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Appendix from W. S. Wolbach et al., "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., vol. 126, no. 2, p. 000)

Supplemental Material

Supplemental Figures

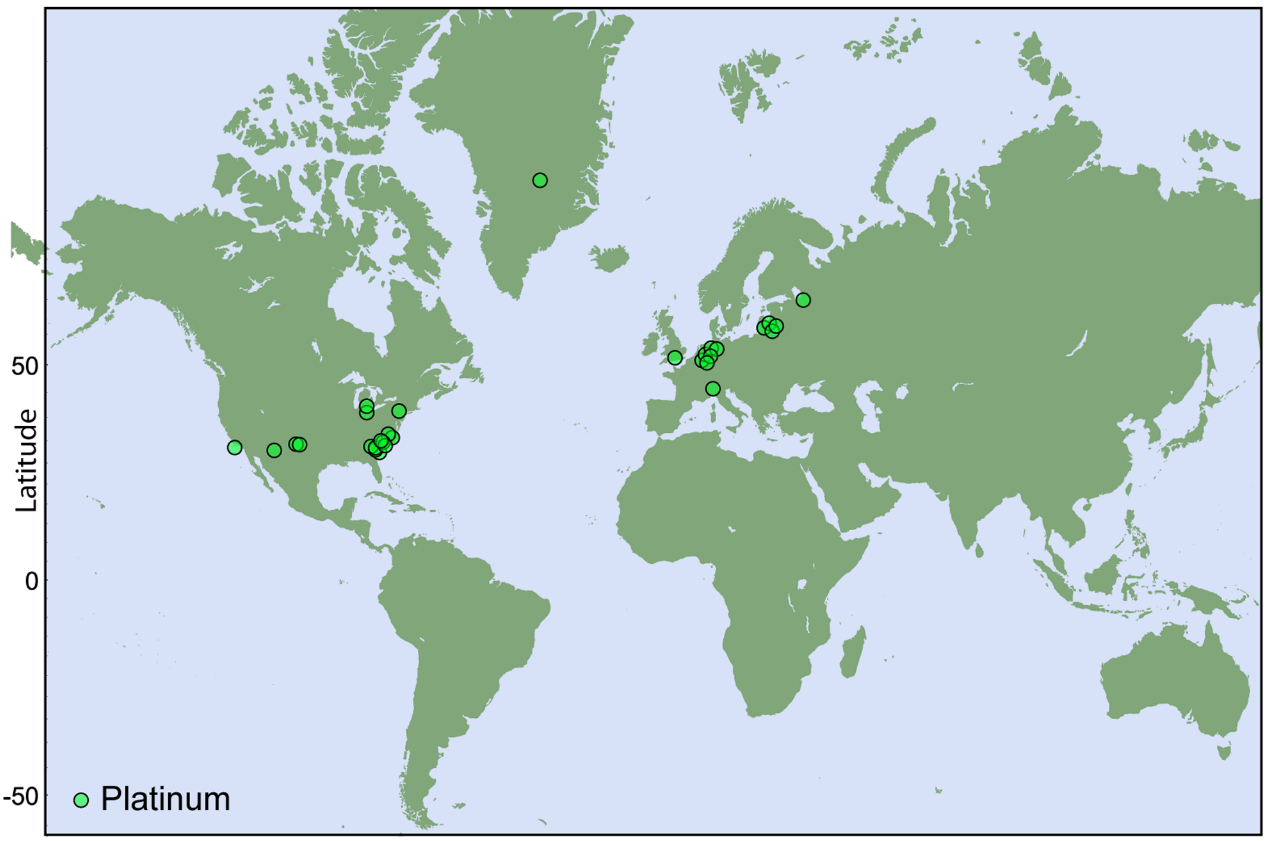

Figure A1. Locations exhibiting Younger Dryas boundary (YDB) Pt peaks. Twenty-six of the 30 YDB sites displaying peaks in Pt concentrations: 4 of 8 in this study and 22 previously studied sites for North America, Europe, and Asia. One site is in Greenland (Petaev et al. 2013), one in Russia (Andronikov et al. 2014), four in Lithuania (Andronikov et al. 2015), one on the French-Italian border (Mahaney et al. 2016*b*), three in the Netherlands (Andronikov et al. 2016*b*), two in Belgium (Andronikov et al. 2016*b*), one in the United Kingdom (this study), one in Germany (this study), and 16 in the United States (Andronikov and Andronikova 2016; Moore et al. 2017; and this study).

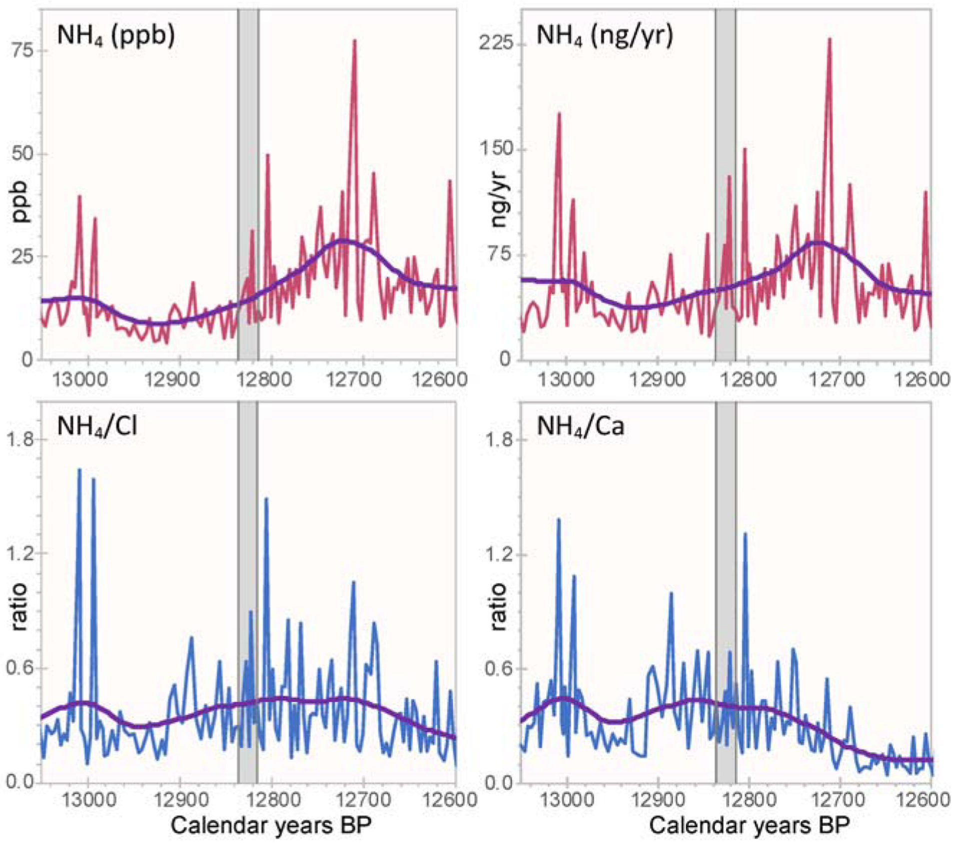

Figure A2. Apparent ramp-up in Greenland Ice Sheet Project 2 NH_4 after the Younger Dryas (YD) onset. *Top left*, raw NH_4 values. *Top right*, NH_4 flux values. *Bottom*, Results of normalizing NH_4 values to Cl (*left*) and Ca (*right*), showing that all values covary. Purple curves represent lowess-smoothed values. These graphs suggest that the apparent century-long ramp-up in NH_4 is not an actual increase in biomass burning but rather an artifact of the increase in climate-related dustiness at the YD onset. High peaks remain, but with reduced amplitude, in some cases.

Supplemental Tables

Table A1. Younger Dryas Boundary (YDB) Sites: Location, Age of YDB Layer, and Selected References

Sites (35)	Location	Continent	Modeled ages (cal BP)	Uncertainty (68% CI)	Latitude	Longitude	References
Well-dated YDB sites with biomass-burning proxies:							
Aalsterhut	Netherlands	Europe	12,780	35	~51.4272	5.5853	van Hoesel et al. 2012, 2014; Kinzie et al. 2014
Abu Hureyra	Syria	Asia	12,825	55	35.8667	38.4000	Bunch et al. 2012; Wittke et al. 2013; Kinzie et al. 2014
Arlington Canyon	California	North America	12,805	55	33.9886	−120.1580	Kennett et al. 2008, 2009*b*; Wittke et al. 2013; Kinzie et al. 2014
Blackville	South Carolina	North America	12,820	1080	33.3615	−81.3043	Bunch et al. 2012; Wittke et al. 2013; Kinzie et al. 2014
Blackwater Draw	New Mexico	North America	12,775	365	34.2756	−103.3261	Becker et al. 2009; LeCompte et al. 2012; Wittke et al. 2013; Wu et al. 2013; Andronikov et al. 2015

Table A1 (*Continued*)

Sites (35)	Location	Continent	Modeled ages (cal BP)	Uncertainty (68% CI)	Latitude	Longitude	References
Bull Creek	Oklahoma	North America	12,840	75	~36.6400	−100.8500	Kennett et al. 2008, 2009*a*, 2009*b*; Bement et al. 2014; Kinzie et al. 2014
Daisy Cave	California	North America	12,730	320	34.0421	−120.3200	Erlandson et al. 1996; Erlandson 2007; Becker et al. 2009; Wittke et al. 2013; Kinzie et al. 2014
Indian Creek	Montana	North America	12,750	425	46.3144	−111.6302	Baker et al. 2008; Kinzie et al. 2014
Lake Cuitzeo	Mexico	South/Central America	12,850	570	19.9365	−101.1556	Israde-Alcántara et al. 2012; Wittke et al. 2013; Kinzie et al. 2014
Lake Hind	Canada	North America	12,745	180	49.4400	−100.6977	Firestone et al. 2007, 2010; Firestone 2009; Kennett et al. 2009*a*; Kinzie et al. 2014
Lindenmeier	Colorado	North America	12,775	180	40.9764	−105.1041	Kinzie et al. 2014
Lingen	Germany	Europe	12,735	85	52.5087	7.3138	Wittke et al. 2013; Kinzie et al. 2014
Lommel	Belgium	Europe	12,735	790	51.2362	5.2546	Beets et al. 2008; Tian et al. 2011; Wittke et al. 2013; Wu et al. 2013; Kinzie et al. 2014
Melrose	Pennsylvania	North America	12,255	2405	41.9254	−75.5104	Bunch et al. 2012; Wittke et al. 2013; Wu et al. 2013; Kinzie et al. 2014
Mucuñuque	Venezuela	South/Central America	12,845	630	8.7757	−70.8181	Mahaney et al. 2010*a*, 2010*b*, 2011*a*, 2011*b*; Mahaney and Krinsley 2012; Wittke et al. 2013
Murray Springs	Arizona	North America	12,750	235	31.5709	−110.1779	Firestone et al. 2007; Haynes 2007, 2008; Becker et al. 2009; Kennett et al. 2009*a*; Haynes et al. 2010; Andronikov et al. 2011; Pigati et al. 2012; Wittke et al. 2013; Wu et al. 2013; Kinzie et al. 2014
Ommen	Netherlands	Europe	12,750	560	52.5269	6.3635	Wittke et al. 2013; Kinzie et al. 2014
Parangueo Lake	Mexico	South/Central America	12,843	228	20.3886	−101.2572	Domínguez-Vázquez 2012
Santa Maira	Spain	Europe	12,785	295	38.7302	−.2150	Kinzie et al. 2014
Sheriden Cave	Ohio	North America	12,840	120	40.9650	−83.4260	Tankersley 1997, 1999, 2009; Tankersley et al. 1997, 2001; Tankerseley and Landefeld 1998; Tankersley and Redmond 1999*a*, 1999*b*; Redmond and Tankersley 2005, 2011; Wittke et al. 2013; Wu et al. 2013; Kinzie et al. 2014
Stara Jimka	Czech Republic	Europe	12,805	70	49.0687	13.4029	Mentlík et al. 2010
Talega	California	North America	12,860	150	33.4702	−117.6004	Wittke et al. 2013
Topper	South Carolina	North America	12,785	185	33.0057	−81.4892	Goodyear 1999, 2005, 2006, 2010, 2013; Goodyear and Steffy 2003; Goodyear et al. 2007; Waters et al. 2009*a*, 2009*b*; LeCompte et al. 2012; Wittke et al. 2013; Kinzie et al. 2014
Inadequately dated YDB sites with biomass-burning proxies:							
Audenge	France	Europe	. . .	. . .	~44.7000	−1.0300	Ge et al. 2009
Caspian Sea	Asia	Asia	. . .	. . .	~38.6000	51.5000	Ge et al. 2009
Chobot	Canada	North America	. . .	. . .	52.9560	−114.7348	Firestone et al. 2007, 2010; Firestone 2009; Kennett et al. 2009*a*; Wittke et al. 2013; Kinzie et al. 2014
Gainey	Michigan	North America	. . .	. . .	42.8859	−83.6143	Wittke et al. 2013; Wu et al. 2013
Guil-Mt. Viso	France/Italy	Europe	. . .	. . .	44.6987	7.0346	Mahaney and Keiser 2012; Wittke et al. 2013; Mahaney et al. 2016*a*

Table A1 (*Continued*)

Sites (35)	Location	Continent	Modeled ages (cal BP)	Uncertainty (68% CI)	Latitude	Longitude	References
Halls Cave	Texas	North America	. . .	. . .	30.1352	−99.5380	Kinzie et al. 2014
Kangerlussuaq	Greenland	Europe	. . .	. . .	67.1564	−50.0233	Kurbatov et al. 2010; Kinzie et al. 2014
Kimbel Bay	North Carolina	North America	. . .	. . .	34.9818	−78.7768	Wittke et al. 2013
Morley	Canada	North America	. . .	. . .	~51.14573	−114.8663	Firestone et al. 2007, 2010; Firestone 2009
Newtonville	New Jersey	North America	. . .	. . .	39.5695	−74.9108	LeCompte et al. 2012; Wittke et al. 2013; Wu et al. 2013; Kinzie et al. 2014
Paijan	Peru	South/Central America	. . .	. . .	ca. −7.7000	−79.3000	Ge et al. 2009
Paw Paw Cove	Maryland	North America	. . .	. . .	38.6974	−76.3422	LeCompte et al. 2012; Wittke et al. 2013
Watcombe Bottom	United Kingdom	Europe	. . .	. . .	50.5939	−1.2308	Wittke et al. 2013; Kinzie et al. 2014

Note. CI = confidence interval.

Table A2. Younger Dryas Boundary (YDB) Sites: Age of YDB Layer, with Types of YDB Proxies Present, as Discussed in Previous Publications

Sites (35)	Modeled ages (cal BP)	Uncertainty (68% CI)	Charcoal/ ash	Carbon spherules	Glass-like carbon	AC/ soot	Fullerenes	PAHs	Dark layer (black mat)	Impact-related spherules	High-temp. melt-glass	Extinct megafauna	Nanodiamonds in sediments	Nanodiamonds, CS/GLC	Ni, Co, Cr, Ir, Os, REEs
Dated carbon-rich YDB sites:															
Aalsterhut	12,780	35	•	•	•				•					•	
Abu Hureyra	12,825	55	•		•	ND			•	•	•	•	•		•
Arlington Canyon	12,805	55	•	•	•	•			•	•	•	•	•	•	
Blackville	12,820	1080	•	•	•	•				•	•			•	•
Blackwater Draw	12,775	365	•		•	ND	•	•	•	•		•			•
Bull Creek	12,840	75				•							•		
Daisy Cave	12,730	320	•		•	ND	•	•	•	•					
Indian Creek	12,750	425		•					•					•	
Lake Cuitzeo	12,850	570	•	•					•	•		•	•		
Lake Hind	12,745	180	•	•	•	ND			•			•	•		•
Lindenmeier	12,775	180	•			•			•		•	•	•		
Lingen	12,735	85	•	•	•				•	•				•	
Lommel	12,735	790	•	•	•	ND			•	•				•	
Melrose	12,255	2405	•	•	•	•			•	•	•		•		
Mucuñuque	12,845	630		•					•	•	•		•		
Murray Springs	12,750	235	•	•	•	•	•	•	•	•	•	•	•		•
Ommen	12,750	560	•	•	•				•	•				•	
Parangueo Lake	12,843	228	•							•					
Santa Maira	12,785	295	•	•	•				•					•	
Sheriden Cave	12,840	120	•	•					•	•		•		•	
Stara Jimka	12,805	70	•							•					
Talega	12,860	150							•	•					
Topper	12,785	185	•	•	•					•				•	•
Inadequately dated carbon-rich YDB sites:															
Audenge	...	...	•	•	•				•	•	•			•	
Caspian Sea	...	...	•	•	•				•	•	•				
Chobot	...	...	•	•	•	ND			•	•	•		•	•	
Gainey	...	...	•	•	•	ND			•	•					•
Guil-Mt. Viso	...	...		•	•					•					•
Halls Cave	...	...				•			•				•		
Kangerlussuaq	...	...		•						•			•		
Kimbel Bay	...	...		•						•					
Morley	...	...	•		•				•	•					•
Newtonville	...	...	•						•	•			•		
Paijan	...	...	•	•	•				•	•	•			•	
Paw Paw Cove	...	...								•					•
Watcombe Bottom	...	...	•	•					•	•				•	
Total			27	24	20	7	3	3	27	29	11	8	13	14	10

Note. AC/soot = aciniform carbon; CI = confidence interval; CS/GLC = carbon spherules/glass-like carbon; ND = not detected; PAHs = polycyclic aromatic hydrocarbons; REEs = rare earth elements. Blank cell = not investigated.

Table A3. References for Younger Dryas Boundary (YDB) Biomass-Burning and Impact-Related Proxies or Consequences

Proxy	Proponents	Independent workers	Critics
Cosmic-impact spherules	Firestone et al. 2007, 2010; Firestone 2009; Bunch et al. 2012; Israde-Alcántara et al. 2012	Haynes et al. 2010; Mahaney et al. 2010*a*, 2010*b*, 2011*a*, 2011*b*, 2013; Redmond and Tankersley 2011; Fayek et al. 2012; LeCompte et al. 2012; Mahaney and Keiser 2012	Surovell et al. 2009; Pinter et al. 2011; Boslough et al. 2012; Pigati et al. 2012
Meltglass (scoria-like objects)	Bunch et al. 2012	Mahaney et al. 2010*a*, 2010*b*, 2011*a*, 2011*b*, 2013; Fayek et al. 2012; Mahaney and Krinsley 2012	. . .
Carbon spherules, glass-like carbon, aciniform carbon, PAHs, fullerenes	Firestone et al. 2007, 2010; Firestone 2009; Israde-Alcántara et al. 2012; Maiorana-Boutilier et al. 2016	Baker et al. 2008; Mahaney et al. 2010*a*, 2010*b*, 2011*a*, 2011*b*, 2013; Redmond and Tankersley 2011; Mahaney and Krinsley 2012	Scott et al. 2010; Pinter et al. 2011; Boslough et al. 2012; van Hoesel et al. 2012, 2014
Nanodiamonds	Firestone et al. 2007; Kennett et al. 2009*a*, 2009*b*; Kurbatov et al. 2010; Israde-Alcántara et al. 2012; Kinzie et al. 2014	Baker et al. 2008; Tian et al. 2011; Redmond and Tankersley 2011; Bement et al. 2014	Daulton et al. 2010; Pinter et al. 2011; Boslough et al. 2012; van Hoesel et al. 2012, 2014
Iridium	Firestone et al. 2007, 2010; Firestone 2009	Haynes et al. 2010; Andronikov et al. 2011, 2016*a*; Marshall et al. 2011	Paquay et al. 2009; Pinter et al. 2011; Boslough et al. 2012; Pigati et al. 2012
Platinum	Mahaney et al. 2016*b*; Moore et al. 2017	Petaev et al. 2013	. . .
Osmium	. . .	Beets et al. 2008; Sharma et al. 2009; Andronikov et al. 2011; Wu et al. 2013	Paquay et al. 2009
Nickel, cobalt, chromium, thorium, ^{14}C, ^{10}Be, ^{26}Al, REEs	Firestone et al. 2007, 2010; Firestone 2009	Melott et al. 2010; Andronikov et al. 2011	. . .
Extinctions, human population declines	Firestone et al. 2007, 2010; Firestone 2009; Anderson et al. 2011	Melott et al. 2010; Andronikov et al. 2011	. . .

Note. PAHs = polycyclic aromatic hydrocarbons; REEs = rare earth elements.

Table A4. Ice-Core Locations and Source References

Ice-core site	Country	Latitude	Longitude	References
GISP2	Greenland	72.6000	−38.5000	Mayewski et al. 1993, 1997; Stuiver et al. 1995
GRIP	Greenland	72.5800	−37.6300	Legrand et al. 1992; Fuhrer and Legrand 1997
NGRIP	Greenland	75.1000	−42.3300	Steffensen et al. 2008; Fischer et al. 2015
Belukha	Russia	49.8072	86.5786	Fujita et al. 2004; Aizen et al. 2006
Taylor Dome	. . .	−77.7800	158.7200	Mayewski et al. 1996; Steig et al. 1998, 2000
Taylor Glacier	. . .	−77.8426	161.7334	Brook et al. 2015

Note. These ice cores were selected because available data included robust age-depth scales and measurements of biomass-burning proxies. Most data were downloaded from ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore. GISP2 = Greenland Ice Sheet Project 2; GRIP = Greenland Ice Core Project; NGRIP = North Greenland Ice Core Project.

Supplemental Text

Biomass Burning in Previous Cosmic-Impact Events

Extraterrestrial events, such as the K-Pg impact, commonly produce biomass-burning markers, including charcoal (Belcher et al. 2003), AC/soot (as in Wolbach 1990; Wolbach et al. 2018), carbon spherules (Adatte et al. 2005), annealed organic matter in framboidal pyrite (Mahaney 2002), and aerosol- and gas-phase polycyclic aromatic hydrocarbons (Belcher et al. 2003). Atmospheric loading of AC/soot from biomass burning and other impact-related aerosols possibly triggered extreme climate change after the K-Pg impact (Kaiho et al. 2016), just as is proposed for the YDB impact event. All of these impact-related, biomass-burning markers are also present in the YDB layer.

In 1908, the cosmic aerial detonation over Tunguska, Siberia, produced a high-pressure wave energetic enough to topple 80 million trees (~2000 km^2; Svetsov 2008). The thermal pulse scorched trees near the epicenter, before transient high temperatures almost instantly subsided from >10,000°C at the center of the airburst many kilometers above the ground. Temperatures and the severity of damage decreased outward with distance from ground zero, initially igniting ~200 km^2, then spreading to consume ~500 km^2 of forest (Svetsov 2008). Some trees left standing beneath the airburst's epicenter were scorched but still alive (Florenskiy 1965), indicating that temperatures at ground level beneath the Tunguska fireball did not remain high long enough to kill them. For fallen trees, the radiant pulse scorched bark facing the airburst but produced little charcoal. Ground fires burned mostly needles, twigs, and underbrush and charred the bottom halves of fallen trees (Florenskiy 1965), although in some cases both top and bottom were charred (Svetsov 2008). The burn layer contained charcoal amounts similar to those associated with normal low-intensity ground fires, such as those caused by lightning (Svetsov 2008), consistent with the observation that the impact-ignited fires did not appear to incinerate any trees (Florenskiy 1965).

For the 65 Ma K-Pg impact event, some studies have found low amounts of impact-related charcoal, interpreted to have resulted from low-temperature wildfires (Belcher et al. 2003). In an alternate explanation, K-Pg charcoal quantities are inferred to have resulted from high-intensity, multicontinental wildfires that turned most charcoal into ash and soot at very high temperatures (Wolbach et al. 1985; Wolbach and Anders 1989; Wolbach 1990; Hammes et al. 2007; Robertson et al. 2013). Whichever interpretation is correct, the widespread K-Pg fires produced mostly low to moderate quantities of charcoal. This is an important point, because if the YDB impact was a large, highly energetic event, some propose that it must have produced a correspondingly large amount of high-temperature charcoal (Scott et al. 2010, 2017; van Hoesel et al. 2012, 2014). Instead, the Tunguska and K-Pg impacts produced quantities of charcoal that were lower than or comparable to those from typical nonimpact wildfires.

In estimating YDB wildfire temperatures, several groups (e.g., Scott et al. 2010, 2017; van Hoesel et al. 2012; Hardiman et al. 2016) used charcoal reflectance (Braadbaart and Poole 2008) to erroneously conclude that YDB wildfire temperatures were low and therefore could not be impact related. Lower-temperature fires produce more charcoal with lower reflectance and less ash, and, conversely, higher-temperature fires produce less charcoal with higher reflectance and more ash. A significant limitation of the reflectance method in estimating temperatures from cosmic-impact events, however, is that extremely high-temperature fires near the epicenter of an extraterrestrial impact can vaporize vegetation and produce no charcoal from which to measure reflectance. In addition, temperatures rapidly decrease with distance from the fireball, and so low-temperature, impact-related fires away from the epicenter will produce only low-reflectance charcoal. Thus, known impact events produce both high- and low-intensity fires, with the latter predominating, and the presence of low-reflectance charcoal cannot be used to preclude impacts as the source of biomass burning, as proposed by others.

The YDB impact is envisioned as the encounter with fragmented debris from a giant comet that also was responsible for igniting numerous individual wildfires, rather than one large, ubiquitous wildfire, but through a different mechanism. Instead of ignition by the influx of molten ejecta, YDB fires are predicted to have resulted from the collision with numerous cometary fragments that potentially caused thousands of separate Tunguska-like airbursts that ignited wildfires beneath the fireball, thus creating a patchwork of numerous individual, isolated wildfires spread over several continents.

In addition, at the end of the Ice Age, areas of North America adjacent to the ice sheets were covered by sparse vegetation that would not have supported extensive wildfires. Locally, each of those individual wildfires is expected to have produced normal amounts of charcoal, similar to that of nonimpact-related wildfires. On the other hand, those wildfires should have collectively produced a high concentration of biomass-burning aerosols (e.g., ammonium [NH_4] and nitrogen compounds [NO_x]) that would have appeared to result from a single, large biomass-burning event. Such evidence is preserved in the Greenland ice sheet.

Sources of Ice-Core Data

Data are from https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/ice-core.

Age-Depth Issues with Greenland Ice Cores

Age-related differences between ice-core data sets can arise because of uncertainties inherent in each data set or because researchers used different proxies for climate change. For example, Steffensen et al. (2008) measured five different proxies for climate change and obtained five seemingly contradictory dates for the YD onset, from oldest to youngest: (1) 12,896 $\pm$ 1.5 cal BP for deuterium excess (d), a proxy of past ocean surface temperatures; (2) 12,787 $\pm$ 24 cal BP for annual layer thickness (λ), a measure of the rate of snowfall; (3) 12,737 $\pm$ 8.9 cal BP for calcium ions (Ca^{2+}), a proxy for source strength and transport conditions from terrestrial sources; (4) 12,735 ± 8.9 cal BP for dust concentrations, a proxy for source strength and transport conditions from terrestrial sources; and (5) 12,712 ± 74 for $\delta^{18}O$, a proxy for past air temperature at the site. Regarding these dating discrepancies, Steffensen et al. (2008) considers that the oldest date, 12,896 ± 1.5 cal BP, is the actual date of YD onset and that the younger dates are due to lags in the response times of the other proxies. All of the above age differences affect the reliability of conclusions that use ice-core data.

Widespread YDB Platinum Deposition

When associated with other established impact markers, abundance peaks in platinum, iridium, and other PGEs are widely considered to support an impact origin. In addition to Petaev et al. (2013), enrichment of PGEs in the YDB layer has been reported by several groups, including Paquay et al. (2009), who found moderate abundance peaks of PGEs (Pt and Ir) in the YDB layer at two sites, one in Arizona and one in Manitoba, Canada, both of which were also reported by Firestone et al. (2010) to contain YDB PGEs. Paquay et al. (2009) argued that their presence did not support a cosmic-impact event, whereas Bunch et al. (2010) pointed out that Paquay et al. offered no evidence from which to conclude that the PGEs do not have a cosmic origin. Kennett et al. (2015) determined that the Pt and nanodiamond deposits in Greenland are statistically isochronous with the YDB impact layer in lacustrine and continental sedimentary sequences.

Petaev et al. (2013) reported that Pt concentrations rose at least 100-fold, to 82 ppt, over a span of ~14 y, before gradually declining for ~7 y. Assuming that the small ice samples examined by Petaev represent typical Pt deposition at the YD onset, one might reasonably expect the highest Pt spike to occur at the beginning of the impact episode, but that did not occur. This possibly is due to (1) multiple impacts spanning 21 y, (2) variations in atmospheric residence time and fallout of the Pt, and/or (3) a "nugget effect," in which one or more large Pt-rich particles were randomly deposited into that particular section of ice, providing an enrichment that is much higher than average, simply because more or larger Pt-rich nuggets fell onto the ice.

Petaev et al. (2013, p. 1) attributed the long episode of Pt deposition to "multiple injections of Pt-rich dust into the stratosphere" by an estimated 800-m-diameter iron asteroid. They did not suggest a mechanism to produce multiple injections, but there are several possibilities. First, the object could have fragmented into numerous pieces in deep space before impact, as occurred with Comet Shoemaker-Levy. Second, if one or more hard impacts occurred, impact debris may have been ejected beyond Earth's atmosphere, to reenter far from impact sites. Third, the ejection of impact debris beyond Earth's atmosphere might have created a debris ring, much like that observed for Jupiter and Saturn (Boslough 2001). If so, the subsequent collapse of that debris ring could have triggered wildfires for decades after the main impact. Fourth, Napier et al. (2015) proposed that after the initial encounter with a disintegrating 100-km-wide megacomet, the ever-widening debris field might have collided with earth annually for several centuries, providing the opportunity for multiple injections of Pt. Any or all of those possibilities could have created multiple collisions that produced sporadic episodes of wildfires for many years after the initial influx of Pt.

Later, Andronikov et al. (2014, 2015, 2016*b*) and Andronikov and Andronikova (2016) found a sharp spike of Pt in the YDB layer in sediments from six sites on two continents, three in Lithuania, and one site each in Belgium, the Netherlands, and eastern Russia. The Pt enrichment is accompanied by elevated abundances in known meteoritic elements, including iridium, nickel, and chromium. Such elemental concentrations in continental sedimentary deposits are expected to be higher than those in ice cores, because of much slower rates of deposition.

Later, Andronikov and Andronikova (2016) analyzed high-temperature, melted magnetic spherules from the YDB layer at Blackwater Draw, New Mexico, confirming the results of Firestone et al. (2007) and LeCompte et al. (2012) but not those of Surovell et al. (2009), who found no peak in YDB spherules at the same site. Andronikov and Andronikova (2016) found that the spherules contained very high concentrations of platinum, ranging from 18 to 460 ppb with high uncertainties, which is up to 5600 times the Pt levels in Greenland and much higher than an average crustal abundance of 0.5 ppb. In those YDB spherules, Andronikov and Andronikova (2016) also found high levels of iridium, confirming the discovery by Firestone et al. (2007) of anomalously high iridium concentrations as well as high levels of YDB osmium, confirming the discovery by Wu et al. (2013). The presence in YDB sediments of small, variable quantities of these spherules, highly enriched in Ir, Pt, and Os, could easily produce nugget effects and account for the high variability of these elements in the YDB and in Greenland ice cores. The nugget effect may also account for the observation by Paquay et al. (2009) of only low enrichments of YDB PGEs, whereas Firestone et al. (2007) measured a wide range of enrichment from undetectable to high on multiple aliquots of the same sample.

In further support of widespread Pt deposition, Moore et al. (2017) reported Pt enrichments in 11 widely separated sedimentary sequences across North America: one site each in California, Arizona, New Mexico, and Ohio, two in North

Carolina, and five in South Carolina. In addition, Mahaney et al. (2016*a*) found anomalously high Pt enrichments in a YDB-age moraine on the French-Italian border but not above or below the moraine. The Pt enrichments averaged 6.0 ppb, with a range of 0.3–65.6 ppb, with most falling within the lower abundance range in YDB spherules reported by Andronikov et al. (2016*a*) but much higher than the Greenland Pt abundances reported by Petaev et al. (2013).

In summary, Pt enrichments in YD-age sediments and ice have been found across parts of North America, Europe, and Asia at 26 widely separated sites (fig. A1). The discovery of such widely distributed Pt anomalies supports the proposal by Petaev et al. (2013) that multiple injections of Pt at the YDB most likely represented a global event.

REFERENCES CITED ONLY IN THE APPENDIX

Andronikov, A. V.; Lauretta, D. S.; Andronikova, I. E.; and Maxwell, R. J. 2011. On the possibility of a late Pleistocene extraterrestrial impact: LA-ICP-MS analysis of the black mat and Usselo Horizon samples. Meteoritics Planet. Sci. 46(suppl.):A11.

Baker, D. W.; Miranda, P. J.; and Gibbs, K. E. 2008. Montana evidence for extra-terrestrial impact event that caused Ice-Age mammal die-off. EOS: Trans. Am. Geophys. Union 89(23), Joint Assembly suppl., abstract P41A-05.

Becker, L.; Poreda R.; Kennett, J. P.; Kennett, D. J.; Erlandson, J. M.; and West. A. 2009. Wildfires, soot and fullerenes in the 12,900 ka Younger Dryas boundary layer in North America. EOS: Trans. Am. Geophys. Union 90(52), Fall Meeting suppl., abstract PP31D-1393.

Beets, C.; Sharma, M.; Kasse, K.; and Bohncke, S. 2008. Search for extraterrestrial osmium at the Allerod–Younger Dryas boundary. EOS: Trans. Am. Geophys. Union 89(53), Fall Meeting suppl., abstract V53A-2150.

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(5):1726–1731.

Boslough, M. 2001. Impact-induced climate change due to an orbiting debris ring. *In* Annual International Space Development Conference, 20th (Albuquerque, NM, 2001), National Space Society.

Boslough, M.; Nicoll, K.; Holliday, V.; Daulton, T. L.; Meltzer, D.; Pinter, N.; Scott, A. C.; et. al. 2012. Arguments and evidence against a Younger Dryas impact event. *In* Giosan, L.; Fuller, D. Q.; Nicoll, K.; Flad, R. K.; and Clift, P. D., eds. Climates, landscapes, and civilizations. Geophys. Monogr. Ser. 198. Washington, DC, American Geophysical Union, p. 13–26.

Braadbaart, F., and Poole, I. 2008. Morphological, chemical and physical changes during charcoalification of wood and its relevance to archaeological contexts. J. Archaeol. Sci. 35:2434–2445.

Bunch, T. E.; West, A.; Firestone, R. B.; Kennett, J. P.; Wittke, J. H.; Kinzie, C. R.; and Wolbach, W. S. 2010. Geochemical data reported by Paquay et al. do not refute Younger Dryas impact event. Proc. Natl. Acad. Sci. USA 107(15):E58.

Daulton, T. L.; Pinter, N.; and Scott, A. C. 2010. No evidence of nanodiamonds in Younger-Dryas sediments to support an impact event. Proc. Natl. Acad. Sci. USA 107(37):16,043–16,047.

Domínguez-Vázquez, G. 2012. Paleoenvironmental conditions at the Bajio during the last glacial maximum. Cordilleran Section Annual Meeting, 108th (Querétaro, Mexico). Geol. Soc. Am. Abstr. Programs 44(3):55.

Erlandson, J. M. 2007. Sea change: the Paleocoastal occupations of Daisy Cave. *In* Neusius, S. W., and Gross, G. T., eds. Seeking our past: an introduction to North American archaeology. Oxford, Oxford University Press, p. 135–143.

Erlandson, J. M.; Kennett, D. J.; Ingram, B. L.; Guthrie, D. A.; Morris, D. P.; Tveskov, M. A.; West, G. J.; and Walker, P. L. 1996. An archaeological and paleontological chronology for Daisy Cave (CASMI-261), San Miguel Island, California. Radiocarbon 38:355–373.

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. 2009. The case for the Younger Dryas extraterrestrial impact event: mammoth, megafauna, and Clovis extinction, 12,900 years ago. J. Cosmol. 2:256–285.

Firestone, R. B.; West, A.; Revay, Z.; Hagstrum, J. T.; Belgya, T.; Smith, A. R.; Que Hee, S. S.; and Smith, A. R. 2010. Analysis of the Younger Dryas impact layer. J. Sib. Fed. Univ. Eng. Technol. 1(3):30–62.

Fujita, K.; Takeuchi, N.; Aizen, V.; and Nikitin, S. 2004. Glaciological observations on the plateau of Belukha Glacier in the Altai Mountains, Russia from 2001 to 2003. Bull. Glaciol. Res. 21:57–64.

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.

Goodyear, A. C. 1999. The early Holocene occupation of the southeastern United States: a geoarchaeological summary. *In* Bonnichsen, R., and Turnmire, K., eds. Ice Age peoples of North America: environments, origins, and adaptations of the first Americans. Corvallis, OR, Center for the Study of the First Americans, p. 432–481.

———. 2005. Evidence of pre-Clovis sites in the eastern United States. *In* Bonnichsen, R.; Lepper, B. T.; Stanford, D.; and Waters, M. R., eds. Paleoamerican origins: beyond Clovis. College Station, TX, Center for the Study of the First Americans, p. 103–112.

———. 2006. Recognizing the Redstone fluted point in the South Carolina Paleoindian point data base. Curr. Res. Pleistocene 23:100–103.

———. 2010. Instrument-assisted fluting as a technochronological marker among North American Paleoindian points. Curr. Res. Pleistocene 27:86–88.

———. 2013. Update on the 2012–2013 activities of the Southeastern Paleoamerican Survey. Legacy (newsletter of the South Carolina Institute of Archaeology and Anthropology) 17(1):10–12.

Goodyear, A. C.; Miller, S.; and Smallwood, S. 2007. Introducing Clovis at the Topper site, 38AL23, Allendale County, South Carolina. *In* Annual meeting of the Society for American Archaeology, 72nd (Austin, TX, 2007), Abstracts, p. 178.

Goodyear, A. C., and Steffy, K. 2003. Evidence of a Clovis occupation at the Topper site, 38AL23, Allendale County, South Carolina. Curr. Res. Pleistocene 20:23–25.

Hammes, K.; Schmidt, M. W. I.; Smernik, R. J.; Currie, L. A.; Ball, W. P.; Nguyen, T. H.; Louchouarn, P.; et al. 2007. Comparison of quantification methods to measure fire-derived (black/elemental) carbon in soils and sediments using reference materials from soil, water, sediment and the atmosphere. Glob. Biogeochem. Cycles 21:GB3016. doi:10.1029/2006GB002914.

Hardiman, M.; Scott, A. C.; Pinter, N.; Anderson, R. S.; Ejarque, A.; Carter-Champion, A.; and Staff, R. A. 2016. Fire history on the California Channel Islands spanning human arrival in the Americas. Philos. Trans. R. Soc. B 371:20150167. doi:10.1098/rstb.2015.0167.

Haynes, C. V., Jr. 2007. Appendix B: nature and origin of the black mat, stratum F_2. *In* Haynes, C. V., Jr., and Huckell, B. B., eds. Murray Springs: a Clovis site with multiple activity areas in the San Pedro Valley, Arizona. Tucson, University of Arizona Press, p. 240–249.

———. 2008. Younger Dryas "black mats" and the Rancholabrean termination in North America. Proc. Natl. Acad. Sci. USA 105(18):6520–6525.

Haynes, C. V., Jr.; Boerner, J.; Domanik, K.; Lauretta, D.; Ballenger, J.; and Goreva, J. 2010. The Murray Springs Clovis site, Pleistocene extinction, and the question of extraterrestrial impact. Proc. Natl. Acad. Sci. USA 107(9):4010–4015.

Israde-Alcántara, I.; Bischoff, J. L.; Domínguez-Vázquez, G.; Li, H.-C.; DeCarli, P. S.; Bunch, T. E.; Wittke, J. H.; et. al. 2012. Evidence from central Mexico supporting the Younger Dryas extraterrestrial impact hypothesis. Proc. Natl. Acad. Sci. USA 109:E738–E747.

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*a*. Nanodiamonds in the Younger Dryas boundary sediment layer. Science 323:94.

Kennett, D. J.; Kennett, J. P.; West, G. J.; Erlandson, J. M.; Johnson, J. R.; Hendy, I. L.; West, A.; Culleton, B. J.; Jones, T. L.; and Stafford, T. W., Jr. 2008. Wildfire and abrupt ecosystem disruption on California's northern Channel Islands at the Ållerød–Younger Dryas boundary (13.0–12.9 ka). Quat. Sci. Rev. 27(27–28):2530–2545.

Kennett, D. J.; Kennett, J. P.; West, A.; West, G. J.; Bunch, T. E.; Culleton, B. J.; Erlandson, J. M.; et. al. 2009*b*. Shock-synthesized hexagonal diamonds in Younger Dryas boundary sediments. Proc. Natl. Acad. Sci. USA 106:12,623–12,628.

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. 2002. Atlas of sand grain surface textures and applications. Oxford, Oxford University Press. 237 p.

Mahaney, W. C.; Kalm, V.; Krinsley, D. H.; Tricart, P.; Schwartz, S.; Dohm, J.; Kim, K. J.; et. al. 2010*a*. Evidence from the northwestern Venezuelan Andes for extraterrestrial impact: the black mat enigma. Geomorphology 116(1–2):48–57.

Mahaney, W. C., and Keiser, L. 2012. Weathering rinds: unlikely host clasts for an impact-induced event. Geomorphology 184:74–83.

Mahaney, W. C.; Keiser, L.; Krinsley, D. H.; Pentlavalli, P.; Allen, C. C. R.; Somelar, P.; Schwartz, S.; et. al. 2013. Weathering rinds as mirror images of palaeosols: examples from the Western Alps with correlation to Antarctica and Mars. J. Geol. Soc. Lond. 170:833–847. doi:10.1144/jgs2012-150.

Mahaney, W. C., and Krinsley, D. 2012. Extreme heating events and effects in the natural environment: implications for environmental geomorphology. Geomorphology 139–140:348–359.

Mahaney, W. C.; Krinsley, D.; and Kalm, V. 2010*b*. Evidence for a cosmogenic origin of fired glaciofluvial beds in the northwestern Andes: correlation with experimentally heated quartz and feldspar. Sediment. Geol. 231(1–2):31–40.

Mahaney, W. C.; Krinsley, D. H.; Kalm, V.; Langworthy, K.; and Ditto, J. 2011*a*. Notes on the black mat sediment, Mucuñuque catchment, northern Mérida Andes, Venezuela. J. Adv. Microsc. Res. 6(3):177–185.

Mahaney, W. C.; Krinsley, D.; Langworthy, K.; Kalm, V.; Havics, T.; Hart, K. M.; Kelleher, B. P.; Schwartz, S.; Tricart, P.; and Beukens, R. 2011*b*. Fired glaciofluvial sediment in the northwestern Andes: biotic aspects of the black mat. Sediment. Geol. 237(1–2):73–83.

Mahaney, W. C.; Somelar, P.; Dirszowsky, R. W.; Kelleher, B.; Pentlavalli, P.; McLaughlin, S.; Kulakova, A. N.; et. al. 2016*a*. A microbial link to weathering of postglacial rocks and sediments, Mount Viso area, Western Alps, demonstrated through analysis of a soil/paleosol bio/chronosequence. J. Geol. 124:149–169.

Mahaney, W. C.; Somelar, P.; West, A.; Krinsley, D.; Allen, C. C. R.; Pentlavalli, P.; Young, J. M.; et al. 2016*b*. Evidence for cosmic airburst in the Western Alps archived in Late Glacial paleosols. Quat. Int. 438B:68–80. doi:10.1016/j.quaint.2017.01.043.

Maiorana-Boutilier, A. L.; Mitra, S.; West, A.; Bischoff, J.; Louchouarn, P.; Norwood, M.; Kennett, J.; and Silva, S. 2016. Organic composition of Younger Dryas black mat. Geological Society of America Conference, Southeastern Section, annual meeting, 65th (Columbia, SC), paper 4-1. Geol. Soc. Am. Abstr. Program 48(3).

Marshall, W.; Head, K.; Clough, R.; and Fisher, A. 2011. Exceptional iridium concentrations found at the Allerød–Younger Dryas transition in sediments from Bodmin Moor in southwest England. International Union for Quaternary Research Congress, 18th (Bern, Switzerland, 2011), paper 2641.

Mentlík, P.; Minár, J.; Břízová, E.; Lisá, L.; Tábořík, P.; and Stacke, V. 2010. Glaciation in the surroundings of Prášilské Lake (Bohemian Forest, Czech Republic). Geomorphology 117(1–2):181–194.

Paquay, F. S.; Goderis, S.; Ravizza, G.; Vanhaeck, F.; Boyd, M.; Surovell, T.; Holliday, V. T.; Haynes, C. V., Jr.; and Claeys, P. 2009. Absence of geochemical evidence for an impact event at the Bølling–Allerød/Younger Dryas transition. Proc. Natl. Acad. Sci. USA 106(51):21,505–21,510. doi:10.1073/pnas.0908874106.

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(19):7208–7212.

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.

Redmond, B. G., and Tankersley, K. B. 2005. Evidence of early Paleoindian bone modification and use at the Sheriden Cave site (33WY252), Wyandot County, Ohio. Am. Antiquity 70(3):503–526.

———. 2011. Species response to the theorized Clovis comet impact at Sheriden Cave, Ohio. Curr. Res. Pleistocene 28:141–143.

Scott, A. C.; Hardiman, M.; Pinter, N.; Anderson, R. S.; Daulton, T. L.; Ejarque, A.; Finch, P.; and Carter-Champion, A. 2017. Interpreting palaeofire evidence from fluvial sediments: a case study from Santa Rosa Island, California, with implications for the Younger Dryas impact hypothesis. J. Quat. Sci. 32(1):35–47.

Scott, A. C.; Pinter, N.; Collinson, M. E.; Hardiman, M.; Anderson, R. S.; Brain, A. P. R.; Smith, S. Y.; Marone, F.; and Stampanoni, M. 2010. Fungus, not comet or catastrophe, accounts for carbonaceous spherules in the Younger Dryas "impact layer." Geophys Res. Lett. 37(14):L14302. doi:10.1029/2010GL043345.

Sharma, M.; Chen, C.; Jackson, B. P.; and Abouchami, W. 2009. High resolution Osmium isotopes in deep-sea ferromanganese crusts reveal a large meteorite impact in the central Pacific at 12 $\pm$ 4 ka. EOS: Trans. Am. Geophys. Union 90(52), Fall Meeting suppl., abstract PP33B-06.

Steig, E. J.; Brook, E. J.; White, J. W. C.; Sucher, C. M.; Bender, M. L.; Lehman, S. J.; Morse, D. L.; Waddington, E. D.; and Clow, G. W. 1998. Synchronous climate changes in Antarctica and the North Atlantic. Science 282(5386):92–95.

Steig, E. J.; Morse, D. L.; Waddington, E. D.; Stuiver, M.; Grootes, P. M.; Mayewski, P. A.; Twickler, M. S.; and Whitlow, S. I. 2000. Wisconsinan and Holocene climate history from an ice core at Taylor Dome, western Ross Embayment, Antarctica. Geogr. Ann. Ser. A Phys. Geogr. 82(2–3):213–235.

Surovell, T. A.; Holliday, V. T.; Gingerich, J. A. M.; Ketron, C.; Haynes, C. V.; Hilman, I.; Wagner, D. P.; Johnson, E.; and Claeys, P. 2009. An independent evaluation of the Younger Dryas extraterrestrial impact hypothesis. Proc. Natl. Acad. Sci. USA 106:18,155–18,158.

Svetsov, V. 2008. Thermal radiation and fires after impacts of cosmic objects. *In* Adushkin, V., and Nemchinov, I., eds. Catastrophic events caused by cosmic objects. Dordrecht, Springer, p. 207–226. doi:10.1007/978-1-4020-6452-4_6.

Tankersley, K. B. 1997. Sheriden: a Clovis cave site in eastern North America. Geoarcheology 12(6):713–724./

———. 1999. Sheriden: a stratified Pleistocene-Holocene cave site in the Great Lakes region of North America. *In* Driver, J. C., ed. Zooarchaeology of the Pleistocene/Holocene boundary: proceedings of a symposium held at the 8th Congress of the International Council for Archeo Zoology (ICAZ). BAR Int. Ser. 800, p. 67–75.

———. 2009. Evidence of the Clovis age comet at Sheriden Cave, Ohio. Midwest Chapter of the Friends of Mineralogy Symposium and Field Conference (Oxford, OH, 2009).

Tankersley, K. B.; Ford, K.; McDonald, G.; Genheimer, R.; and Hendricks, R. 1997. Late Pleistocene archaeology of Sheriden Cave, Wyandot County, Ohio. Curr. Res. Pleistocene 14:81–83.

Tankersley, K. B., and Landefeld, C. S. 1998. Geochronology of Sheriden Cave, Ohio: the 1997 field season. Curr. Res. Pleistocene 15:136–138.

Tankersley, K. B., and Redmond, B. 1999*a*. Fluoride/radiocarbon dating of late Pleistocene bone from Sheriden Cave, Ohio. Curr. Res. Pleistocene 16:107–108.

———. 1999*b*. Radiocarbon dating of a projectile point from Sheriden Cave, Ohio. Curr. Res. Pleistocene 16:76–77.

Tankersley, K. B.; Redmond, B. G.; and Grove, T. 2001. Radiocarbon dates associated with a single-beveled bone projectile point from Sheriden Cave, Ohio. Curr. Res. Pleistocene 18:61–63.

Tian, H.; Schryvers, D.; and Claeys, P. 2011. Nanodiamonds do not provide unique evidence for a Younger Dryas impact. Proc. Natl. Acad. Sci. USA 108(1):40–44.

van Hoesel, A.; Hoek, W. Z.; Pennock, G. M.; and Drury, M. R. 2014. The Younger Dryas impact hypothesis: a critical review. Quat. Sci. Rev. 83:95–114.

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(2):7648–7653.

Waters, M. R.; Forman, S.; Stafford, T. W., Jr.; and Foss, J. 2009*a*. Geoarchaeological investigations at the Topper and Big Pine Tree sites, Allendale County, South Carolina. J. Archaeol. Sci. 36(7):1300–1311.

Waters, M. R.; Stafford, T. W., Jr.; Redmond, B. G.; and Tankersley, K. B. 2009*b*. The age of the Paleoindian assemblage at Sheriden Cave, Ohio. Am. Antiquity 74:107–111.

Wittke, J. H.; Weaver, J. C.; Bunch, T. E.; Kennett, J. P.; Kennett, D. J.; Moore, A. M. T.; Hillman, G. C.; et. al. 2013. Evidence for deposition of 10 million tonnes of impact spherules across four continents 12,800 y ago. Proc. Natl. Acad. Sci. USA 110(23):E2088–E2097.

Wolbach, W. S. 1990. Carbon across the Cretaceous-Tertiary boundary. Ph.D. dissertation, University of Chicago.

Wolbach, W. S.; Lewis, R. S.; and Anders, E. 1985. Cretaceous extinctions: evidence for wildfires and search for meteoritic material. Science 230:167–170.