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Review Article

The Younger Dryas impact hypothesis: a cosmic catastrophe

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ABSTRACT: In this paper we review the evidence for the Younger Dryas impact hypothesis (YDIH), which proposes that at ~12.9k cal a BP North America, South America, Europe and the Middle East were subjected to some sort of extraterrestrial event. This purported event is proposed as a catastrophic process responsible for: terminal Pleistocene environmental changes (onset of YD cooling, continent-scale wildfires); extinction of late Pleistocene mammals; and demise of the Clovis 'culture' in North America, the earliest well-documented, continent-scale settlement of the region. The basic physics in the YDIH is not in accord with the physics of impacts nor the basic laws of physics. No YD boundary (YDB) crater, craters or other direct indicators of an impact are known. Age control is weak to non-existent at 26 of the 29 localities claimed to have evidence for the YDIH. Attempts to reproduce the results of physical and geochemical analyses used to support the YDIH have failed or show that many indicators are not unique to an impact nor to ~12.9k cal a BP. The depositional environments of purported indicators at most sites tend to concentrate particulate matter and probably created many 'YDB zones'. Geomorphic, stratigraphic and fire records show no evidence of any sort of catastrophic changes in the environment at or immediately following the YDB. Late Pleistocene extinctions varied in time and across space. Archeological data provide no indication of population decline, demographic collapse or major adaptive shifts at or just after ~12.9 ka. The data and the hypotheses generated by YDIH proponents are contradictory, inconsistent and incoherent.

KEYWORDS: Clovis; extinction; extraterrestrial impact; Younger Dryas; Younger Dryas impact hypothesis.

Introduction

One of the key characteristics of the Quaternary is rapid environmental change, perhaps at human generational time scales. Some changes were cyclic, such as the cooling and warming that produced glacial–interglacial cycles and attendant changes in sea level, flora and fauna. Catastrophic events may have played a role in forcing some changes during the Quaternary, especially volcanic eruptions (e.g. the Toba eruption: Ambrose, 1998; Haslam *et al.*, 2012; Petraglia *et al.*, 2012, the Campanian Ignimbrite eruption: Fedele *et al.*, 2003; Hoffecker *et al.*, 2008; Fitzsimmons *et al.*, 2013, and the Laacher See eruption: Baales *et al.*, 2002). Beginning with the meetings of the American Geophysical Union in 2007, much attention has focused on the 'Younger Dryas impact hypothesis' (YDIH), a proposed explanation for terminal Pleistocene environmental change across North America and perhaps other continents. The YDIH has many variants, all proposing that at ~12.9k cal a BP (the Younger Dryas Boundary or YDB of Firestone *et al.*, 2007, marking the beginning of the Younger Dryas Chronozone or YDC), North America was subjected to some sort of extraterrestrial 'event' (either an impact or impacts, airburst or airbursts, or some combination thereof) (Firestone *et al.*, 2006, 2007; Kennett *et al.*, 2008a, 2009a; Bunch *et al.*, 2012; Israde-Alcántara *et al.*, 2012; LeCompte *et al.*, 2012; Wittke *et al.*, 2013). For simplicity, we often use the term 'impact' in the present paper to represent all of these possible combinations. More significantly, this event is proposed as a catastrophic process responsible for: (i) terminal Pleistocene environmental changes, including the onset of YD cooling and continent-scale wildfires; (ii) the extinction of late Pleistocene mammals; and (iii) the demise of the Clovis 'culture' in North America, the earliest (~13.4 to ~12.7k cal a BP) well-documented, continent-scale settlement of the region.

Thirty impact structures <3.0 million years old are known worldwide (www.passc.net/EarthImpactDatabase/Agesort.html), but none has been linked to catastrophic environmental changes. If the YDIH were to hold up to scientific scrutiny and testing, and in particular if its catastrophic environmental consequences were to be demonstrated, it would change our understanding of environmental processes in the final millennia of the Pleistocene and suggest that cosmic impacts might have been an important environmental agent during the Quaternary in general.

Since it was first proposed in 2006, a series of questions have been raised about the YDIH, most of which still remain. The questions focus on the nature of the impactor, the presence or absence of geomorphic evidence for an impact, and the reliability and reproducibility of proposed impact indicators and the dating of these indicator layers.

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[1]12 900 ± 100 calendar years BP was originally identified as the age of the YDB, based on the IntCal04 radiocarbon calibration curve (e.g. Firestone *et al.*, 2007). This date was revised by Wittke *et al.* (2013) after introduction of IntCal09. In discussions of specific sites we use whichever calibration was used in the paper under discussion.

This paper is a critical evaluation of the YDIH focused on the above questions in the context of contemporary Quaternary research. A number of critiques of the YDIH have appeared in the scientific literature since it was proposed (e.g. Buchanan *et al.*, 2008; Pinter and Ishman, 2008; Marlon *et al.*, 2009; Paquay *et al.*, 2009; Surovell *et al.*, 2009; French and Koeberl, 2010; Holliday and Meltzer, 2010; Pinter *et al.*, 2011; Boslough *et al.*, 2012; Pigati *et al.*, 2012; Van Hoesel *et al.*, 2014; Meltzer *et al.*, 2014). Most have dealt with either specific aspects of the geochemical evidence for an impact, or specific implications of the YDIH, such as evidence for continent-wide burning or the archeological record for a cultural catastrophe. The issues raised by the hypothesis (late Pleistocene extinctions, numerical age control, stratigraphic correlation, the evidence for environmental change) are key issues in Quaternary studies, but for the most part have never been addressed as such. We attempt to rectify that deficit here. Our focus is on the evidence for an impact, the dating of the purported evidence and the consequences of an impact. A variety of stratigraphic, sedimentological and geochemical data from 29 sites and localities (see Supporting information, Table S1) in the Americas, Europe and the Middle East are offered to support the hypothesis. We examine some of these data, introduce additional data and provide alternative interpretations. We also examine several hypotheses that are corollaries to the YDIH.

Our ultimate goal is to know what was happening in North America environmentally and culturally at the close of the Pleistocene. As properly observed by Pinter and Ishman (2008), hypotheses as extraordinary as the YDIH require extraordinary scrutiny of data, rigorous testing and reproducible results. Our critique here is in that spirit.

Background

The history of the YDIH is summarized elsewhere (Pinter *et al.*, 2011; Boslough *et al.*, 2012) and will not be repeated here. One important point to stress here is that the proponents of the YDIH have not presented a coherent hypothesis but rather one that has evolved since the initial publications of Firestone *et al.* (2006, 2007). Indeed, there is not just one YDIH but several and they conflict with one another (Boslough *et al.*, 2012, p. 13). The present paper does not deal with the various YDIH scenarios but focuses instead on key elements of the data and interpretations as presented in a book by Firestone *et al.* (2006) and in subsequent statements by Firestone *et al.* (2007), Kennett *et al.* (2008a, 2009a, b), LeCompte *et al.* (2012), Israde-Alcántara *et al.* (2012), Bunch *et al.* (2012), Wittke *et al.* (2013) and Wu *et al.* (2013), and how and whether there are reliable and valid indicators of an impact, indirect and direct.

Evidence presented in support of the YDIH has included a wide array of indirect markers but few direct clues. Since the hypothesis was first presented (Firestone *et al.*, 2006, 2007) 12 'impact indicators' have been offered (Pinter *et al.*, 2011). Of these, seven remain under debate and discussion, the others having apparently been dropped by YDIH proponents (see French and Koeberl, 2010; Pinter *et al.*, 2011; Boslough *et al.*, 2012 for further discussion). The impact is also suggested to have had four widespread results: 'abrupt environmental changes that contributed to YD cooling, major ecological reorganization, broad-scale extinctions, and rapid human behavioral shifts at the end of the Clovis Period' (Firestone *et al.*, 2007, p. 16016).

The YDIH raises a series of questions that provide testable or at least partially testable hypotheses. Most importantly, what is the evidence for an extraterrestrial impact and/or airburst at ~12.9k cal a BP over or on the North American continent? Is the impact evidence reliable and reproducible? Does the age control clearly link this evidence to a unique event at ~12.9k cal a BP? What is the evidence for catastrophic environmental disruption? If there was some sort of ET event, did it cause (i) the climate changes that are linked to the YDC? (ii) late Pleistocene extinctions? and (iii) changes in the archeological record? We address these questions from most specific to most general beginning with geomorphic indicators of an impact, including a discussion of cratering. We continue with discussions of the geochronological data for the YDIH, the purported indirect indicators of an impact and the depositional environments of YDB marker beds. We close by testing related hypotheses raised by the proposed YD impact regarding environmental devastation, late Pleistocene extinctions and Clovis archeology.

Geomorphic indicators

In their first journal article on the YDIH, Firestone *et al.* (2007) discuss three important aspects of geomorphology and geomorphic processes said to be a consequence of the YDIH: (i) craters and cratering, (ii) the Laurentide Ice Sheet and (iii) the Carolina Bays. In other publications, the proponents discuss the Great Lakes and small playa basins of the High Plains (Firestone, 2009; Firestone *et al.*, 2006, 2010a). Here we deal with impact, airburst and cratering processes, the geomorphic record of the Laurentide ice sheet at and around ~12.9k cal a BP and possible effects of catastrophic disruption of the ice sheet, the Carolina Bays, and small playa basins.

Cratering and comet physics

The YDIH controversy ultimately comes down to a single, basic question: was North America and other regions of the globe subjected to a sufficiently large extraterrestrial event at the YDB to cause a catastrophic environmental change? Among the many pages published on the topic, very little discussion has dealt with the plausibility of what has been proposed relative to what is known about impact physics. The exception is Boslough *et al.* (2012) (see also Van Hoesel *et al.*, 2014). That discussion is the basis for the following summary.

The YDIH impact mechanism has variously been described as an airburst, a cluster of airbursts, an ice sheet impact, multiple continent-spanning impacts (Firestone *et al.*, 2007; Boslough *et al.*, 2012) and 'a swarm of comets or carbonaceous chondrites [that] produced multiple air shocks and possible surface impact' (Kennett *et al.*, 2009b, p. 94). However, there are no well-dated craters of terminal Pleistocene age (see further discussion under 'Geochronology') in North America. The impact proponents have instead argued for: (i) an impact on the Laurentide ice sheet, which they suggest would produce no lasting crater; or (ii) an airburst that affected the entire continent and likewise left no crater; or (iii) a combination of the two.

Firestone *et al.* (2007) estimate the impactor size by assuming that it had effects over the entire continent. They argue that it needed to be more than 4 km wide and explode at the optimum height for blast damage at the surface. Moreover, the authors also suggest that it may have fragmented to produce a barrage of airbursts that generated continental-scale wildfires and destabilized the ice sheet, but produced no craters. As summarized by Boslough *et al.* (2012, p. 13), 'Fragmentation and explosion mechanisms proposed for some of the versions [of the YDIH] do not conserve energy or momentum.' No physical mechanism is known to produce an airburst that would affect the entire continent. Moreover, a

4-km-diameter comet impacting an ice sheet would shock the underlying rock strata and leave an impact structure. The various scenarios for impactors are inconsistent with impact and airburst physics (Boslough *et al.*, 2012, p. 14). The proposed YD impactor of Firestone *et al.* (2007) would have had enough mass 'to produce more than a million Meteor Craters' (i.e. craters the size of the well-known Meteor Crater site in central Arizona) (Boslough *et al.*, 2012, p. 20). The much smaller impactor proposed by Israde-Alcántara *et al.* (2012) would be capable of producing thousands.

Moreover, the probability of the fragmented comet impact event specified by the hypothesis is infinitesimal, about one in 10^{15}. The combination of proposed size, configuration and trajectory of the putative impactor is exceedingly unlikely to have occurred together as a single event in the entire history of the Earth (Boslough *et al.*, 2012).

Wittke *et al.* (2013) provide a 'Preliminary Impact Model' that diverges significantly from the original of Firestone *et al.* (2007), but still lacks any physics-based argument. They (E2096) state that the impactor probably broke apart in solar orbit before encountering Earth, as do most comets 'including Comet Shoemaker–Levy 9 [SL9]'. However, SL9 was orbiting Jupiter, not the sun, when it broke apart, and, moreover, most comets do not break up in solar orbit. The reason that all the fragments of SL9 collided with Jupiter is because they were in orbit around Jupiter. The processes that led to the multiple impacts on Jupiter do not apply to comets in solar orbit or for approaches to Earth (Bottke *et al.*, 1997). Moreover, a spontaneous break up in solar orbit, such as Comet 73P/Schwassmann–Wachmann (Sekanina, 2007) would have had to be exquisitely timed in order for an expanding cloud of debris to strike the Earth. Dispersed impacts of multiple fragments would be at least 1000 times less frequent (probable) than the impact of a single nucleus, which is already an extraordinarily rare event.

Wittke *et al.* (2013, E2096) propose that fragments of the YDB impactor entered Earth's atmosphere, fragmented even further and yielded 'multiple atmospheric airbursts that each produced shock fronts'. They do not present a physical model of cascading aerodynamic fragmentation nor describe any mechanism by which fragments can attain a large enough lateral displacement from the entry track before airburst or impact. Grazing impacts such as the Chelyabinsk meteor do not show large radial separation, but generate a distributed 'linear' energy deposition along the track (Brown *et al.*, 2013). The putative distribution of impact markers at the YDB spans about 70° in latitude and 180° in longitude. Fragments with a common radiant over an entire hemisphere would enter the atmosphere at angles ranging from grazing to near-vertical.

Wittke *et al.* (2013, E2096) also suggest that 'thermal radiation from the air shocks was intense enough to melt Fe-rich and Si-rich surficial sediments … at >2,200 °C', a temperature only briefly exceeded in an air shock over a small area near the ablating impactor as it traverses the atmosphere (Nemtchinov, 1995). The proponents provide no calculation of physical estimate of radiative flux at the Earth's surface. A 1-km object, if broken into about 10 000 Tunguska-impactor-sized objects and distributed over 10% of the earth's surface, would be separated by an average distance of 100 km. Like Tunguska, these airbursts would melt no surface material. The proponents suggest instead that passage through a cluster of fragments from a broken comet would probably 'yield several impactors with energies up to 5,000 megatons, fully adequate for surface melting' (Napier *et al.*, 2013, E4171). However, cometary impactors of this energy would be about 1 km in diameter and there is no physical mechanism to prevent them from striking the ground and forming 10-km-diameter craters. Proposing such large fragments undermines the original argument for a broken comet which was intended to explain the lack of a crater.

Many of the YDIH papers appeal to airbursts as a mechanism by which surface materials can be combusted or melted by a non-crater-forming impact. Wu *et al.* (2013) propagated misunderstandings of airburst physics by citing Bunch *et al.* (2012) instead of the original publications which used physics-based models to suggest that layered tektites and Libyan Desert Glass are products of airbursts (Boslough, 1996; Boslough and Crawford, 2008). The airbursts proposed by Bunch *et al.* (2012) are not consistent with the physics of either published mechanism.

Ice sheets and the Great Lakes

Firestone *et al.* (2007) argue that an impact on the Laurentide Ice would have produced 'ice-sheet disruption' (p. 16020) and 'partial destabilization and/or melting of the ice sheet' (p. 16021). As noted above, physical modeling shows that an impact of the size proposed should have produced a crater. But other evidence should be apparent as well. Destabilized or melted ice is argued as the cause of the YD, but there is no field evidence for such destabilization. The moraines of the southern margin of the Laurentide ice sheet, around the Great Lakes, have been studied and mapped for decades and a comprehensive chronology is also available. A catastrophic disruption as proposed in the YDIH should certainly be apparent in the glacial geomorphology, stratigraphy and sedimentology around the Great Lakes. Mapping clearly shows that the moraines conform or are roughly parallel to one another until ~9900 ^{14}C a BP (Mickelson *et al.*, 1983, their fig. 1.9). Further, radiocarbon dating in the Great Lakes area shows that a phase of ice retreat began ~11 500 ^{14}C a BP and did not readvance until ~9800 ^{14}C a BP, perhaps as a surge (Mickelson *et al.*, 1983, p. 26; Mickelson and Colgan, 2004, pp. 8–9, their fig. 3).

An impact of the proposed magnitude on the ice sheet would also be expected to disrupt the proglacial lakes scattered around the southern, south-western and western margins of the retreating Laurentide ice sheet. Floods shifted among various outlets of the lakes and lake waters overtopped the southern sill and flowed down the Mississippi several times until ~12.8k cal a BP (Teller, 2004, their fig. 9). These floods are easily and logically explained by the opening and closing of various outlets and sills (Teller, 2004). However, the sort of 'disruption' and 'destabilization' proposed by Firestone *et al.* (2006, 2007) should have resulted in catastrophic floods simultaneously down most if not all outlets. No such event is documented in the geomorphic or stratigraphic record.

Firestone *et al.* (2010a) suggest that there is evidence for cratering in the Great Lakes basins themselves and 'enigmatic depressions or disturbances in the Canadian Shield (e.g. under the Great Lakes or Hudson Bay)' (Firestone *et al.*, 2007, p. 16020). The problem with that speculation is that at ~12 900 cal a BP only the Lake Superior basin was still under glacial ice (Fig. 1) (Dyke *et al.*, 2003). Firestone *et al.* (2010a, pp. 57–58) now suggest 'deep holes' beneath four of the Great Lakes could represent impact craters. They dismiss the possibility that these holes were the result of glacial erosion, citing only the latest edition of a 19th century book by Dawson (1891), who had no bathymetric evidence of 'deep holes' beneath the Great Lakes. They provide no evidence that these depressions are 12 900 years old. Further, they are elongated, oriented parallel to local ice flow in the up-ice end of the respective lake basins. Thus, the 'enigmatic depressions' are probably the result of glacial erosion.

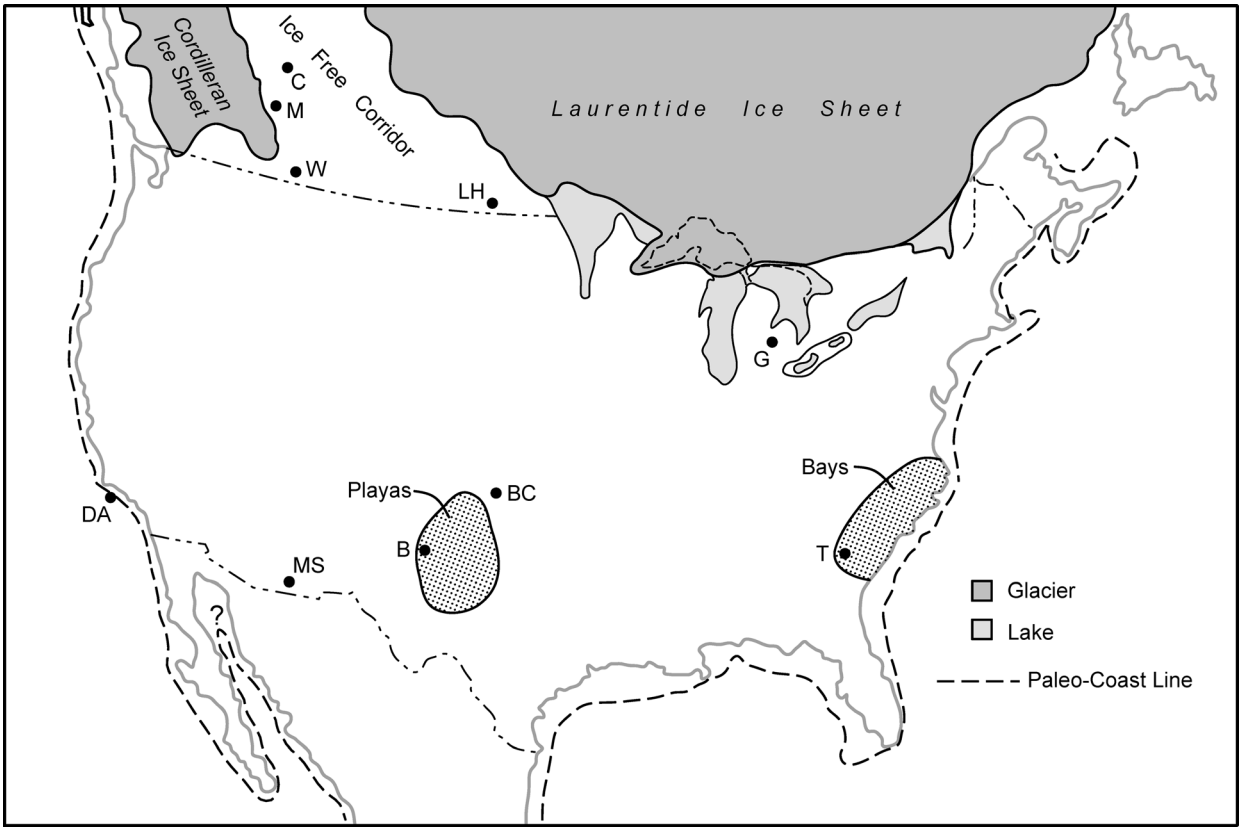

Figure 1. North America at ~13k cal a BP showing the extent of the two ice sheets (based on Dyke *et al.*, 2003), sea-level position, approximate distribution of Carolina Bays on the Atlantic Coastal Plains and small playa basins on the Southern High Plains, and sites mentioned in the text (B = Blackwater Draw Clovis site, BC = Bull Creek, C = Chobot, DA = Daisey Cave and Arlington Springs, G = Gainey, M = Morley, LH = Lake Hind, T = Topper, W = Wally's Beach).

A crater in Canada?

Corossol Crater in the Gulf of St Lawrence has been offered as a possible YDB impact site (Higgins *et al.*, 2011). The upper age limit of the crater is set at ~12 900 cal a BP based on extrapolation of an unknown number of unspecified radiocarbon dates <12 900 cal a BP from a core through crater fill. The maximum age of the crater is the end of the Ordovician. This provides a dating uncertainty that spans hundreds of millions of years. Although Israde-Alcántara *et al.* (2012, E739) refer to the crater as 'containing basal sedimentary fill dating to 12.9 ka' its age is obviously unknown.

Wu *et al.* (2013), by contrast, reject Corossol Crater as the YDB candidate on geochemical grounds. Based on data from the Melrose and Newtonville sites (supporting Table S1; Meltzer *et al.*, 2014) they suggest that 'the impact took place near the southern margin of the Laurentide Ice Sheet' (p. 3565). Thus, their conclusions are drawn from two undated sections correlated to an unknown crater.

Carolina Bays and playa basins

The Carolina Bays and the small playa basins of the Great Plains have been offered as physical geomorphic evidence for an impact at ~12.9k cal a BP (Firestone *et al.*, 2006, 2007). The Carolina Bays are thousands of elliptical depressions scattered along the Atlantic Coastal Plain. Sandy 'rims' are reported from the perimeter margins of many of these Bays. The age and origins of the depressions have been debated and discussed for decades (e.g. Thom, 1970; Kaczorowski, 1977), including a decades-old proposal that they formed from impacts (Melton and Schriever, 1933). The stratigraphy and dating reported by Firestone *et al.* (2006, 2007, p. 2010a) are inconsistent, confusing and, being focused on Bay rims, have no bearing on formation of the Bays themselves (see also Pinter *et al.*, 2011, pp. 4–5; Meltzer *et al.*, 2014). Dating clearly indicates that the Bays formed over time throughout the late Pleistocene, but before ~12.9k cal a BP (supporting Table S1; Meltzer *et al.*, 2014).

The playas are smaller than the Bays, more circular in shape and hold water only seasonally. They are found across the Central and Southern High Plains, but have been most intensively studied on the Southern High Plains (e.g. Judson, 1950; Wood and Osterkamp, 1987; Sabin and Holliday, 1995; Holliday *et al.*, 1996, 2008). Of the >20 000 playa basins on the Southern Great Plains, only one is known to be the result of an impact. The well-known Odessa Meteor Crater, in western Texas and dating to ~60k cal a BP, exhibits typical impact characteristics: a deep basin with upturned beds on the crater margin; thick impact fallout debris flanking the crater; and meteorite fragments (Evans and Mear, 2000; Holliday *et al.*, 2005). All other reported playa exposures exhibit an erosional disconformity between the playa fill and older strata, which is more or less horizontal (Holliday *et al.*, 1996, 2008). They formed by terrestrial geomorphic processes, not by an extraterrestrial impact.

Firestone (2009) suggests that there are ~15 basins scattered across the southern half of the Great Plains that line up in directions that lead back to supposed impact sites in the Great Lakes. However, the 20 000+ small circular to elliptical basins scattered throughout this region have a wide range of orientations (Sabin and Holliday, 1995). The orientation of 15 basins out of ~20 000 is of no significance.

Geochronology and Stratigraphy

One of the single most important aspects of the argument for continental-scale environmental effects of an extraterrestrial 'event' at ~12.9k cal a BP is precise and accurate dating of both direct and indirect indicators of the 'event' (also noted by Van Hoesel *et al.*, 2014, and addressed in detail by Meltzer *et al.*, 2014). YDIH proponents (Kennett *et al.*, 2008b, E107) argue that 'only 14C dates with measurement precisions <100 years, and preferably <60 years, should be used because larger error margins blur probability distributions; many dates had precisions from 200 years to >2,000 years'. Furthermore, 'only bone dates processed with modern techniques [e.g. XAD… or ultrafiltration…] are valid because of the catastrophic consequences of poor chemical preparation…' Kennett *et al.* (2008a, p. 2531) also argue 'The apparent suddenness of the event that occurred at the onset of the YD requires investigations of very high chronological resolution to test the hypothesis'. They recommend 'analysis of existing stratigraphic and chronological datasets, removing erroneous radiocarbon dates that have large error margins … or other problems'. All of these observations are true and the recommendations would be ideal, but none of the research used to support the YDIH meets these criteria. van Hoesel *et al.* (2014) note problems of calibration, sample context and inconsistent results for some of the reported dates. Meltzer *et al.* (2014) examined the dating reported for each of the key 29 sites in YDIH publications (Firestone *et al.*, 2006, 2007; Kennett *et al.*, 2008a, 2009a, b; Israde-Alcántara *et al.*, 2012; Bunch *et al.*, 2012; LeCompte *et al.*, 2012; Wittke *et al.*, 2013; Wu *et al.*, 2013) and found the age control wanting in virtually all cases (summarized in Table S1). Several of the sites lack any age control and others have radiometric ages that are chronologically irrelevant. Nearly a dozen have ages inferred by statistically and chronologically flawed age–depth interpolations. At several sites the ages determined directly on the supposed impact layer are older or younger than 12 900 cal a BP. Only three of the 29 sites fall within the temporal window of the YDB. The YDIH fails the critical chronological test of an isochronous event at the YDB.

Approaches used to date layers with purported impact indicators include stratigraphic correlation, archeological correlation, radiocarbon dating, luminescence dating and age–depth models. The principal stratigraphic marker used in correlation and dating of proposed YDB levels is the so-called 'black mat' (BM) of Haynes (2008). Firestone *et al.* (2007, p. 16016), in the most comprehensive paper on the YDIH, describe the BM as a carbon-rich black layer, dating to the YDB. They also note that it was 'identified by C.V. Haynes… at >50 sites across North America as black mats, carbonaceous silts or dark organic clays…'

The BM is ubiquitous in deposits along the Upper San Pedro Valley and its tributaries in south-eastern Arizona. In that setting it is described as a black algal mat and it tends to date to ~10 800 to ~9800 ^{14}C a BP (Haynes and Huckell, 2007, p. 237) or ~12 680 to ~11 200 cal a BP. Haynes (2008, p. 6520) notes, however, that the BM includes dark gray to black diatomites, white diatomites, white to gray diatomaceous layers and white marl. Therefore, 'black mat' is a general term that includes all such deposits. Furthermore, some are both older and younger than the YDB (Table S1; Fig. 2). The radiocarbon age variation is also well documented by Quade *et al.* (1998) and Pigati *et al.* (2012) who identified black algal mats in North and South America ranging in age from 40 000 years BP to modern. In summary, there are many ways to form dark, organic-rich layers and they are not unique to the YD.

Several important points in this description of the BM, as the term is used by Haynes, are directly germane to the YDIH. (i) The BM ranges in color from black to dark gray to light gray and even includes white diatomites and marls. (ii) By definition the BM dates to the YD. These are critical points because they mean that a black layer not dating to the YD cannot be easily differentiated from a YD BM unless there is some direct age control. Some YDIH papers identify a generic black or gray layer (i.e. an organic-rich or otherwise dark colored zone) as *the* BM (i.e. as YD age) with no evidence that it is in fact a YD-age zone. This has led to circular reasoning where purported impact markers are found below, at the base of or even in a dark layer and this is taken as *prima facie* evidence that the dark layer is of YD age and the

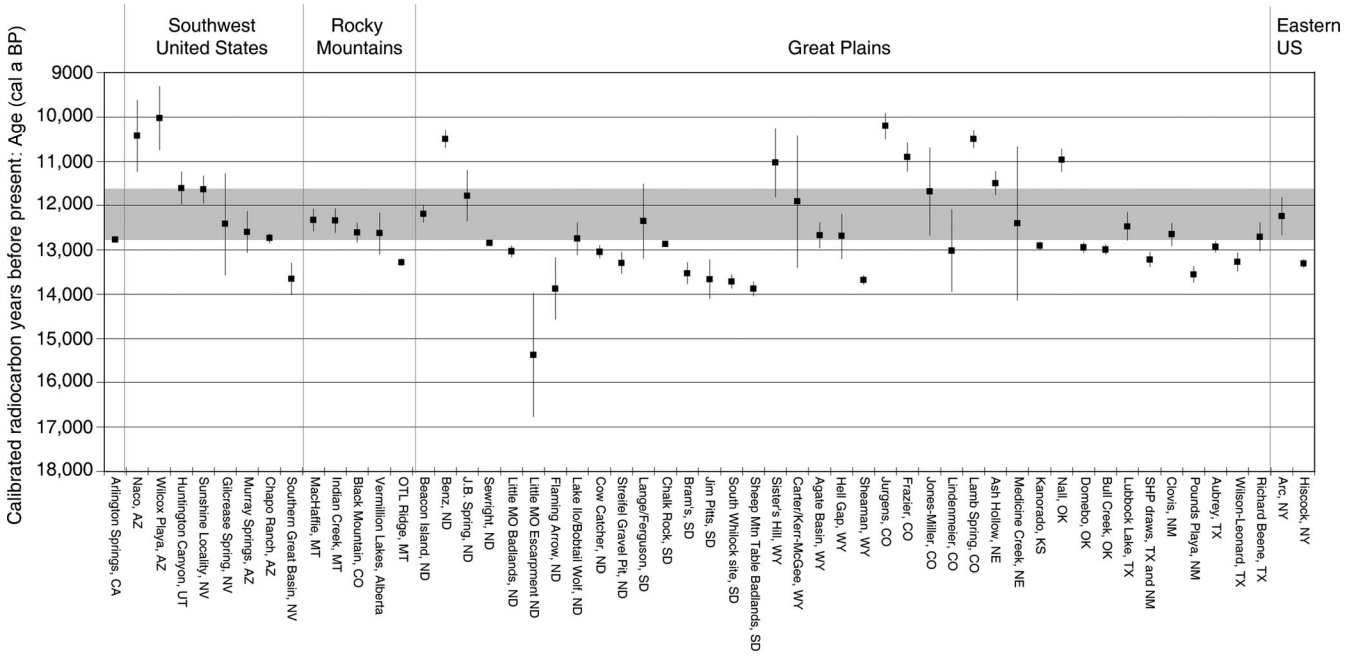

Figure 2. Boxplot showing calibrated ages (center diamond) and 1 standard deviation (vertical bars) for lowest or oldest (or only) 'black mats' from sites largely in the central and western US. The shaded area represents the Younger Dryas Chronozone (modified from Holliday and Meltzer, 2010, their fig. 3).

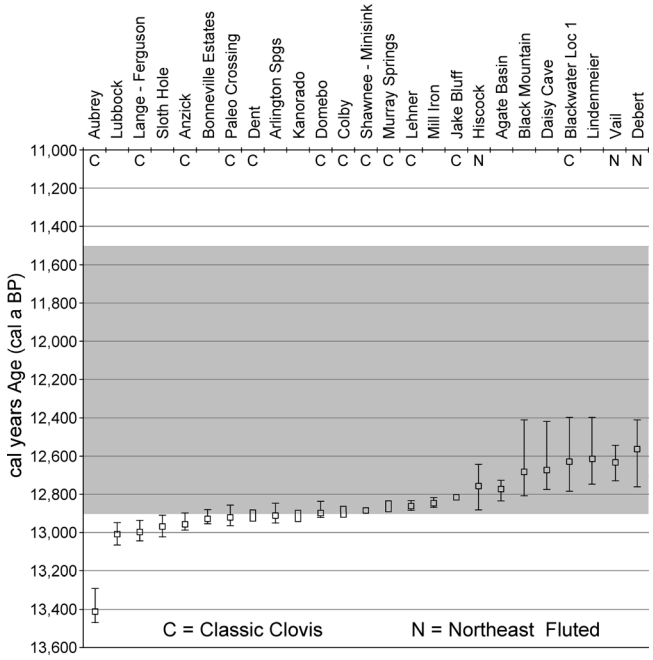

Figure 3. Boxplot showing calibrated ages (center square) and 1 standard deviation (vertical bars) for Clovis, Clovis-age and North-eastern-Fluted points (modified from Meltzer and Holliday, 2010, Fig. 3).

markers are the YDB layer (ignoring the definition – from Firestone *et al.*, 2007, pp. 16–17 – that the YDB is at the base of or immediately below the BM where present). This is the case with the Chobot site, Alberta (Firestone *et al.*, 2007, SI text; Wittke *et al.*, 2013, SI fig. 5) and MUM7B in Venezuela (Mahaney *et al.*, 2010), for example. More broadly, in the study by Wittke *et al.* (2013, E2090), 'Other criteria helped confirm the identification of the YDB layer, including … the presence at 12 sites of darker lithologic units, e.g. the "black mat" layer'.

A key archeological marker used for dating in some YDIH studies is the presence of Clovis occupation debris just below purported impact indicators. Clovis archeology represents the oldest widely accepted, continent-wide archeological horizon in North America (Haynes, 2002; Miller *et al.*, 2013). The hallmark of Clovis archeology is the distinctive Clovis projectile point, although there are several regional variations of this artifact in both morphology and age range (Miller *et al.*, 2013; Buchanan *et al.*, 2013). Firestone *et al.* (2007, SI; 2010a, Table S1) and Kennett *et al.* (2008a, p. 2531) use Clovis artifacts as distinctive time markers representing an interval of only 200 calendar years (~11 050 to ~10 800 ^{14}C a BP; the 'short chronology'), following the work of Waters and Stafford (2007). The age range of Clovis presented by Waters and Stafford, however, is as little as 200 calendar years (13 125–12 925 cal a BP) but as much as 450 calendar years (13 250–12 800 cal a BP) (pp. 1123–1124), as indicated by Wittke *et al.* (2013). The preponderance of evidence, however, indicates that the Clovis occupation was much longer, ~13.3k to ~12.7k cal a BP (~11 500 to 10 800 ^{14}C a BP) (Holliday, 2000; Haynes *et al.*, 2007; Faught, 2008; Meltzer, 2009, pp. 254–255; Miller *et al.*, 2013). Waters *et al.* (2011) also indicate that it was of longer duration, based on optically stimulated luminescence (OSL) dating.

Wittke *et al.* (2013, E2090) further argue that 'Clovis points have never been found in situ in strata younger than ~12.8 ka'. The dating of Clovis ≥12.8 ka as proposed by Wittke *et al.* is also misleading. It is based on their use of IntCal09, which revises the YDB from 12.9 ka based on IntCal04. But as noted above, Waters and Stafford (2007, p. 1123) place the upper end of Clovis at 12.8 ka using IntCal04. Applying the IntCal09 calibration to Clovis dating shows that several classic Clovis sites plus most of the 'eastern fluted' Clovis sites are ≤12.8 ka (Fig. 3).

Gainey, Barnes, Cumberland, Redstone and some unspecified artifacts in the south-east US have also been used as age indicators, suggested as being slightly younger than Clovis (Firestone *et al.*, 2006, p. 113; Anderson *et al.*, 2011, pp. 571–574; Wittke *et al.*, 2013, SI p. 9). Indeed, Firestone *et al.* (2006, p 113) claim that Paleoindian sites in the south-east are 'well-dated' and provide evidence for a population decline just after the Clovis occupation. None of these assertions is true. Numerical age control or even basic stratigraphic relationships for Paleoindian archeological sequences in the south-east are almost non-existent (Anderson *et al.*, 2011, p. 572).

Wittke *et al.* (2013) also use the Magdalenian (Upper Paleolithic) occupation of Western Europe as a time marker, referring to 'the decline near 12.8 ka of the Magdalenian and related cultures' (E2091) and 'a significant population and cultural decline at the onset of the YD'. But in the Magdalenian 'heartland' of Spain and Portugal, Paleolithic specialists see 'significant continuity' in the archeological record of the post-glacial late Pleistocene (Aura *et al.*, 2011, p 352) and no significant changes 'in site distributions, technologies or subsistence strategies that would correlate with the YD' (Straus, 2011, 328; see also Bicho *et al.*, 2011).

Radiocarbon and luminescence (primarily OSL but also thermoluminescence) dating are used as numerical age control for many of the alleged YDB sites, but in almost all cases there are serious problems with the dating, discussed in detail by Meltzer *et al.* (2014 text and SI). Many dates from key sites are left out by Wittke *et al.* (2013) with no explanation. Some sites (Blackville, Gainey, Melrose) were not dated by radiocarbon due to concerns over mixing based on field observation but were dated with OSL. Mixing of sedimentary particles used for luminescence can have equally deleterious effects on the resulting dates. Mixing or redeposition of charcoal in radiocarbon-dated zones was also indicated at other sites (Arlington Canyon, Big Eddy; Table S1).

Indirect Indicators

An important aspect of testing the YDIH is reproducing the results of the analyses and verifying the assertions presented by the proponents. Firestone *et al.* (2007, p. 16016) assert that 'Clovis-age sites in North America are overlain by a thin, discrete layer with varying peak abundances of (i) magnetic grains with iridium, (ii) magnetic microspherules, (iii) charcoal, (iv) soot, (v) carbon spherules, (vi) glass-like carbon containing nanodiamonds, and (vii) fullerenes with ET helium, all of which are evidence for an ET impact and associated biomass burning at 12.9 ka'. The claim of ubiquity and uniqueness of these indicators as indirect evidence of an impact is a cornerstone of the debate over the YDIH, as indicated in the following discussion (see also Firestone *et al.*, 2006, 2007; Surovell *et al.*, 2009; Paquay *et al.*, 2009; Tian *et al.*, 2011; Pinter *et al.*, 2011; Bunch *et al.*, 2012; Boslough *et al.*, 2012; van Hoesel *et al.*, 2014).

Peaks in soot and charcoal from samples immediately above the purported ~12.9-ka level were used to argue that North America was the scene of continent-scale wildfires (Firestone *et al.*, 2006, 2007, 2010a; Kennett *et al.*, 2008a, 2009a, b; Wittke *et al.*, 2013). Independent studies found no unusual amounts of soot or charcoal in samples dated to ~12.9k cal a BP, however. Charcoal records from

35 lake sediment cores (Marlon *et al.*, 2009) and data from pollen cores (Gill *et al.*, 2009), exactly the kinds of settings that should contain evidence for regional burning, reveal no indication of 'extreme wildfires'. Further, Haynes *et al.* (2010a, p. 4014), in searching for impact markers at the Murray Springs archeological site in Arizona, note that despite the claim by Kennett *et al.* (2008a, p. 2542) for 'intense wildfires' during the onset of the YD, two of three samples from Murray Springs did not yield such material and that among hundreds of ^{14}C-dated samples, very few YD-age black mats were found to contain adequate charcoal.

Wittke *et al.* (2013, p. 11) argue that the charcoal at the surface of the Usselo soil in north-west Europe is further evidence of biomass burning. But abundant evidence shows that the soil is just that: a stable surface of weathering, including accumulation of organic matter (see discussion below), such as charcoal (Hoek, 1997; Kaiser *et al.*, 2009; van Hoesel *et al.*, 2012, 2014). van der Hammen and van Geel (2008) make a case for late Allerød climate change in northern Europe resulting in widespread tree mortality, which in turn led to increased wildfires and widespread charcoal. Hoek (1997) and Kaiser *et al.* (2009) further show that the age of the charcoal spans ~1400 ^{14}C years, consistent with pedogenesis over time.

Another marker used to support the interpretation of an impact is the content of magnetic microspherules at ~12.9k (Firestone *et al.*, 2007, p. 16017). These particles, measuring 10–250 μm, are relatively easy to extract from samples (but via a very tedious process) (following procedures in Firestone *et al.*, 2007, and provided by A. West, 2008). The sampling intervals and sample size for the microsphere analyses are not specified by Firestone *et al.*, however. Nevertheless, they report distinct spikes (~150 to ~600 spheres g^{-1}) above a background of about zero spheres g^{-1}, although the laboratory counts themselves were never published.

Surovell *et al.* (2009) provided an independent test for reproducibility of the magnetic microsphere results. Seven sites were sampled, including two reported by Firestone *et al.* (2007). The results of the study by Surovell *et al.* show low levels of magnetic microspheres or none, but no evidence for high concentrations at or around ~12.9k cal a BP. LeCompte *et al.* (2012) report an evaluation of these conflicting results. Their conclusions and Surovell's response are presented in the supporting Appendix S1. To summarize, LeCompte *et al.* (2012) claim that 'the analytical protocol employed by Surovell *et al.* deviated significantly from Firestone *et al.* (p. 2960)'. LeCompte *et al.* (2012) suggest that there were five methodological 'deficiencies' in the work of Surovell *et al.*, but in doing so grossly mischaracterize the protocols used by Firestone *et al.* (2007), use novel protocols in their own study and have some of the same 'deficiencies' in their own work. Most troubling, impact proponents have made *post hoc* modifications to laboratory methods and then criticized prior researchers for not using them.

The assertion by LeCompte *et al.* (2012: E2960, 2013, p. 1 and Wittke *et al.* (2013, E2089) that other studies (including Haynes *et al.*, 2010a; Fayek *et al.*, 2012; Israde-Alcántara *et al.*, 2012; Pigati *et al.*, 2012) reproduce 'abundances and peaks' in magnetic microspherules at the YDB is also misleading. The dating proposed by Israde-Alcántara *et al.* is problematic (Table S1; Meltzer *et al.*, 2014). Fayek *et al.* (2012) examined the 12.9 ka layer at Murray Springs, but not sediments above and below, to determine if YDB 'indicators' are unique to the YDB.

Haynes *et al.* (2010a) report abundant magnetic spheres and elevated Ir levels from the stratigraphic equivalent of the lower YDC at the Murray Springs archeological site in Arizona. They used very different methods from that reported by Firestone *et al.* (2007) (contra LeCompte *et al.*, 2012; C. V. Haynes, personal communication, 2013), although Kennett *et al.* (2008a), Firestone *et al.* (2010a, b), and LeCompte *et al.* (2012, 2013) accept their results. However, as Haynes *et al.* (2010a, b) emphasize, they also recovered abundant spheres and high levels of Ir in modern stream alluvium at the site. Haynes *et al.* (2010b) also note higher-than-background levels of Ir at, above and below the ~12.9k cal a BP level at Murray Springs, the Blackwater Draw Clovis site, New Mexico and the Sheaman site, Wyoming. Kennett *et al.* (2009b, their fig. 1) illustrate a single 'spike' in Ir at Murray Springs, but (i) it is only 4 p.p.b. (above a background of 0 p.p.b.) and (ii) they provide no information on sampling intervals or sample sizes.

Pigati *et al.* (2012), following the protocols of Firestone *et al.* (2007) 'as closely as possible' (p. 7212) produced evidence for high levels of magnetic spheres and Ir at about the level of the YDB, results accepted by LeCompte *et al.* (2012, 2013). But Pigati *et al.* also report multiple peaks in magnetic spheres and Ir from black mats across the south-west US and in Argentina ranging in age from 40 to 6 ka. Those data were not mentioned by LeCompte *et al.* (2012) and in fact were rejected by other YDIH proponents (Bunch *et al.*, 2012: E1907). There seems to be little consistency in the acceptance or rejection of data.

At Arlington Canyon (Santa Rosa Island, California), Kennett *et al.* (2008a, 2009a) report a 5-m sequence of alluvium. Most of the radiocarbon ages from throughout this sequence date to ~13.0 ka, but only the basal deposits (at 5-m depth) have any carbon spheres. In contrast, Pinter *et al.* (2011) examined samples from nearby exposures. Sections over 10 m thick spanning the Last Glacial Maximum (LGM) to modern time yielded multiple layers with abundant magnetic grains and spheres at and above YDB counts reported by Firestone *et al.* (2007).

Paquay *et al.* (2009) analysed samples from the ~12.9-ka level at five sites in North America and Europe investigated by Firestone *et al.* (2007), plus two continental margin cores. They looked for anomalies in iridium, other platinum group element (PGE) concentrations and Os isotopes. They did not reproduce previously reported elevated Ir concentrations. The Os isotopic ratios in the samples are similar to average crustal values, indicating the absence of a significant meteoritic Os contribution to these sediments. And there are no PGE anomalies distinct from crustal signatures. Paquay *et al.* (2009) have no evidence of an extraterrestrial PGE enrichment anomaly.

Similarly, Wu *et al.* (2013) examined spherules and magnetic grains from what was inferred by them to be the YDB (following Firestone *et al.*, 2007; Bunch *et al.*, 2012) collected at Blackwater Draw, Gainey, Lommel, Melrose, Murray Springs, Newtonville and Sheridan Cave. They concluded that only Melrose yielded evidence supporting an extraterrestrial origin, based on Os content, for the spheres. But as noted above (and in Table S1 and Meltzer *et al.*, 2014), there is no evidence supporting a YDB age for any part of the Melrose section. Their conclusions are essentially restatements of two assumptions: (i) spherules and magnetic grains are impact indicators, and (ii) the presumed impact indicators are stratigraphic markers that define the YDB. The claimed YDB age represents circular reasoning, based primarily on the assumption that there should be an increased concentration of assumed impact markers at the boundary, and then using those markers to define the location of the YDB.

The carbon spherules from the Gainey site, one of the 10 'well documented and dated' sites of Firestone *et al.* (2007),

are argued as impact indicators. They are from a near-surface context, however, based on the original archeological research at the site (Simons *et al.*, 1984), and one spherule dated to ~200 a BP (Boslough *et al.*, 2012). Carbon spherules from other sites also have modern or future dates (Firestone, 2009). Clearly they cannot be related to any sort of YD 'event' and their presence suggests that the protocols used by YDIH proponents are flawed and do not eliminate the possibility of contamination.

The identification and significance of nanodiamonds as a component of the YDB suite of impact indicators has been a particular problem. There are several crystalline structures of nanodiamond and not all generated by terrestrial impacts (see discussions in Daulton *et al.*, 2010; French and Koeberl, 2010; Tian *et al.*, 2011; van Hoesel *et al.*, 2012, 2014; Bement *et al.*, 2014). Kennett *et al.* (2008a, 2009a, b) identified hexagonal nanodiamonds in claimed YDB samples and used them as strong support for an impact. Daulton *et al.* (2010) and Tian *et al.* (2011) argue that the purported hexagonal diamonds appear to have been misidentified. Bull Creek was one of the first localities offered as a YDB site on the basis of nanodiamonds (Kennett *et al.*, 2009b), but recent work (Bement *et al.*, 2014) raises questions about the extraterrestrial origins of the nanodiamonds. Cubic nanodiamonds were also identified in surface soils (i.e. modern or recent deposits) at Lommel and other sites in Belgium and Germany (Yang *et al.*, 2008; Tian *et al.*, 2011). At present, several questions remain regarding the nature and distribution of cubic nanodiamonds in terrestrial sediments and the processes that formed them.

One of the most widely publicized nanodiamond reports was the discovery of lonsdaleite crystals in ice collected during a television-sponsored expedition to Greenland in 2008 (Kurbatov *et al.*, 2010). This result was never reproduced either by independent researchers or by members of the original team, and seems to be losing acceptance even by the impact proponents. A map of YDB sites published by Wittke *et al.* (2013, their fig. 1) excludes Greenland.

The GISP2 (Greenland Ice Sheet Project 2) core revealed a large platinum (Pt) anomaly, but no striking Ir anomaly at the Bølling–Allerød/YD transition (Petaev *et al.*, 2013a). The source of the Pt anomaly is unclear but precedes an ammonium and nitrate spike in the core by ~30 years and therefore the source of the Pt is unlikely to have triggered purported biomass burning. In response to Boslough (2013), Petaev *et al.* (2013b) accept arguments against the Pt-depositing event being the cause of the YD cooling.

Finally, all the claimed YDB indicators should also be uniquely associated with the YDB zone, but data from several sites and studies clearly indicate that they are not (Kennett *et al.*, 2008a, their fig. 5 and table 3; 2009b, their fig. 1A; Surovell *et al.*, 2009; Pinter *et al.*, 2011; Wittke *et al.*, 2013, table S3). Spherules are reported from all samples collected from Blackwater Draw and Topper (LeCompte *et al.*, 2012, their figs 3 and 4), albeit at lower levels than the purported YDB. But this could be related to soil-forming processes, as discussed below. Some studies also illustrate multiple peaks in claimed YDB indicators; Haynes *et al.* (2010a, b), for example, noted above. Firestone *et al.* (2007, their fig. 1) shows: double carbon spherule and double charcoal peaks at Chobot; the magnetic grain and spherule peak higher than the main carbon spherule peak at Chobot; two Ir peaks and one carbon spherule peak matching neither Ir peak at Lake Hind; and a variety of peaks that do not match up at Topper. Multiple peaks in claimed YDB indicators are also illustrated by Kennett *et al.* (2009b, their fig. 1A, Israde-Alcántara *et al.* (2012, their fig. 4) and Bunch *et al.* (2012, their fig. 2). A single 'event' should sprinkle its traces across the continent at the same time. Mixing processes (e.g. redeposition or bioturbation) should mix all indicators and should result in gradual change in amount with depth. No sedimentological or weathering process is identified that could discretely and vertically sort the various indicators.

Radiocarbon dating also suggests that claimed YDB indicators are not unique to the YD onset (following Table S1 and

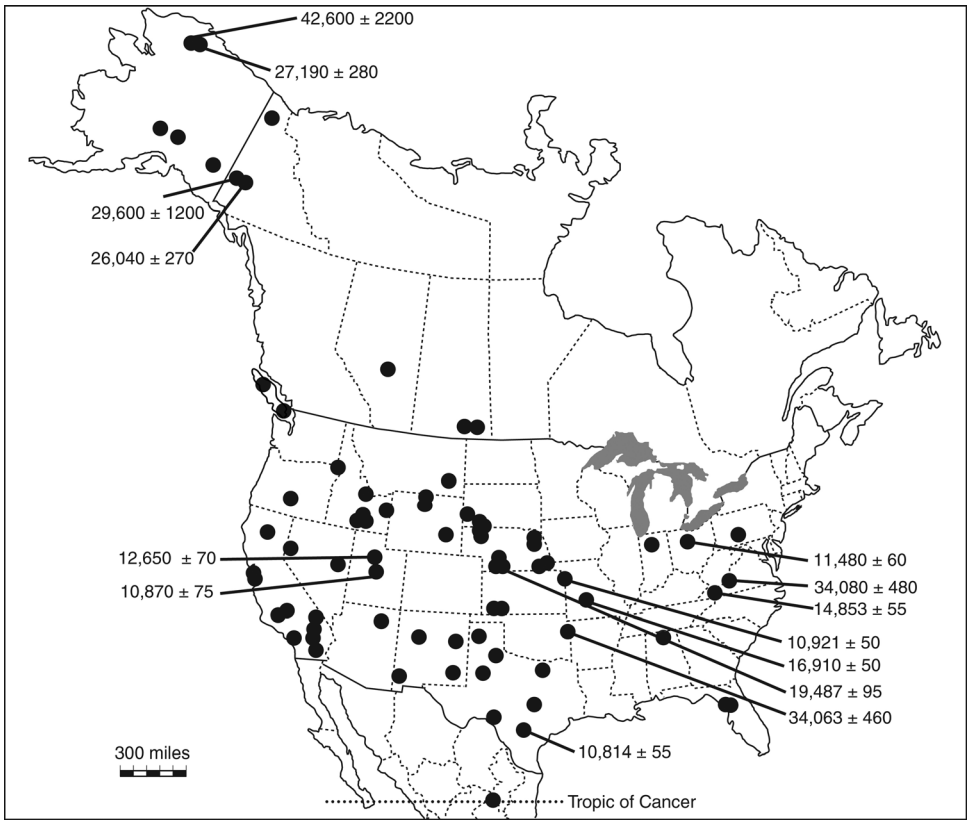

Figure 4. The distribution of Late Pleistocene *Arctodus* sites and direct ^{14}C bone dates in North America. Site distribution after Faunmap II (: www.ucmp.berkeley.edu/neomap/use.html), Ferrusquía-Villafranca *et al.* (2010), Schubert (2010) and Schubert *et al.* (2010). Dates from Schubert (2010) and Mann *et al.* (2013). Where more than a single date is available from a given site, the youngest trustworthy date is used.

Meltzer *et al.*, 2014): the carbon spheres are Historical age at Gainey (Boslough *et al.*, 2012) and probably at Chobot (Firestone, 2009); nanodiamonds at Bull Creek are >11 000 ^{14}C a BP and also <3000 ^{14}C a BP; spherules at Barber Creek <10 500 ± 50 ^{14}C a BP (~12.5k cal a BP); and carbon spheres and magnetic grains at Lake Hind ~10 610 ^{14}C a BP (~12 755 cal a BP). At Newtonville, late Wisconsin-age sediment yielded more magnetic microspherules than the upper, younger loamy sand of claimed YDB age (Wu *et al.*, 2013).

Another problem is the use of claimed YDB indicators as stratigraphic markers, which results in more circular reasoning. These materials were used to help confirm and correlate the YDB layer in 15 Carolina Bays (Firestone *et al.*, 2007, p. 16019), at Chobot (Wittke *et al.*, 2013, E3900), and the three exposures of the Usselo soil (Lingen, Lommel, and Ommen) (Wittke *et al.*, 2013, SI 12, 15). This self-fulfilling approach can be seen in the sampling where thin (1–2 cm) samples are collected from presumed YDB zones but thicker samples (which, as Firestone, 2009, suggests, could dilute the results) are collected above and below (e.g. Wittke *et al.*, 2013, table S3). Moreover, most sampling reported is from in and around the presumed YDB zone rather than throughout thicker or more continuous sections to see if claimed indicators are at other stratigraphic levels. To date, only Bement *et al.* (2014) report such an approach and their data show peaks above and below the YD.

Depositional Environments

The stratigraphic, depositional and pedogenic contexts of the YDIH have rarely been addressed in the many papers that have appeared on the topic. Yet, as suggested in some of the above discussion, they probably had and have a significant effect on the record of indirect indicators of impacts and their interpretation. Here we summarize the key issues regarding the physical, geologic contexts of the YDIH.

Significant points raised by the sedimentological and geochemical data presented in support of the YDIH are the nature of the depositional environments, changes in the rates of sedimentation given that magnetic microspherules, nanodiamonds and other features of cosmic dust are regularly raining on the Earth (Brownlee, 1985; Dai *et al.*, 2001), and lithologic discontinuities created by erosion. The 'black mats' discussed above, regardless of age, all represent stability following more rapid or more energetic sedimentation. The BM at Clovis and Lake Hind is at the base of lake or marsh deposits. At Clovis and Murray Springs, the BM also represents a change from alluviation (relatively high-energy deposition) to marsh deposition (low- or no energy deposition). Lake Hind is probably similar, with the 'black mat' representing stability in a marsh setting following drainage of the paleolake (Boyd *et al.*, 2003). Sediments left by moving water should contain a very small fraction of extraterrestrial dust, because dust will be carried in suspension and deposited only in standing water or wetland deposits or by direct airfall.

The posited YDB at Bull Creek, Oklahoma (Kennett *et al.*, 2009b), soil b8 (Bement *et al.*, 2007, 2014), and at Lommel, Ommen and Lingen, in north-west Europe, the Usselo Soil (Firestone *et al.*, 2007, their fig. 8; Van der Hammen and Van Geel, 2008; Kaiser *et al.*, 2009) is within the former surface horizon of a now buried soil. Many of the black mats, representing former zones of plant growth, are also probably buried soils (Holliday, 2004; Haynes, 2008; Meltzer and Holliday, 2010).

Soils represent surfaces of stability that persist over time following deposition of the sediment that acts as the soil parent material. In many if not most cases, the stability and soil formation reflect much more time than the accumulation of the sediment in which the soil forms (e.g. Birkeland, 1999; Holliday, 2004; Schaetzl and Anderson, 2005). This means that radiocarbon dating of buried soils (i.e. the dates from Bull Creek and Usselo soils) represents dating of carbon that accumulated through the formation of the soil and therefore cannot indicate a specific moment in time (Holliday, 2004, pp. 178–184; Walker, 2005, pp. 31–32). This is well illustrated by the ~1400 ^{14}C year age range for the charcoal in the Usselo soil (Hoek, 1997; Kaiser *et al.*, 2009). The pedologic character and age range of the soil led Kaiser *et al.* to reject the notion that the soil is related to a YDB 'event'.

Another significant and very common characteristic of soils and soil formation is the process of translocation whereby water moving through a soil (usually downward) can move both particulates and solutes (Birkeland, 1999; Buol *et al.*, 2003; Schaetzl and Anderson, 2005). The material translocated can be part of the original parent material or can be introduced from dust. These constituents moving down through a soil can accumulate with depth, for example due to the loss of water driving the translocation (in drier environments) or lithologic discontinuities (e.g. fine sand over coarse sand or vice versa), or a combination of the two.

The particulate materials (e.g. spherules) used in part to identify the YDB may be a common component of at least some sediments that include the claimed YDB. As noted above, spherules were present in all samples collected from Blackwater Draw and Topper (LeCompte *et al.*, 2012, their figs 3 and 4). These materials may therefore be affected by the processes of translocation and accumulation in a soil. Magnetic microspherules and magnetic grains are silt-sized (<500 μm) and finer (clay-sized, <2 μm) (Firestone *et al.*, 2007, p. 16017) and nanodiamonds are clay-sized (2–300 nm) (Kennett *et al.*, 2009b), which are the typical size range of translocated materials. These particulates increase in frequency with depth in the black mats at Arlington Canyon (Kennett *et al.*, 2008a, their fig. 5 and table 3; 2009a, their fig. 1) and at Blackwater Draw and Topper (LeCompte *et al.*, 2012, figs 3 and 4). Similar depth trends are apparent in the independent study of black mats by Pigati *et al.* (2012, their fig. 3). Further, the claimed YDB indicators commonly are associated with a lithologic change (23 out of 29 sites; Table S1). Particulate material such as fine silt and clay commonly 'hangs up' at such discontinuities (Birkeland, 1999, pp. 112–114; Schaetzl and Anderson, 2005, p. 225). The peaks in 'YDB indicators' in at least some situations may represent such a pedologic feature rather than a primary airfall deposit.

The accumulation of supposed impact indicators at the Topper site may represent a particular type of pedogenic accumulation. In their study of magnetic microspherules at Topper, LeCompte *et al.* (2012) describe spherules occurring essentially atop Clovis lithic debitage with a 'shadow' (a significant decline in spheres) below the artifacts, implying that the spheres were draped across artifacts exposed at the surface. The layer of spheres was ~4 cm thick and buried by only ~50 cm of sand, however. As noted, *all* samples collected below and above the highest concentration of spheres (~260 spheres kg^{-1}) yielded measurable amounts of spheres (~20 – ~120 spheres kg^{-1}) (see also Firestone *et al.*, 2007, their fig. 1). This strongly suggests that either: (i) all the sand from just below the Clovis artifacts to or near the surface was deposited with spheres and the amount of spheres depends on the rate of sand deposition (which must have been slow; 50 cm in 13 000 years = 1 cm in 260 years) or (ii) the spheres were translocated downward and

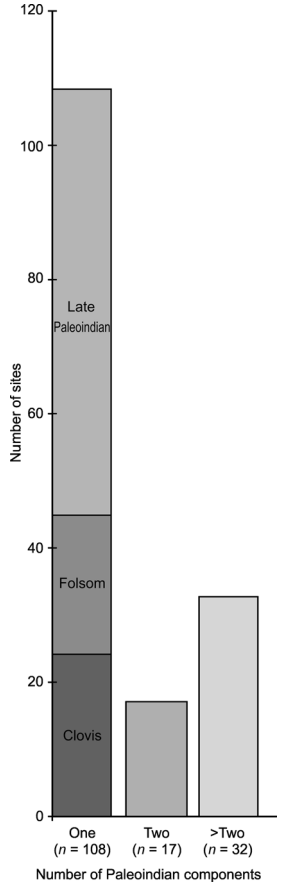

Figure 5. Frequency of Paleoindian features in archeological sites (modified from Holliday and Meltzer, 2010, their fig. 2).

accumulated at the lithologic break created by the artifacts. Accumulation of thin bands of fine particles is a common characteristic of soils formed in sandy parent material, and is well documented in sand mantles in the south-east (Rawling, 2000; Larsen and Schuldenrein, 1990), including Big Pine, ~3 km from Topper (Waters *et al.*, 2009), the Kimbel Bay YDB site (Wittke *et al.*, 2013, p. 10) and the Usselo soils in Europe (Wittke *et al.*, 2013, their SI figs 9 and 12). The artifact zone just below the peak in spheres would also be a suitable lithologic break in the soil column. Regardless of the process, the likelihood that the maximum in spheres is contemporaneous with the artifacts, which may or may not be in primary context (Meltzer *et al.*, 2014), seems remote.

Failure to differentiate the effects of soil formation from lithostratigraphic layers has resulted in further confusion by proponents of the YDIH. Firestone *et al.* (2006, p. 121) ponder the issue of 'tan sand turning white' in surface and near-surface deposits in the south-eastern US. They offer two explanations: acid removing iron oxides from the surface of quartz sand grains or 'searing heat'. They decide that acid is the least plausible explanation, but in fact acid leaching in soils is a ubiquitous soil-forming process, called 'podzolization', in sands under humid to wet forested landscapes, such as the south-eastern US (Buol *et al.*, 2003; Schaetzl and Anderson, 2005). The result is formation of a white, sandy, eluvial 'E' horizon immediately below thin organic-rich surface horizons. The same process and soil horizonation dominates the sandy soils of north-west Europe and is a characteristic of the buried Usselo soil (Kaiser *et al.*, 2009). The white E horizon is the 'bleached sand' below the charcoal-rich buried surface at Lingen, Lommel and Ommen. The 'bleaching' or podzolization took place after deposition of the widespread 'coversands' as the charcoal and other organic matter accumulated during the >1000-year duration of pedogenesis. This process is also indicated by the mixing of charcoal into the white sand (Wittke *et al.*, 2013, SI 11).

The YDIH proponents provide their own contradictory stratigraphic evidence. In the Carolina Bays, charcoal 'reaches peaks in four Bays with paleosols' (Firestone *et al.*, 2007, p. 16018). This statement contradicts those made elsewhere in the same publication, however. Firestone *et al.* (2007, SI; and Firestone *et al.* (2010a, pp. 40, 42) state 'The Bays have poorly stratified, sandy, elevated rims (up to 7 m). … All of the Bay rims examined were found to have, throughout their entire 1.5- to 5-m sandy rims, a typical assemblage of YDB markers (magnetic grains, magnetic microspherules, Ir, charcoal, soot, glass-like carbon, nanodiamonds, carbon spherules, and fullerenes with ^{3}He)'. No stratigraphic descriptions nor profiles were published to document the stratigraphic character of the rims.

Hypothesis Testing: Major Ecological Reorganization and Environmental Disruption

The YDIH includes suggestions of 'major ecological reorganization' (Firestone *et al.*, 2007, p 16016), 'major catastrophic effects' (p. 16017), 'dramatic ecological change' (p. 16021) and 'massive environmental changes' (Kennett *et al.*, 2009b, p. 94). The record of late Pleistocene ecosystems and environments includes reconstructions of paleoclimate, paleovegetation, paleohydrology and paleolandscapes. An environmental catastrophe at a continental scale as proposed by the YDIH should be apparent in paleorecords. Such records at and either side of ~12.9k cal a BP across North America provide little support for these assertions, however.

The literature on YDC conditions in unglaciated North America south of the continental ice sheets is extensive (e.g. papers and citations in Straus and Goebel, 2011; Eren, 2012; Bousman and Vierra, 2012; and specific studies of the YDC and YDIH, such as Yu and Wright, 2001; Meltzer and Gill *et al.*, 2009; Holliday, 2010; Marlon *et al.*, 2009; Holliday and Miller, 2013). Some general patterns are evident but there is also considerable variation, especially when comparing diverse records such as paleobotany and paleohydrology.

A few general comments (distilled from Meltzer and Holliday, 2010, and Holliday and Miller, 2013) suffice to make the point. Not all of North America experienced cooling: some regions saw relative warming or at least temperate climates during the YDC. This was particularly so across the south-eastern US and portions of the mid-continent east of the Rocky Mountains. Precipitation and run-off patterns likewise varied spatially both on a continental and a subcontinental scale. Wetter conditions prevailed across a wide area of the south-east. Elsewhere, precipitation was more variable. Just as environmental conditions varied over space in the final millennia of the Pleistocene, they also changed over that time. Many streams on the Gulf and Atlantic Coastal Plains and on the Central and Southern Great Plains were changing from braided to meandering regimes, but the timing of that change and, in particular, patterns of cutting and filling were out of phase. In the Great Basin, the well-known paleolakes likewise have out-of-phase lake-level histories.

The YDC and the immediately preceding millennia cannot be generalized environmentally across North America. The environment and the directions of environmental change varied across time and space. Overall, the long-term trends of vegetation change were more significant than the short-term

ones. Depending on the area, these trends began before the onset of the YD, or became evident only well into or after this period. There is no evidence of an environmental catastrophe or disruption, with the possible exception of mammoth extinction, at ~12.9k cal a BP.

Hypothesis Testing: Late Pleistocene Extinctions

Firestone *et al.* (2007, p. 16016) assert that the extinction of some 37 genera of mammals and an unstated number of avian taxa occurred 'abruptly and perhaps catastrophically at the onset of the YD'. They also claim that an impact event explains those losses. To understand why this cannot be true requires some knowledge of the fate of late Pleistocene vertebrates in the Americas as a whole.

Sometime towards the end of the Pleistocene, North America lost 37 genera of mammals (Grayson, 2011; Lundelius *et al.*, 2013), and it is this set of organisms to which Firestone *et al.* (2007) refer. It is, however, a serious mistake to assume that these losses occurred in a geographic vacuum, and few scientists attempting to understand late Pleistocene extinctions make this mistake. Although debate continues over the genus-level taxonomy of the extinct late Pleistocene mammals of South America, all recognize that South America was the scene of massive mammalian extinctions during the late Pleistocene, with approximately 52 genera lost. Given that some genera occurred in both North and South America, some 77 genera of mammals were lost from the Americas as the Pleistocene came to an end.

The taxa that became extinct were large. In fact, 77% of late Pleistocene mammalian genera whose constituent species weighed more than 45 kg were lost in the Americas as a whole. In South America, 47 of 57 (82%) of those genera were lost; in North America, 32 of 45 (71%), with the differences statistically insignificant ($\chi^2 = 1.85$, $P = 0.19$; D. K. Grayson, unpublished data).

If a YD impact caused these extinctions, the effects of that impact must have spread from the southern tip of Patagonia to the far northern edges of Alaska and Canada, a span of some 126° latitude and 16 000 km. In addition, it must have done so while taking the same proportion of large mammals in both North and South America. It must also have managed to do this while allowing mammoths on St. Paul Island, Alaska, to survive until 5700 ^{14}C a BP, and those on Wrangel Island, Siberia, to survive until 3700 ^{14}C a BP, even while causing those animals to become extinct on the adjacent mainlands thousands of years earlier (Guthrie, 2004; Boeskorov, 2006; Solow *et al.*, 2006; Vartanyan *et al.*, 2008; Veltre *et al.*, 2008; Nikolskiy *et al.*, 2011).

Reasonable scientists disagree about the chronology of North American Pleistocene extinctions. On the one hand, some observe that of the 37 genera of extinct mammals, only 16 can be shown to have survived to between 12 000 and 10 000 ^{14}C a BP (e.g. Grayson, 2007, 2011). On the other, some observe that the quantitative structure of the North American paleontological record is compatible with nearly all the extinctions having taken place within this time frame (e.g. Martin and Steadman, 1999; Faith and Surovell, 2009). No matter which position is taken, however, at least some of the extinctions were time-transgressive. In eastern Beringia, for instance, the most recent records for the giant bear *Arctodus* fall before the LGM in this region (Mattheus, 2001; Schubert, 2010), even though the genus survived until the terminal Pleistocene south of glacial ice (Fig. 4). It would not be surprising to learn that many of the North American extinctions were significantly time-transgressive, but even if this were not the case, the current chronological record provides no support for the suggestion that they were instantaneous, as the YDIH requires.

Firestone *et al.* (2007) assert that the YD impact event also swept away a significant number of avian taxa. It is true that some 20 genera of birds, ranging from jays and quails to condors and eagles, were lost sometime towards the end of the Pleistocene (Emslie, 1998; Grayson, 2011). However, our chronology for these losses is essentially non-existent. While we do have a good understanding of the late Pleistocene range retraction of the extant California condor *Gymnogyps californicus* (Emslie, 1987, 1990; Brasso and Emslie, 2006), and a few scattered dates for other taxa, it is simply false to claim that late Pleistocene bird losses in North America are known to have been 'abrupt and catastrophic', no matter how much Firestone *et al.* (2007) might wish this to have been the case.

Late Pleistocene vertebrate extinctions in the Americas were complex, time-transgressive and geographically far-reaching. We do not know what caused them but they cannot be explained by a YD impact event.

Hypothesis Testing: Clovis Archeology

'Clovis' is the name given to the oldest well-dated, visible, and widespread human occupation in North America. Firestone *et al.* (2007, p. 16016) state that 'Causes for the… termination of the Clovis culture have long been controversial' and further propose a supposedly unexplained 'major adaptive shift' as well as a 'population decline' which caused the 'termination' of the Clovis archeological culture at 12.9 ka (Firestone *et al.*, 2007, p. 16021). These assertions are not explained nor elaborated upon, however. A review of the general literature on Paleoindian archeology (i.e. the archeology of the earliest Americans, including Clovis and other technocomplexes) yields little evidence for controversy concerning the end of the Clovis occupation of the continent nor evidence for a 'major adaptive shift' (Shutler, 1983; Hofman *et al.*, 1989, 1996; Bonnichsen and Turnmire, 1991, 1999; Holliday, 1997; Hofman and Graham, 1998; Morrow and Gnecco, 2006; Graf and Schmitt, 2007; Meltzer, 2009; Kornfeld *et al.*, 2010; Grayson, 2011; Straus and Goebel, 2011; Eren, 2012; Bousman and Vierra, 2012; Chapdelaine, 2012; Gingerich, 2013; Graf et al., 2013).

For example, Firestone *et al.* (2006) assert that the Blackwater Draw site (Clovis type site) was abandoned by humans for 1000 years after the YDB. Kennett and West (2008, p. E110) similarly claim a hiatus of 500 years following the YDB at the Blackwater Draw site and LeCompte *et al.* (2012, p. 2967) refer to a 'culturally dead zone' at the site. The voluminous archeological, stratigraphic and chronological data for the site clearly contradict these claims.

More broadly, Kennett and West (2008, p. E110) assert that 'Archaeological sites containing both Clovis and immediately post-Clovis material are rare… Of the 11 well-dated credible Clovis sites [Waters and Stafford, 2007], none has post-Clovis materials immediately above, suggesting a potential disruption in settlement or landscape use'. These comments are misleading. Most Paleoindian sites are single-component sites, i.e. just one feature; nothing below nor above and this applies at non-Clovis Paleoindian sites as well. Of ~150 published accounts of buried, intact Paleoindian sites, Holliday and Meltzer (2010: their fig. 2, supplementary data table) document that fully two-thirds are single component (Fig. 5). That is, re-use of the same site was relatively rare throughout Paleoindian time.

van Hoesel *et al.* (2014, p. 106) consider both sides of the argument over the validity of the YDIH and arguments for and against a post-Clovis population decline, citing assertions

by Jones (2008) and Kennett and West (2008), and data from Anderson *et al.* (2008). Anderson *et al.* (2008) use the frequency of finds of Clovis and post-Clovis artifacts in the south-eastern US as an indicator of population, but elsewhere Anderson *et al.* (2011, p. 572) acknowledge that neither numerical nor stratigraphic age control exists for most Paleoindian artifact styles in the region. The assessment by van Hoesel *et al.* (2014), however, does not include the data presented by Holliday and Meltzer (2010), noted above, based on archeological literature from dated, stratigraphic sequences that clearly illustrate that there is no evidence for a population decline after Clovis.

The 'termination' of the Clovis culture is, in fact, the relatively subtle evolution of parts of a tool assemblage (Holliday and Meltzer, 2010), a process that is one of the hallmarks of the global archeological record. There is no basis to argue that such a change in tool types is due to an environmental catastrophe.

An examination of archeological, geochronological and stratigraphic evidence fails to demonstrate a demographic collapse of post-Clovis human populations, especially where the Clovis and post-Clovis site records are reasonably well constrained chronologically (Holliday and Meltzer, 2010). Although few Clovis sites contain evidence of an immediate post-Clovis occupation, interpreting that absence as population collapse is likewise problematic as the great majority of later Paleoindian localities also lack immediately succeeding occupations. Where multiple occupations do occur, stratigraphic hiatuses between them are readily explained by geomorphic processes. Furthermore, calibrated radiocarbon ages demonstrate continuous occupation across the time of the purported 'YD event' (Fig. 3). Holliday and Meltzer (2010, p. 575) conclude that the YDIH 'is an unnecessary "solution" for archaeological problems that do not exist'.

Discussion and conclusions

The YDIH has generated significant interest on the part of Quaternary researchers, such as paleontologists, paleobotanists, paleoclimatologists, stratigraphers, geomorphologists and archeologists. It appeared to provide a 'unifying theory' for at least some of the key environmental events in the post-LGM Pleistocene, including YDC cooling and faunal extinctions. Since first appearing in book form (Firestone *et al.*, 2006) and in a scientific journal (Firestone *et al.*, 2007) the YDIH has generated lively debate in both the scientific literature, noted above, and in the popular scientific press (e.g. *Discovery*, *American Archaeology*, *Mammoth Trumpet*) and on television (e.g. PBS *NOVA*).

A broad array of scientists have carefully examined the published data, the interpretations and the hypotheses generated by the YDIH, and have attempted to reproduce some of the data. In all cases, the results of these independent investigations leave the YDIH wanting.

1. *Impactor*. The basic physics of the proposed impact or airburst has never been addressed by the YDIH proponents. Those aspects of an impact that have been mentioned are not in accord with the physics of impacts or airbursts nor, moreover, the basic laws of physics. No craters, crater or other direct indicators of an impact have been identified. A shower of comet fragments, which is extremely unlikely on a physical basis alone, should have produced many craters across North America.
2. *Glaciers*. An impactor striking the Laurentide ice is argued to have destabilized it. Evidence for such an event should be preserved in the record of landforms and sediments left at the ice margin. However, these geologic features provide no evidence whatsoever for a catastrophic 'destabilization' of the ice sheet at or around 12.9 ka.
3. *The, Carolina Bays of the Atlantic Coastal Plain and the Small Playa Basins* of the High Plains have been offered as evidence of extraterrestrial impact. No impact debris (meteorites) or impact morphologies (upturned beds around the basin rims) are reported, save for the Odessa Meteor Crater on the southern Plains, which is pre-LGM. Almost all of these landforms pre-date 12.9 ka; the Carolina Bays are significantly older.
4. *Dating*. The argument for an 'extraterrestrial event' at ~12.9k cal a BP requires that all proposed indicators of the event must be accurately and precisely dated, and uniquely related to the age of ~12.9 ka. Few are.
5. *Reproducibility of indirect indicators*. Several studies have attempted to reproduce the results of YDB geochemical analyses or applied the same methods at other sites and came up wanting. This lack of reproducibility raises serious questions about the appropriateness of the methods to detect the purported indirect indicators or the laboratory protocols themselves are less than exacting. Two studies (Haynes *et al.*, 2010a, b; Pigati *et al.*, 2012) were able to extract some indirect indicators from YDB zones at a variety of sites, but their work also extracted high levels of these 'indicators' from samples ranging in age from 40 ka to modern. Kennett *et al.* (2008a), Firestone *et al.* (2010a, b) and LeCompte *et al.* (2012, 2013) accept the methods and some results of that work. They must per force accept that either (i) there were multiple extraterrestrial impacts over the past 40k cal a BP (including modern times when no impacts were observed) or (ii) there are other mechanisms for producing increases in magnetic microspheres and Ir in the stratigraphic record.
6. *Depositional environments*. The YDB zones at most sites used to support the YDIH are in depositional environments that either select for purported microscopic indicators (e.g. magnetic microspherules) by being in very low-energy depositional environments (lakes and marshes) compared with immediately underlying high-energy alluvium or the 'indicators' are from soils that represent landscape stability over a significant period, therefore concentrating those materials.
7. *Major ecological reorganization*. The post-LGM environment was undergoing a variety of changes that varied in character, direction and rate over the course of hundreds to thousands of years until well into the Holocene. Geomorphic, stratigraphic and fire records from across North America show no evidence of any sort of catastrophic changes in the environment at or immediately following 12.9 ka.
8. *Late Pleistocene extinctions*. Late Pleistocene extinctions were not confined to North America, but occurred throughout the Western Hemisphere. If a YD impact event had been involved in these extinctions, it must have been disastrous enough to have affected animals ranging from horses in Alaska to ground sloths in Patagonia while leaving mammoths on such places as St. Paul and Wrangel islands unscathed. And how, one wonders, did such a wide range of large mammals, from musk-oxen (*Ovibos moschatus*) and elk (*Cervus elaphus*) in North America to capybaras (*Hydrochoerus hydrochaeris*) and tapirs (*Tapirus* spp.) in South America, survive such an event? The YDIH is not compatible with the history of American vertebrate faunas.
9. *Clovis archeology*. Well-dated, stratified archeological sites provide no indication of any sort of population decline, demographic collapse or major adaptive shifts at or just after 12.9 ka.

In summary, the data and the hypotheses generated by YDIH proponents contain errors of fact and errors of omission, and are contradictory, inconsistent and incoherent. Much of the evidence used to support the idea is unfounded assertion and the corollary hypotheses are demonstrably false. Further, the published assertions are based on a lack of understanding of basic principals of Quaternary geology, of the well-established geochronologic records at sites and locality, of the records of North American Paleoindian archaeology and late Pleistocene extinction, and of the physics of hypervelocity impact processes. The YDIH is poorly supported on the basis of data published by those on both sides of the debate and proponents rarely consider alternative hypotheses in interpreting those data. If there was an extraterrestrial impact at 12.9 ka, it had no terrestrial impact.

Supporting Information

Additional Supporting Information can be found in the online version of this article.

Table S1. Summary of stratigraphy, and sampling and dating (from Meltzer *et al.*, 2014) at proposed YDB sites.
Appendix S1. A Response to LeCompte *et al.* (2012) which includes:
Figure S1. Two figures provided to T.S. by Allen West to aid in spherule identification.

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Abbreviations. BM, black mat; LGM, Last Glacial Maximum; OSL, optically stimulated luminscence; PGE, platinum group element; YDB, Younger Dryas boundary; YDC, Younger Dryas Chronozone; YDIH, Younger Dryas impact hypothesis

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