the claim of Holliday et al., there is overwhelming evidence that the Tunguska airburst generated an intense wildfire that burned as much as 500 km² over the course of at least 5 d.

Regarding carbon spherules: “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.” This claim is in error. In Wolbach et al. (2018b), the appendix reads, “Laboratory experiments previously conducted by coauthors of this article suggest that these carbon-rich spherules were produced from *airborne droplets of burning coniferous tree sap*” (emphasis added). These laboratory experiments are also reported in LeCompte et al. (2018) and Kinzie et al. (2014), who

wrote, “Furthermore, carbon spherules containing NDs [nanodiamonds] have been demonstrated to form *from tree sap under laboratory conditions that duplicate the temperature, pressure, and redox values within an impact fireball*” (p. 476–477; emphasis added), suggesting a formation mechanism for YDB nanodiamonds.

“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. . . . 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.” This statement is a misrepresentation. Wolbach et al. (2018b, fig. A6) state, “Charcoal-rich black layers (arrows), or ‘black mats,’ lie at the *boundary* [emphasis added] between the underlying Usselo Formation and overlying sandy sediment.” Contrary to the claim of Holliday et al., Kaiser et al. (2009) actually provided support for the YDB hypothesis by writing, “However, after checking further palaeosols for geochemical impact tracers, the first positive result from the Lommel section, Belgium (Firestone et al. 2007), *can probably be confirmed* [emphasis added]. In that case, the pre-existing Usselo soil only received impact matter” (p. 606). The YDB group supports this conclusion that impact material fell on and mixed into the top of the Usselo, which existed before the impact event.

Megafauna Extinctions and Human Population Decline

“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.” This claim is a misrepresentation of the YDB impact hypothesis. Most recently, Pino et al. (2019, p. 21) wrote, “the proposed YDB impact event *contributed* [emphasis added] to the South American megafaunal extinctions.” YDB publications have never argued that the impact was the sole cause of the extinctions and, instead, claim it was one major factor in a complex extinction event.

“No stratigraphic or chronologic data exist to indicate a post-Clovis population decline.” This is a false claim. Holliday et al. (2020) neglect to mention Anderson et al. (2011), who report widespread evidence for post-Clovis population decline. Anderson et al. report three lines of supporting evidence. First, frequency analyses of 30,000 Paleoindian projectile points across North America show a drop of ~50%

in post-Clovis fluted points, representing a major population decline across North America. Second, radiocarbon dates are a first-order approximation of population levels—that is, less human-produced charcoal at a site suggests fewer people there at the time. Summed probability analyses of >5300 radiocarbon dates from human-related sites indicate an average population decline of >50% across the Northern Hemisphere. The population pattern was similar across many continents, generally exhibiting an increase until the YD onset, followed by an abrupt decline with a population recovery several centuries later. Third, time series of lithic assemblages from 11 Paleoindian chert quarry sites in the southeastern United States show that all were in continuous usage for hundreds of years until the YD onset, after which nearly all were abandoned for hundreds of years. Because chert was an indispensable raw material for Paleoindian tools, abandonment of these quarries suggests that few people remained. After a multi-century hiatus, the quarries began to be used again.

Holliday et al. (2020) also neglect to mention LeCompte et al. (2012), who reported the results of Al Goodyear's experiment to examine sediment samples taken from directly above and beneath Clovis chert waste flakes (debitage), which are the youngest Clovis artifacts in the Topper quarry in South Carolina. Abundant impact-proxy glass and magnetic microspherules were found immediately atop the debitage, but none were discovered in sediment samples directly beneath the chert. Here is the inferred sequence of events: (1) ~12,800 y ago, Clovis artisans at Topper were producing chert projectile points just before the YDB impact event occurred, as shown by the lack of YDB spherules beneath the debitage; (2) then, the YDB impact event occurred, as shown by spherules directly atop the debitage; (3) a multi-century hiatus in quarry usage followed, after which post-Clovis Paleoindians resumed quarry activity after the middle of the Younger Dryas.

Thus, a wide range of evidence across at least four continents supports a severe, abrupt population decline at the YD onset (Anderson et al. 2011). In one notable example, genetic evidence of a severe, abrupt decline in human population densities in Spain at the YD onset is presented by de Pablo et al. (2019). The title of their independent publication summarizes their results: "Palaeodemographic Modelling Supports a Population Bottleneck During the Pleistocene-Holocene Transition in Iberia."

Fundamental Problems and Questions

"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." On the contrary, it is well known that widespread major changes occurred at the YD onset, as summarized in Kennett et al. (2018) and Teller et al. (forthcoming). These include changes in biotic assemblages, proglacial lake levels, ice sheet stability, atmospheric circulation, and ocean circulation. For example, ice dams simultaneously failed on multiple proglacial lakes, including the largest ones—Lake Agassiz in Canada and the Baltic Ice Lake in northern Europe—causing extensive meltwater flooding into the Arctic and North Atlantic Oceans (Kennett et al. 2018; Teller et al., forthcoming). There were huge, continent-wide hydrological changes during which most of the Mississippi River drainage was diverted from the Gulf of Mexico into the North Atlantic and Arctic Oceans. Ocean water from the Atlantic abruptly advanced westward within a few years into the Champlain Sea as the Gulf of St. Lawrence opened (Cronin et al. 2008). There is also extensive evidence indicating the destabilization of ice-sheet margins across the Northern Hemisphere, including Greenland. The massive input of freshwater floods into the Arctic and North Atlantic abruptly altered ocean circulation. After that, global atmospheric and precipitation patterns shifted abruptly in middle and high latitudes, causing temperatures to become cooler in the Northern Hemisphere and generally warmer in the Southern Hemisphere (Pino et al. 2019). As a result, the onset of the YD climate episode is marked by broad global biotic changes, particularly in the Americas, as reflected by major, anomalous migrations of plant assemblages (Kennett et al. 2018). Considerable evidence supports the hypothesis that the large-scale extinction of some megafaunal genera and species occurred at or close to the YD onset within the uncertainties of radiocarbon dating (Firestone et al. 2007; Surovell et al. 2016; Kennett et al. 2018; Pino et al. 2019). This extinction event is unprecedented in the last several million years.

Figures

"Panel B, right, shows that the plot of the actual data can be reconciled with Wolbach and colleagues' (2018a) fig. 4C only if the age axes for NH₄ and $\delta^{18}\text{O}$ values are shifted 'younger' (to the right) by 10 and 50 y, respectively." (fig. 2B; emphasis added). This statement is erroneous. Regarding the ~60-y (50 + 10) age differences claimed by Holliday et al. (2020), we stand by our figures. The cause of their claimed 60-y discrepancies is unknown, but we suggest the discrepancies could have resulted from their misunderstanding of the age scale for the data set of Mayewski

et al. (1997). The lead author of that publication is a coauthor of this contribution (P. A. Mayewski) and was the first to recognize the significance of the anomalously large NH_4 peak in the GISP2 ice core.

In their table 6, Holliday et al. report using the data from Mayewski et al. (1997) and the GICC05 age model from Rasmussen et al. (2014) and Seierstad et al. (2014), minus 50 y to convert to “before 1950,” accounting for 50 y of their discrepancy. Mayewski et al. reported their data on a pre-GICC05 age scale that cannot be directly converted to GICC05 because the ice layers were subsequently recounted. Instead, the original GISP2 age scale must be interpolated to the GICC05 scale using the ages of depths that are common to both scales, yielding an average difference of 10–15 ice-layer years. We made that necessary conversion (Wolbach et al. 2018a, 2018b), but it appears that Holliday et al. did not. Without this conversion, the discrepancies between the two age scales amount to 64–66 y, close to the ~60 y (50 + 10 y) reported by Holliday et al. Examples from the original data are shown in table 2.

Regarding the 50-y discrepancy, Holliday et al. wrote, “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.” (emphasis added). This is a mischaracterization of their own methods. In their table 6 for the age scale used for the NGRIP $\delta^{18}\text{O}$, Holliday et al. (2020) cite Rasmussen et al. (2014) and Seierstad et al. (2014), who both state that their data are reported in “years before A.D. 2000.” However, in their statement above, Holliday et al. assert that all those ages “already were on the latter scale” of “years BP1950,” which is incorrect. We suggest that this is one possible source of the 50-y discrepancies claimed by Holliday et al.

Regardless of what caused the plotting errors, Holliday et al. have questioned the crucial conclusion in Wolbach et al. (2018a, 2018b) that the onset of YD climate change overlaps the platinum peak in

GISP2. We acknowledge that the $\delta^{18}\text{O}$ record is highly variable, and thus it is difficult to use the $\delta^{18}\text{O}$ record alone to determine whether climatic changes occurred exactly at the YD onset. Therefore, here we examine other ice-core proxies that are widely accepted to indicate the onset of YD climate change (Mayewski et al. 1997). Figure 1 shows five such proxies from Steffensen et al. (2008) for NGRIP and one proxy from Mayewski et al. (1997). These data are compared with the 21-y interval of peak platinum deposition from 12,836 to 12,815 cal BP (Petaev et al. 2013). All data are plotted with no changes except for subtracting 50 y, when necessary, to adjust from the “before 2000” age scale to “before 1950.” These six proxies are compared with the independently published age range for the YD onset from 12,915 to 12,777 cal BP (138-y uncertainty in counting ice layers; from Steffensen et al. 2008).

It is widely accepted that the onset of YD cooling was marked by a noticeable increase in dust, interpreted as resulting from a sudden increase in wind strength (Ram and Koenig 1997; Brauer et al. 2008). This increase corresponds to the peak of platinum deposition (fig. 1A). Similarly, windiness increased the deposition of calcium (fig. 1B: Ca^{2+}), considered to represent airborne continental dust, along with sodium (fig. 1C: Na^+) and chlorine (fig. 1F); the latter two represent the deposition of airborne sea salt onto Greenland ice. In addition, there was an increase in deuterium excess (fig. 1D), a proxy for past ocean surface temperatures, indicating that ocean temperatures became colder at the YD onset. In addition, annual ice-layer thicknesses decreased by 25% from an average of ~0.04 to 0.03 cm across the platinum interval (fig. 1E), consistent with a decrease in precipitation during the cool YD episode.

In summary, these six lines of evidence indicate that the climate shift marking the YD onset began within or close to the time of the 21-y peak in platinum deposition. This conclusion is supported by Steffensen et al. (2008), who concluded that YD

Table 2. Comparison of Age-Scales to Account for Purported ~60-y Discrepancy

GISP2 ice core reference	Depth (m)	Published age	BP	Claimed discrepancy
Mayewski et al. (1997)	1712.40	12,893	12,893	
Seierstad et al. (2014)	1712.41	12,877	12,827	
Difference			66 y	~60 y (10 + 50)
Mayewski et al. (1997)	1713.00	12,910	12,910	
Seierstad et al. (2014)	1713.03	12,896	12,846	
Difference			64 y	~60 y (10 + 50)

Note. Fifty years must be subtracted from the dates published by Seierstad et al. to convert the dates to BP (before 1950).

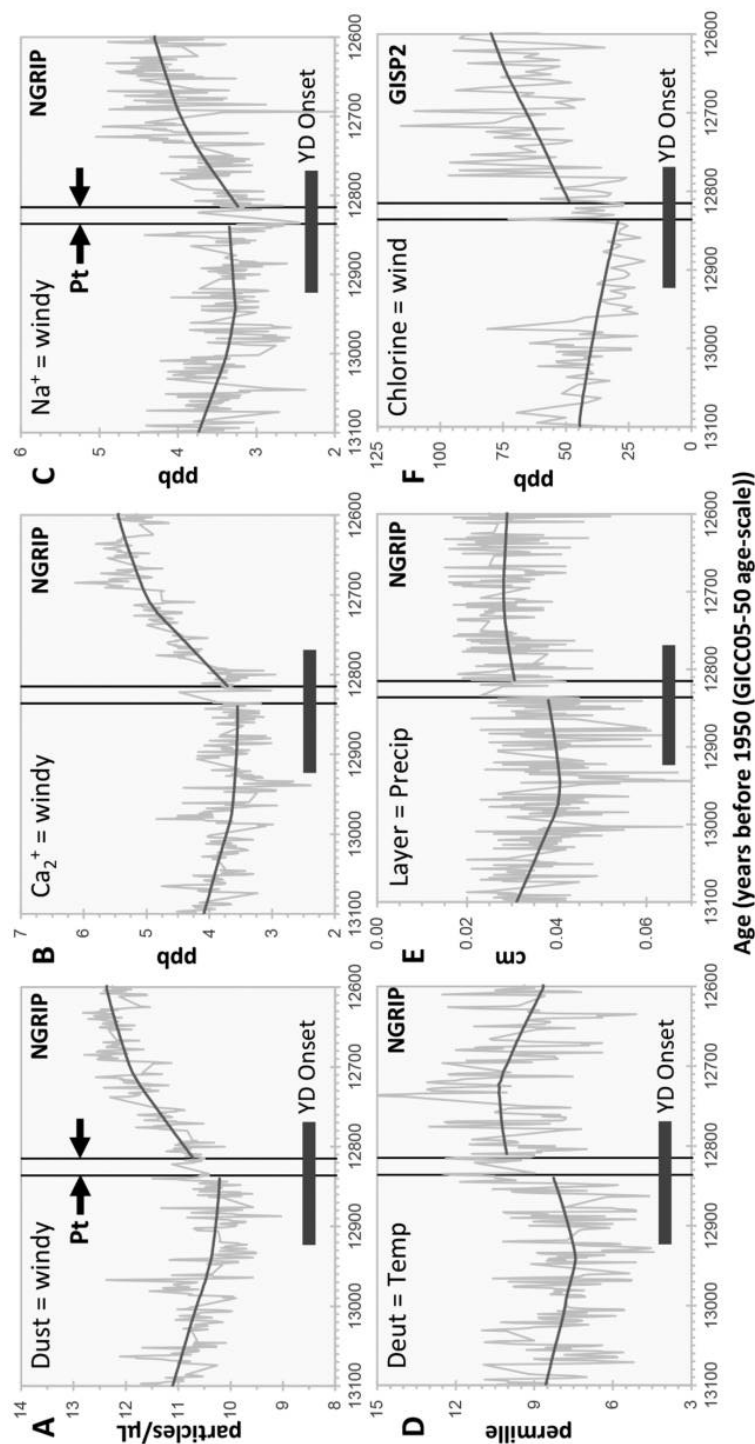


Figure 1. Six proxies showing that the onset of Younger Dryas (YD) climate change closely corresponds to peak platinum deposition. Light gray lines are for raw data from North Greenland Ice Core Project (NGRIP) and Greenland Ice Sheet Project 2 (GISP2), as labeled. The two vertical black lines represent the 21-year interval of peak platinum deposition from 12,836 to 12,815 cal BP. The thick horizontal black bar from Steffensen et al. (2008) is the age range for the YD onset between 12,915 and 12,777 cal BP, representing the 138-y uncertainty from counting ice layers. Curved trendlines represent lowess-smoothed data with a window of ~155 y, segmented at the platinum interval. All show significant shifts in trend at or close to the interval of peak platinum deposition. Data for panels A–E are from Steffensen et al. (2008; <http://science.sciencemag.org/content/suppl/2008/06/19/1157707.DC1>). Data for F are from Mayewski et al. (1997; <ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/greenland/summit/gisp2/chem/iond.txt>). Deut. = deuterium.

climate change began within the interval of 12,915 to 12,777 cal BP, a span that includes the 21-y interval of peak platinum deposition between 12,836 and 12,815 cal BP.

Tables

“As noted by Surovell et al. (2009, p. 18,157; SI [supplementary information], 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.” (table 2). Surovell et al. (2009) and Holliday et al. (2014, 2016) investigated spherules in YDB layers and reported negative results. A. West, a co-author of this contribution, provided those researchers with information on the spherule protocol that had been published previously. The protocol provided to them was from Firestone et al. (2007), who wrote “Selected microspherules were . . . placed onto an SEM mount or double-sided tape on a microscope slide. These spherules were either left whole or sectioned and given a microprobe polish for analysis by laser ablation or x-ray fluorescence (SEM/XRF)” (SI, p. 16; emphasis added). However, Surovell et al. (2009) and Holliday et al. (2016), along with Pigati et al. (2012), do not mention such analyses in their methods, do not show any scanning electron microscope (SEM) imagery, and do not report any energy dispersive X-ray spectroscopy (EDS) analyses for the spherules. Holliday et al. (2016) acknowledged that their previous work had been criticized because they had “performed no SEM or EDS analyses to determine whether their spherules are volcanic, cosmic, or impact-related, as stipulated by Firestone et al. (2007)” (p. 8). Thus, in spite of being fully aware that SEM-EDS analyses had been stipulated, they performed none. Furthermore, West did not “confirm” any microsphere IDs, as Holliday et al. (2020) claim, but rather confirmed candidate particles for SEM analyses, which were never performed. It is not possible to correctly identify melted YDB spherules without performing such analyses, thus making the results of these three studies meaningless.

In another study, Pinter et al. (2011) investigated two sites in California and claimed that “magnetic spherules are heterogeneously distributed in sediments” and stated that this evidence refuted the YDB impact hypothesis. However, figures 3 and 4 in Pinter et al. show that they did not sample any 12,800-y-old strata and instead acquired samples up to thousands of years younger and older. They failed to sample the YDB age interval at all, resulting in a fatally flawed investigation. Although these authors acquired SEM images to support their argument, they presented no SEM images of melted, dendritic YDB spherules and instead showed only images

of unmelted frambooids and unmelted detrital grains. The lack of SEM imagery calls into question their negative conclusions.

In contrast, eight independent groups followed the prescribed protocol and identified YDB spherules, as reported by Pino et al. (2019):

1. Baker et al. (2008) reported finding a YD-age site in Montana, writing that “the black mat contains . . . unrusted iron micro-meteorites [native iron magnetic spherules]. SEM photos of iron micro-meteorites reveal fusion crusts, flow lines, and micro-impact craters—direct evidence for an extraterrestrial origin.”
2. At Murray Springs, Arizona, Fayek et al. (2012) found that impact material contains iron oxide spherules (frambooids) in a “glassy iron-silica matrix . . . consistent with . . . material associated with meteorite impact sites. . . . Such a high formation temperature is only consistent with impact . . . conditions” (p. 251, 256). Because the frambooids were encased in meltglass, they are inferred to have resulted from a cosmic impact.
3. Ge et al. (2009) reported YD-age “microtektite-like glassy spherules” from three widely separated sites, in France, in the Caspian Sea, and in the Peruvian coastal desert. They state that the evidence “supports an impact origin from an ejecta plume.”
4. Laub (2010) investigated sediment samples from the Hiscock archaeological-paleontological site in western New York state. He performed SEM analyses and reported that “iron-rich spherules, 50–65 μm in diameter, were found in the Pleistocene horizon” (p. 168) spanning the YD onset.
5. Mahaney et al. (2010a, 2010b), before collaborating with the YDB group, found “a mixed assemblage . . . of Fe spherules” (Mahaney et al. 2010a, p. 52) in a YD-age layer and concluded that the “new evidence . . . point[s] tentatively to either an asteroid or comet event that reached far into South America” (Mahaney et al. 2010b, p. 31).
6. Wu et al. (2013) reported YDB spherules from two sites in North America and found evidence of high-temperature melting under low-oxygen conditions. They concluded that Fe-rich spherules could have been generated in a meteorite impact.
7. LeCompte et al. (2012), before collaborating with the YDB group, compared the results of Firestone et al. (2007) and Surovell et al. (2009) at two sites: Blackwater Draw, New Mexico, and Topper, South Carolina. They reported that their “spherule abundances . . . are consistent with those reported by Firestone et al. and inconsistent with those reported by Surovell et al” (p. E2968). They concluded that Surovell et al. were unable to reproduce the results

of Firestone et al. primarily due to their failure to adhere to the (correct) protocol, mainly by failing to perform SEM-EDS analyses. At a third site, Paw Paw Cove, where Surovell et al. reported finding no YDB spherules, LeCompte et al. found abundant YDB spherules, confirmed in all cases by SEM-EDS analyses that Surovell et al. did not perform.

8. Andronikov et al. (2016) reported peak abundances of spherules in the YDB layer at Blackwater Draw, New Mexico. SEM-EDS analyses showed that some spherules were highly enriched in iridium and platinum, supporting the platinum peak observed in YDB bulk sediment. Andronikov et al. stated that “Our observations confirm those made by Firestone et al. (2007) and LeCompte et al. (2012),” (p. 55) contradicting the previously reported lack of a spherule peak by Surovell et al. (2009).

The importance of performing SEM-EDS to identify impact-related YDB spherules is emphasized by Pino et al. (2019), who reported finding several groups of spherulitic particles: (1) high-temperature, melted YDB impact spherules with dendritic textures and/or vesicles; (2) melted glassy volcanic spherules; (3) unmelted, authigenic framboids with numerous cube-like crystals; (4) melted anthropogenic spherules in surface sediments; and (5) unmelted, rounded, detrital grains. Only the first group contains high-temperature, melted spherules of impact origin, and these can be distinguished from the nonimpact spherulitic objects only by using a reflected-light microscope; SEM-EDS analyses are required.

In summary, the eight independent studies in which SEM-EDS analyses were conducted confirmed the presence of high-temperature, melted YDB spherules in layers that date to ~12,800 cal BP. The three that did not conduct SEM-EDS failed to identify melted, impact-related YDB spherules, emphasizing the importance of following the correct protocol.

“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,” in Pigati et al. (2012). (table 6). This is misleading. Holliday et al. (2020) fail to mention that Pigati et al. (2012) collected spherules from the bases of South American volca-

noes. Production of volcanic spherules by these volcanoes has been previously documented (Pino et al. 2019), and yet, Pigati et al. performed no SEM-EDS analyses to differentiate volcanic and high-temperature, impact spherules. Holliday et al. also neglect to mention that for the US Southwest, Pigati et al. found a peak in spherules in the YDB layer at Murray Springs, Arizona, consistent with the previous reports by Firestone et al. (2007); however, by not performing SEM-EDS, Pigati et al. could not have determined their origin.

“Multiple Pt peaks are documented just before the YDB and in the Holocene,” in Moore et al. (2017). (table 6). This is a misleading claim. Holliday et al. did not acknowledge that platinum is ubiquitous in the sediment of all ages at variable concentrations averaging ~0.5 ppb (Rudnick and Gao 2003). All but one of the secondary platinum peaks to which they refer are minor and close to or below background levels and thus are normal concentrations. In any event, the presence of secondary platinum peaks does not refute the YDB impact hypothesis, given the association of the largest platinum peak with up to 15 high-temperature, impact-related proxies.

There are non-YDB platinum peaks in sediment that are associated with volcanism. However, volcanogenic platinum peaks are invariably associated with evidence such as enriched sulfur, tephra, volcanogenic minerals, and crystals (Tankersley et al. 2018). Such volcanic evidence has never been found associated with the platinum peaks at the YDB; instead, the platinum is associated only with impact-related proxies, such as high-temperature spherules and nanodiamonds.

Secondary platinum peaks also may be caused by reworking, which does not refute the YDB hypothesis either. Moore et al. (2017, p. 6) wrote, “For . . . Squires Ridge, multiple abundance peaks in both Pt and high-temperature YDB magnetic spherules (Fig. 3a) begin at the YD onset and continue upward for ~25 cm into post-YD-age sediments. This observation is consistent with known reworking of sediment at this site by aeolian and fluvial processes after ca. 12,800 Cal B.P.” At every site investigated by Moore et al., the largest platinum concentrations occur in the YDB layer.

REFERENCES CITED

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| <p>Anderson, D. G.; Goodyear, A. C.; Kennett, J. P.; and West, A. 2011. Multiple lines of evidence for possible human population decline/settlement reorganization during the early Younger Dryas. <i>Quat. Int.</i> 242:570–583.</p> <p>Andronikov, A. V.; Andronikova, I. E.; Loehn, C. W.; Lafuente, B.; Ballenger, J. A.; Crawford, G. T.; and Lauretta,</p> | <p>D. S. 2016. Implications from chemical, structural and mineralogical studies of magnetic microspherules from around the lower Younger Dryas boundary (New Mexico, USA). <i>Geogr. Ann. Ser. A Phys. Geogr.</i> 98:39–59.</p> <p>Baker, D. W.; Miranda, P. J.; and Gibbs, K. E. 2008. Montana evidence for extra-terrestrial impact event</p> |
|--|---|

- that caused ice-age mammal die-off. EOS: Trans. Am. Geophys. Union 89(23), Joint Assembly suppl., abstract P41A-05.
- Bement, L. C.; Madden, A. S.; Carter, B. J.; Simms, A. R.; Swindle, A. L.; Alexander, H. M.; Fine, S.; and Benamara, M. 2014. Quantifying the distribution of nanodiamonds in pre-Younger Dryas to recent age deposits along Bull Creek, Oklahoma Panhandle, USA. *Proc. Natl. Acad. Sci. USA* 111:1726–1731.
- Brauer, A.; Haug, G. H.; Dulski, P.; Sigman, D. M.; and Negendank, J. F. W. 2008. An abrupt wind shift in western Europe at the onset of the Younger Dryas cold period. *Nat. Geosci.* 1:520–523.
- Cooke, R. 1998. Human settlement of Central America and northernmost South America (14,000–8000 BP). *Quat. Int.* 49–50:177–190.
- Cronin, T. M.; Manley, P.; Brachfield, S.; Manley, T.; Willard, D. A.; Guilbault, J.-P.; Rayburn, J. A.; Thunell, R.; and Berke, M. 2008. Impacts of post-glacial lake drainage events and revised chronology of the Champlain Sea episode 13-9 ka. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 262:46–60.
- Daniau, A.-L.; Harrison, S. P.; and Bartlein, P. J. 2010. Fire regimes during the Last Glacial. *Quat. Sci. Rev.* 29(21–22):2918–2930.
- Daulton, T. L.; Amari, S.; Scott, A. C.; Hardiman, M.; Pinter, N.; and Anderson, R. S. 2017. Comprehensive analysis of nanodiamond evidence relating to the Younger Dryas Impact Hypothesis. *J. Quat. Sci.* 32:7–34.
- de Pablo, J. F. L.; Gutiérrez-Roig, M.; Gómez-Puche, M.; McLaughlin, R.; Silva, F.; and Lozano, S. 2019. Palaeodemographic modelling supports a population bottleneck during the Pleistocene-Holocene transition in Iberia. *Nat. Commun.* 10(1):1872. <https://doi.org/10.1038/s41467-019-09833-3>.
- Durda, D. D., and Kring, D. A. 2004. Ignition threshold for impact-generated fires. *J. Geophys. Res.* 109:E08004.
- Fayek, M.; Anovitz, L. M.; Allard, L. F.; and Hull, S. 2012. Framboidal iron oxide: chondrite-like material from the black mat, Murray Springs, Arizona. *Earth Planet. Sci. Lett.* 319–320:251–258.
- Firestone, R. B.; West, A.; Kennett, J. P.; Becker, L.; Bunch, T. E.; Revay, Z. S.; Schultz, P. H.; et al. 2007. Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling. *Proc. Natl. Acad. Sci. USA* 104:16,016–16,021.
- Fischer, H.; Schüpbach, S.; Gfeller, G.; Bigler, M.; Röthlisberger, R.; Erhardt, T.; Stocker, T. F.; Mulvaney, R.; and Wolff, E. W. 2015. Millennial changes in North American wildfire and soil activity over the Last Glacial cycle. *Nat. Geosci.* 8:723–727. <https://doi.org/10.1038/ngeo2495>.
- Florenskiy, K. P. 1965. Preliminary results from the 1961 Combined Tunguska Meteorite Expedition. *Spectrum Translation and Research*, transl. <http://abob.libs.uga.edu/bobk/tungmet.html>. Originally published in Russian in 1963. *Meteoritika* 23:3–37, 279.
- Ge, T.; Courty, M. M.; and Guichard, F. 2009. Field-analytical approach of land-sea records for elucidating the Younger Dryas Boundary syndrome. EOS: Trans. Am. Geophys. Union 90(52), Fall Meeting suppl., abstract PP31D-1390.
- Holliday, V. T.; Bartlein, P. J.; Scott, A. C.; and Marlon, J. R. 2020. Extraordinary biomass-burning episode and impact winter triggered by the Younger Dryas cosmic impact ~12,800 years ago, parts 1 and 2: a discussion. *J. Geol.* 128:XXX–XXX.
- Holliday, V. T.; Surovell, T.; and Johnson, E. 2016. A blind test of the Younger Dryas Impact Hypothesis. *PLoS ONE* 11:e0155470. <https://doi.org/10.1371/journal.pone.0155470>.
- Holliday, V. T.; Surovell, T.; Meltzer, D. J.; Grayson, D. K.; and Boslough, M. 2014. The Younger Dryas Impact Hypothesis: a cosmic catastrophe. *J. Quat. Sci.* 29:525–530.
- Jenniskens, P.; Popova, O. P.; Glazachev, D. O.; Podobnaya, E. D.; and Kartashova, A. P. 2019. Tunguska eyewitness accounts, injuries, and casualties. *Icarus* 327:4–18.
- Kaiser, K.; Hilgers, A.; Schlaak, N.; Jankowski, M.; Kuhn, P.; Bussemer, S.; and Przegliska, K. 2009. Palaeopedological marker horizons in northern central Europe: characteristics of Lateglacial Usselo and Finow soils. *Boreas* 38:591–609.
- Kennett, D. J.; Kennett, J. P.; West, A.; Mercer, C.; Que Hee, S. S.; Bement, L.; Bunch, T. E.; Sellers, M.; and Wolbach, W. S. 2009. Nanodiamonds in the Younger Dryas Boundary sediment layer. *Science* 323:94.
- Kennett, J. P.; Kennett, D. J.; Culleton, B. J.; Aura Tortosa, J. E.; Bischoff, J. L.; Bunch, T. E.; Randolph, D. I., Jr.; et al. 2015. Bayesian chronological analyses consistent with synchronous age of 12,835–12,735 cal BP for Younger Dryas Boundary on four continents. *Proc. Natl. Acad. Sci. USA* 112:E4344–E4353.
- Kennett, J. P.; Kennett, D. J.; LeCompte, M. A.; and West, A. 2018. Potential consequences of the YDB cosmic impact at 12.8 ka. In Goodyear, A. C., and Moore, C. R., eds. *Early human life on the Southeastern Coastal Plain*. Gainesville, University Press of Florida, p. 175–192.
- Kinzie, C. R.; Que Hee, S. S.; Stich, A.; Tague, K. A.; Mercer, C.; Razink, J. J.; Kennett, D. J.; et al. 2014. Nanodiamond-rich layer across three continents consistent with major cosmic impact at 12,800 cal BP. *J. Geol.* 122:475–506.
- Kruege, M. A.; Stankiewicz, A.; Crelling, J. C.; and Montanari, A. 1994. Fossil charcoal in Cretaceous-Tertiary boundary strata: Evidence for catastrophic firestorm and megawave. *Geochim. Cosmochim. Acta* 58:1393–1397.
- Laub, R. 2010. Observations from the Hiscock site (New York) bearing on a possible late-Pleistocene extraterrestrial impact event. *Curr. Res. Pleistoc.* 27:168–171.
- LeCompte, M.; Adedeji, V.; Kennett, J.; Bunch, T. E.; Wolbach, W. S.; and West, A. 2018. Brief overview of the Younger Dryas Cosmic Impact datum layer 12,800 years ago and its archaeological utility. In Goodyear, A. C., and Moore, A. M., eds. *Early human life on the Southeastern*

- Coastal Plain. Gainesville, University Press of Florida, p. 155–174.
- LeCompte, M. A.; Goodyear, A. C.; Demitroff, M. N.; Batchelor, D.; Vogel, E. K.; Mooney, C.; Rock, B. N.; and Seidel, A. W. 2012. Independent evaluation of conflicting microspherule results from different investigations of the Younger Dryas impact hypothesis. *Proc. Natl. Acad. Sci. USA* 109:E2960–E2969.
- Mahaney, W. C.; Kalm, V.; Krinsley, D. H.; Tricart, P.; Schwartz, S.; Dohm, J.; Kim, K. J.; et al. 2010a. Evidence from the northwestern Venezuelan Andes for extraterrestrial impact: the black mat enigma. *Geomorphology* 116:48–57.
- Mahaney, W. C.; Krinsley, D.; and Kalm, V. 2010b. Evidence for a cosmogenic origin of fired glaciofluvial beds in the northwestern Andes: correlation with experimentally heated quartz and feldspar. *Sediment. Geol.* 231:31–40.
- Mayewski, P. A.; Meeker, L. D.; Twickler, M. S.; Whitlow, S. I.; Yang, Q.; Lyons, W. B.; and Prentice, M. 1997. Major features and forcing of high-latitude Northern Hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series. *J. Geophys. Res.* 102(C12):26,345–26,366.
- Moore, C. R.; West, A.; LeCompte, M. A.; Brooks, M. J.; Daniel, I. R., Jr.; Goodyear, A. C.; Ferguson, T. A.; et al. 2017. Widespread platinum anomaly documented at the Younger Dryas onset in North American sedimentary sequences. *Sci. Rep.* 7:44031. <https://doi.org/10.1038/srep44031>.
- Napier, W. M. 2010. Palaeolithic extinctions and the Taurid Complex. *Mon. Notes R. Astron. Soc.* 405:1901–1906.
- Petaev, M. I.; Huang, S.; Jacobsen, S. B.; and Zindler, A. 2013. Large Pt anomaly in the Greenland ice core points to a cataclysm at the onset of Younger Dryas. *Proc. Natl. Acad. Sci. USA* 110:12,917–12,920.
- Pigati, J. S.; Latorre, C.; Rech, J. A.; Betancourt, J. L.; Martínez, K. E.; and Budahn, J. R. 2012. Accumulation of impact markers in desert wetlands and implications for the Younger Dryas Impact Hypothesis. *Proc. Natl. Acad. Sci. USA* 109:7208–7212.
- Pino, M.; Martel-Cea, A.; Astorga, G.; Abarzúa, A. M.; Cossio, N.; Navarro, X.; Lira, M. P.; et al. 2019. Sedimentary record from Patagonia, southern Chile supports cosmic-impact triggering of biomass burning, climate change, and megafaunal extinctions at 128 ka. *Sci. Rep.* 9:4413.
- Pinter, N.; Scott, A. C.; Daulton, T. L.; Podoll, A.; Koeberl, C.; Anderson, R. S.; and Ishman, S. E. 2011. The Younger Dryas Impact Hypothesis: a requiem. *Earth-Sci. Rev.* 106:247–264.
- Power, M. J.; Marlon, J.; Ortiz, N.; Bartlein, P. J.; Harrison, S. P.; Mayle, F. E.; Ballouche, A.; et al. 2008. Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. *Clim. Dyn.* 30:887–907.
- Ram, M., and Koenig, G. 1997. Continuous dust concentration profile of pre-Holocene ice from the Greenland Ice Sheet Project 2 ice core: dust stadials, interstadials, and the Eemian. *J. Geophys. Res. Oceans* 102(C12):26,641–26,648.
- Rasmussen, S. O.; Bigler, M.; Blockley, S.; Blunier, T.; Buchardt, B.; Clausen, H.; Cvijanovic, I.; et al. 2014. A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. *Quat. Sci. Rev.* 106:14–28.
- Robertson, D. S.; Lewis, W. M.; Sheehan, P. M.; and Toon, O. B. 2013. K-Pg extinction: reevaluation of the heat-fire hypothesis. *J. Geophys. Res. Biogeosci.* 118(1):329–336.
- Rudnick, R. L., and Gao, S. 2003. Composition of the continental crust. In Rudnick, R. L., ed. *The crust*. Vol. 3 of *Treatise on geochemistry*. Amsterdam, Elsevier, p. 1–64.
- Scott, A. C.; Lomax, B. H.; Collinson, M. E.; Upchurch, G. R.; and Beerling, D. J. 2000. Fire across the K/T boundary: initial results from the Sugarite Coal, New Mexico, USA. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 164:381–395.
- Seierstad, I. K.; Abbott, P. M.; Bigler, M.; Blunier, T.; Bourne, A. J.; Brook, E.; Buchardt, S. L.; et al. 2014. Consistently dated records from the Greenland GRIP, GISP2 and NGRIP ice cores for the past 104 ka reveal regional millennial-scale $\delta^{18}\text{O}$ gradients with possible Heinrich event imprint. *Quat. Sci. Rev.* 106:29–46.
- Steffensen, J. P.; Andersen, K. K.; Bigler, M.; Clausen, H. B.; Dahl-Jensen, D.; Fischer, H.; Goto-Azuma, K.; et al. 2008. High-resolution Greenland ice core data show abrupt climate change happens in few years. *Science* 321(5889):680–684.
- Surovell, T.; Holliday, V. T.; Gingerich, J. A. M.; Ketron, C.; Haynes, C. V., Jr.; Hilman, I.; Wagner, D. P.; Johnson, E.; and Claes, P. 2009. An independent evaluation of the Younger Dryas extraterrestrial impact hypothesis. *Proc. Natl. Acad. Sci. USA* 106:18,155–18,158.
- Surovell, T. A.; Pelton, S. R.; Anderson-Sprecher, R.; and Myers, A. D. 2016. Test of Martin's overkill hypothesis using radiocarbon dates on extinct megafauna. *Proc. Natl. Acad. Sci. USA* 113:886–891.
- Tankersley, T. B.; Dunning, N. P.; Owen, L. A.; Huff, W. D.; Park, J. H.; Kim, C.; Lentz, D. L.; and Sparks-Stokes, D. 2018. Positive platinum anomalies at three late Holocene high magnitude volcanic events in Western Hemisphere sediments. *Sci. Rep.* 8:11298. <https://doi.org/10.1038/s41598-018-29741-8>.
- Teller, J.; Boyd, M.; LeCompte, M.; Kennett, J.; West, A.; Telka, A.; Diaz, A.; et al. Forthcoming. A multi-proxy study of changing environmental conditions in a Younger Dryas sequence in southwestern Manitoba, Canada, and evidence for an extraterrestrial event. *Quat. Res.*
- Tian, H.; Schryvers, D.; and Claes, P. 2011. Nanodiamonds do not provide unique evidence for a Younger Dryas impact. *Proc. Natl. Acad. Sci. USA* 108:40–44.
- van der Hammen, T., and van Geel, B. 2008. Charcoal in soils of the Allerød-Younger Dryas transition were the result of natural fires and not necessarily the effect of an extra-terrestrial impact. *Neth. J. Geosci.* 87:359–361.

- van Hoesel, A.; Hoek, W. Z.; van der Plicht, J.; Pennock, G. M.; and Drury, M. R. 2012. Nanodiamonds and wildfire evidence in the Usselo horizon postdate the Allerød–Younger Dryas boundary. *Proc. Natl. Acad. Sci. USA* 109:7648–7653.
- Wolbach, W. S. 1990. Carbon across the Cretaceous–Tertiary boundary. PhD dissertation, University of Chicago.
- Wolbach, W. S.; Ballard, J. P.; Mayewski, P. A.; Adedeji, V.; Bunch, T. E.; Firestone, R. B.; French, T. A.; et al. 2018*a*. Extraordinary biomass-burning episode and impact winter triggered by the Younger Dryas cosmic impact ~12,800 years ago. 1. Ice cores and glaciers. *J. Geol.* 126:165–184.
- Wolbach, W. S.; Ballard, J. P.; Mayewski, P. A.; Parnell, A. C.; Cahill, N.; Adedeji, V.; Bunch, T. E.; et al. 2018*b*. Extraordinary biomass-burning episode and impact winter triggered by the Younger Dryas cosmic impact ~12,800 years ago. 2. Lake, marine, and terrestrial sediments. *J. Geol.* 126:185–205.
- Wolbach, W. S.; Gilmour, I.; and Anders, E. 1990. Major wildfires at the Cretaceous/Tertiary boundary. *In* Sharpton, V. L., and Ward, P., eds. *Global catastrophes in Earth history: an interdisciplinary conference on impacts, volcanism, and mass mortality*. *Geol. Soc. Am. Spec. Pap.* 247:391–400.
- Wolbach, W. S.; Widicus, S. L.; and Kyte, F. T. 2003. A search for soot from global wildfires in central Pacific Cretaceous–Tertiary boundary and other extinction and impact horizon sediments. *Astrobiology* 3:91–97.
- Wu, Y.; Sharma, M.; LeCompte, M. A.; Demitroff, M. N.; and Landis, J. D. 2013. Origin and provenance of spherules and magnetic grains at the Younger Dryas boundary. *Proc. Natl. Acad. Sci. USA* 110:E3557–E3566.