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Citation for published version:
Sweatman, M 2021, 'The Younger Dryas impact hypothesis: review of the impact evidence', *Earth-Science Reviews*, vol. 218, 103677. https://doi.org/10.1016/j.earscirev.2021.103677

Digital Object Identifier (DOI):
10.1016/j.earscirev.2021.103677

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Earth-Science Reviews

The Younger Dryas impact hypothesis: review of the impact evidence

Martin B. Sweatman, Institute of Materials and Processes, School of Engineering, King's Buildings, University of Edinburgh, UK. EH9 3FB

martin.sweatman@ed.ac.uk

Keywords: cosmic impact, Younger Dryas, platinum anomaly, impact microspherules, nanodiamonds, climate change, Clovis culture, megafaunal extinctions

Abstract

Firestone et al., 2007, PNAS 104(41): 16016-16021, proposed that a major cosmic impact, *circa* 10,835 cal. BCE, triggered the Younger Dryas (YD) climate shift along with changes in human cultures and megafaunal extinctions. Fourteen years after this initial work the overwhelming consensus of research undertaken by many independent groups, reviewed here, suggests their claims of a major cosmic impact at this time should be accepted. Evidence is mainly in the form of geochemical signals at what is known as the YD boundary found across at least four continents, especially North America and Greenland, such as excess platinum, quench-melted materials, and nanodiamonds. Their other claims are not yet confirmed, but the scale of the event, including extensive wildfires, and its very close timing with the onset of dramatic YD cooling suggest they are plausible and should be researched further. Notably, arguments by a small cohort of researchers against their claims of a major impact are, in general, poorly constructed, and under close scrutiny most of their evidence can actually be interpreted as supporting the impact hypothesis.

1. Introduction

Since its introduction in 2007, the Younger Dryas impact hypothesis (YDIH) has received considerable attention, and sparked heated debate (Firestone et al., 2007). The occurrence of a global cosmic catastrophe, which the impact hypothesis suggests only slightly preceded the onset of human civilisation in the Fertile Crescent of south west Asia (as revealed by excavation of remarkable sites like Gobekli Tepe in this region), represents a paradigm-shift in understanding with profound consequences (Dietrich et al., 2012; Dietrich et al., 2017; Schmidt, 2012).

The debate surrounding catastrophism versus gradualism goes back at least as far as the great classical philosophers (Palmer, 2003). It was thought for many years to be resolved by Darwinian evolution and Hutton's uniformitarian geological principles, at least within the general scientific community. But in recent decades, with the discovery of many large impact craters on terrestrial planets and moons, including Earth and our own moon, and with the discovery of over 1,000 large (> 1 km) asteroids in near-Earth space, the situation has reversed. Now, globally important cosmic impacts on Earth are expected on the timescale of millions of years (Harris and D'Abramo, 2015).

However, the possibility of such a large cosmic event on the timescale of human civilisation, just the last 13,000 years, is perhaps surprising. Indeed, its apparent occurrence at the dawn of the Palaeolithic - Neolithic transition within the Fertile Crescent of south west Asia is intriguing in the light of recent archaeological discoveries like Gobekli Tepe (Notroff et al., 2017; Notroff et al., 2016; Sweatman, 2019; Sweatman and Tsikritsis, 2017a; Sweatman and Tsikritsis, 2017b). The impact theory also has far-reaching consequences for other cultural transitions, such as the end of the Clovis culture in North America, and for our understanding of Earth's local cosmic environment, for late Pleistocene megafaunal extinctions and the related issue of Earth's climate system. Intense debate in this context is therefore expected.

Before describing this research debate in detail, it is necessary to first state the main claims of the hypothesis. Firestone et al. (2007) write,

We propose that one or more large, low-density ET objects exploded over northern North America, partially destabilizing the Laurentide Ice Sheet and triggering YD cooling. The shock wave, thermal pulse, and event-related environmental effects (e.g., extensive biomass burning and food limitations) contributed to end-Pleistocene megafaunal extinctions and adaptive shifts among PaleoAmericans in North America.

It is important to note that the main claim is for a major cosmic impact near 12.9 ka. The proposal is that this impact **triggered** the Younger Dryas (YD) cooling and **contributed** to the end-Pleistocene megafaunal extinctions and human cultural changes. Equally, it should be clear that Firestone et al. (2007) are not claiming that the impact event itself wiped out many genera of megafauna or an entire human culture in an instant. It should be emphasized also that they claim the impact was caused by **one or more large, low density extraterrestrial (ET) objects.** This should be interpreted to mean one or more large comet fragments, and therefore they envisage a scenario where an impact crater might be absent. Furthermore, they expect the largest impacts took place over the Laurentide ice sheet, reducing further the possibility that any large crater will be found.

Of course, such broad claims will be difficult to assess and establish. While it should be possible with currently available scientific resources to ascertain whether a major cosmic impact event occurred at this time, it will likely remain difficult to tease apart the longer-term consequences of such an event, and distinguish them from non-impact related causes. For example, how can we know for sure whether extinction of a specific species of animal 200 years, say, after the impact event was really triggered by the impact event itself or caused by human hunting? Probably, several factors will be important in such a case.

For these reasons, this review covers only the evidence for a major cosmic impact at this time (section 2), and the likely impact scenario (section 3). Research that deals with other consequences of the proposed impact event, namely changes in climate and human cultures, or megafaunal extinctions, are excluded. The impact evidence is summarized in section 4, and conclusions are made in section 5.

2. Geochemical evidence

The YDIH explicitly claims the impact event was caused by one or more low density ET objects falling onto the Laurentide Ice sheet. It is generally accepted that a small low density, i.e. comet, fragment will explode high in the atmosphere without creating a crater, although significant shock and heat damage might still be felt on the ground (Matthias et al., 2017). The Tunguska event, 1908, is thought by many to be a typical event of this type (Asher and Steel, 1998; Melott et al., 2010; Napier and Asher, 2009). As fragment size increases, the bolide can be expected to approach more closely to Earth's surface before exploding. Keeping all other variables fixed, a ground impact and therefore a crater can be expected for comet fragments of sufficiently large size. However, the angle of incidence, impact velocity and the precise mechanical and chemical nature of the impactor will all play an important role in determining whether a ground impact occurs (Matthias et al., 2017). An impact onto an ice sheet will undoubtedly also play a significant role in determining whether a crater will be formed in the ground beneath. Clearly, as ice sheet thickness increases, the likelihood of a crater in the ground itself reduces. It follows that the properties of such a crater will also be affected by ice thickness.

Clearly, it is therefore possible that an impact event involving multiple comet fragments onto an ice sheet several kilometres thick might be very destructive and yet not form a crater, or at least might not form an obvious and typical crater. Since this is the scenario proposed for the YDIH, we cannot base our investigation of the impact event on the detection of a YD-age crater, although, clearly, the discovery of such a crater will tend to confirm the impact theory. Instead, we must assess impact proxies (also called markers or indicators), typically geochemical in nature.

Proponents of the YDIH have described the discovery of several kinds of impact proxy that support their case, mainly distal ejecta proxies. After the initial announcement in 2007 that included claims of discovery of somewhat exotic substances, such as fullerenes containing ET helium, the research debate focussed on the most robust impact proxies, namely abundances of platinum group elements (PGEs), especially platinum itself, silica and iron-rich impact microspherules, other high-temperature melts, nanodiamonds and evidence for extensive wildfires. Each of these impact proxies is claimed to form a coetaneous layer, or boundary, typically at the base of what is known as the ‘Younger Dryas black mat’, across several continents. It is important to note that these specific signals have only ever been found together in the context of a cosmic impact. Each of these lines of geochemical evidence is discussed in the next section.

Figure 1: the YD black mat at Murray Springs (image courtesy of the Comet Research Group).

But before we deal with them, it is useful to describe the Younger Dryas black mat itself (see Figure 1). Haynes (2008) describes the black mat as a dark to light grey stratigraphic marker that covers much of the Clovis-age landscape of N. America. Discolouration can have several causes, including sometimes an abundance of charcoal, but is generally thought to indicate a wet paleosol, i.e. moist conditions relative to the strata above and below, containing abundant organic carbon indicative of mollisols, aquolls, pond sediments and algal mats. Around one hundred black mat sites across N. America have been discovered. Most *in-situ* Clovis sites are found directly under the black mat, with none above. Artifacts relating to the later broad Palaeoindian technocomplex, however, are often found within the black mat itself. Moreover, according to Haynes (2008), at 27 black mat sites mammoth bones are blanketed directly by the black mat. More generally, many extinct megafaunal species are found below the black mat, but not within or above, including horse, camel, mastodon, direwolf, American lion, short-faced bear, sloth and tapir. The only megafaunal species with remains found directly within the black mat is the bison (*bison bison antiquus*). Apparently similar discoloured layers of YD age can also be found in western Europe (e.g. the Usselo horizon) and S. America.

Figure 2 shows the distribution of YD black mat sites discovered to date on four continents. Most sites are located in N. America, spanning the entire continent, but other YD black mat sites have also been found in S. America, Europe and south west Asia, including within the burned ruins of one of the world's first settlements, Abu Hureyra in modern-day Syria, only around 160 km from Gobekli Tepe.

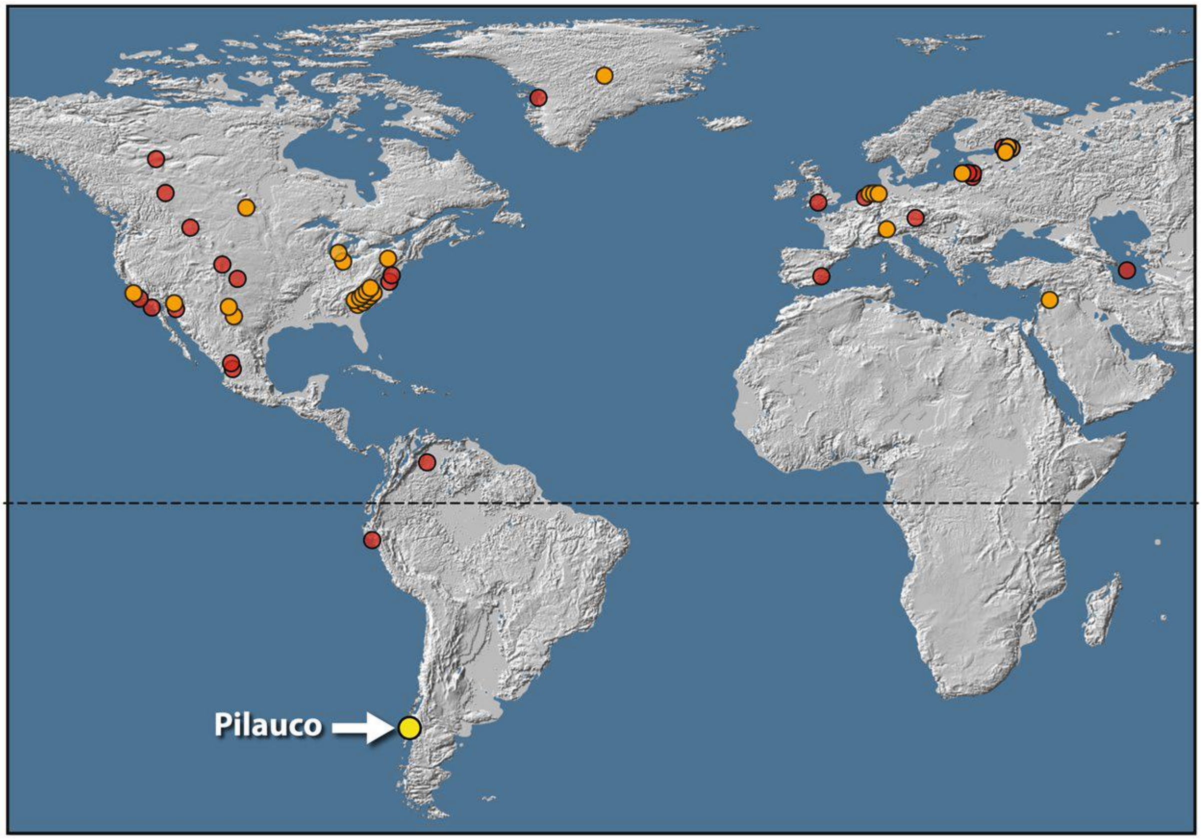


Figure 2. Location map showing 53 YD boundary (black mat) sites (reproduced from Pino et al. (2019) under the terms of the CCA 4.0 International License). Orange dots represent 28 sites with peaks in both platinum and other impact proxies such as high-temperature iron-rich microspherules. Red

dots represent 24 sites with impact proxies but lacking platinum measurements. The yellow dot indicates the Pilauco site, Chile, described in detail in Pino et al. (2019). A new site in South Africa, Wonderkrater, has been identified since this map was first published (Thackeray et al., 2019).

2.1 Platinum and other PGEs

Earth's crust is depleted in PGEs relative to its interior and to cosmic bodies generally. Therefore, a coetaneous abundance of PGEs over a large fraction of Earth's surface is a clear signal for either an ET source or a volcanic eruption (Evans and Chai, 1997). However, not all PGEs need to be equally represented in these abundances, as the precise abundance of PGEs in different cometary bodies, especially, is not well understood (Tagle and Claeys, 2004). Other geochemical signals can distinguish reliably between these two possibilities, including abundances of tephra and sulphate, both of which clearly point towards volcanism. It follows that their absence at the Younger Dryas boundary strongly indicates an ET source for any excess PGEs. A coetaneous abundance of other impact proxies, such as iron-rich microspherules, also reliably points towards a cosmic impact as these kinds of spherule have never been associated with volcanism.

Firestone et al. (2007) focussed initially on iridium abundances at the Younger Dryas boundary (YDB) in their original paper. However, the significant iridium excesses they reported at several YD sites could not be replicated reliably by others (Bunch et al., 2010; Paquay et al., 2010; Paquay et al., 2009). Although significant excess iridium in the magnetic fraction of samples from some YDB sediments was confirmed, sometimes more than 3,000 times average crustal values, these high values were considered inconclusive by others when averaged over an entire bulk sample (Firestone et al., 2010; Haynes et al., 2010a; Haynes et al., 2010b). Osmium isotope measurements by Paquay et al. (2009), on the other hand, were within normal bounds and considered to contra-indicate an extraterrestrial impact. However, given the uncertainty over the PGE composition of comets, their haste in ruling-out a cometary source on this evidence alone is unwarranted. This view is supported by Wu et al. (2013) who analysed microspherules from a range of YDB sites in North America and Belgium. They found that any extraterrestrial osmium in these sediment layers is likely overwhelmed by terrestrial sources, but nevertheless, on the basis of detailed examination of elemental abundances concluded in favour of the impact theory, preferring an impact in Quebec. Interestingly, Paquay et al. (2009) were able to confirm a clear bulk sediment iridium enhancement at the YDB at one site, Lake Hind, although it was around 30 times lower than the value reported by Firestone et al. (2007). Possibly this large difference is caused by their use of much smaller samples and the so-called 'nugget' effect, where rare elements are concentrated within specific particles. They attributed this excess iridium, around 5 times average crustal values, to natural processes, such as collection and concentration of cosmic dust by surface waters.

Since 2013 attention has switched mainly to platinum. A clear and anomalous platinum signal, around 80 ppt at its peak (see Figure 3a), was discovered by Petaev et al. (2013a) in the GISP2 ice core coeval, within the resolution of the data, with a rapid shift in climate, taken by the authors to be the onset of Younger Dryas cooling at 10,890 BP in the GISP2 chronology. Here, BP indicates 'years before 1950 CE'. Petaev et al. (2013a) also plotted strong sulphate and ammonium ion peaks measured in the same GISP2 ice core. Ammonium ions are a good proxy for extensive biomass burning. As wildfires cannot have been extensive in Greenland itself, the ammonium must have been prevalent elsewhere in the environment and carried to Greenland by the wind. However, none of the sulphate or ammonium abundances plotted by Petaev et al. (2013a) were coeval with the platinum signal. This was taken by Petaev et al. (2013a) to indicate the platinum derived from an impact locally onto Greenland ice. Furthermore, the platinum signal was relatively broad, with a lifetime approaching 20 years. This indicates the platinum was carried high into the atmosphere on microscopic aerosols and dispersed around the globe. It should therefore be a global signature of the impact. In the absence of coetaneous sulphate and ammonium ions, they concluded in favour of a massive cosmic impact onto the Greenland ice, sufficiently large to trigger the YD cooling, but without extensive wildfires across the continent. However, in their analysis of the impactor type, they did not consider a cometary source favoured by Firestone et al. (2007).

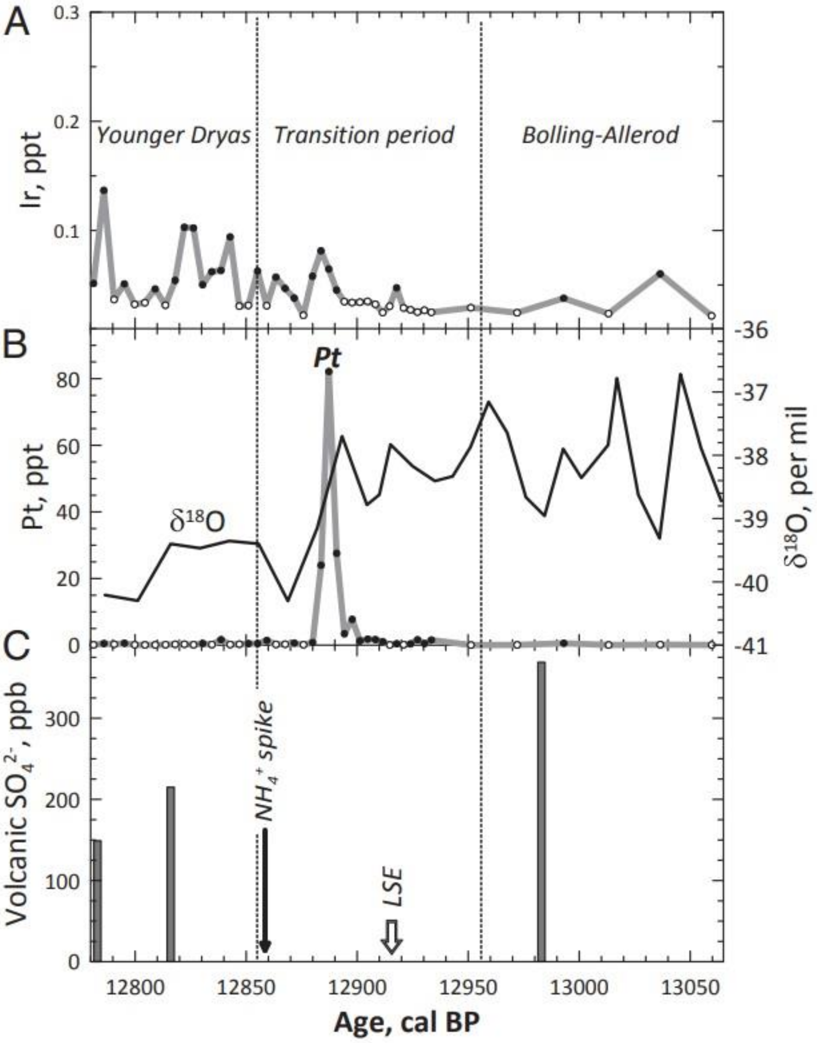


Figure 3a. GISP2 Platinum signal coeval with a change in climate, thought to be the onset of the Younger Dryas, both plotted on the GISP2 timescale (Petaev et al., 2013a). The sulphate spikes (vertical grey bars) are correctly plotted, but the ammonium ion spike is mis-plotted – it should be placed around 40 years earlier (see text and Figure 3b), very close to the platinum signal. The timing of the Laacher See event (LSE) is measured in calibrated radiocarbon years. Therefore, its position relative to the GISP2 chronology is uncertain. Probably, it should be identified with the earlier sulphate peak. Reproduced with permission from the NAS.

Boslough (2013) pointed out that the platinum signal might have been created by a small local impactor. But the lifetime and magnitude of the platinum signal effectively rules this out. Petaev et al. (2013a) maintained it must have been a massive event, likely caused by a ~ 0.8 km iron-rich meteorite. An impactor of this size and density would likely create a large crater, regardless of Greenland's ice shield.

However, the ammonium ion signal was plotted in error by Petaev et al. (2013a). The ammonium ion abundance was measured originally by Mayewski et al. (1993) and reported in Figure 2 of their work. Examination of their plot clearly shows the ammonium signal begins around 12,900 BP. But the ammonium signal is reported in their text to begin at 12,859 BP, around 40 years too late compared to their plot. And it is this incorrect textual date that is used by Petaev et al. (2013a) in their paper (see Figure 3a). Figure 3b compares the original plot of Mayewski et al. (1993) with the plot of Petaev et al. (2013a), and by aligning their time-scales it is clear the beginning of the ammonium ion signal lines up very well with the GISP2 platinum signal and the sudden shift in climate.

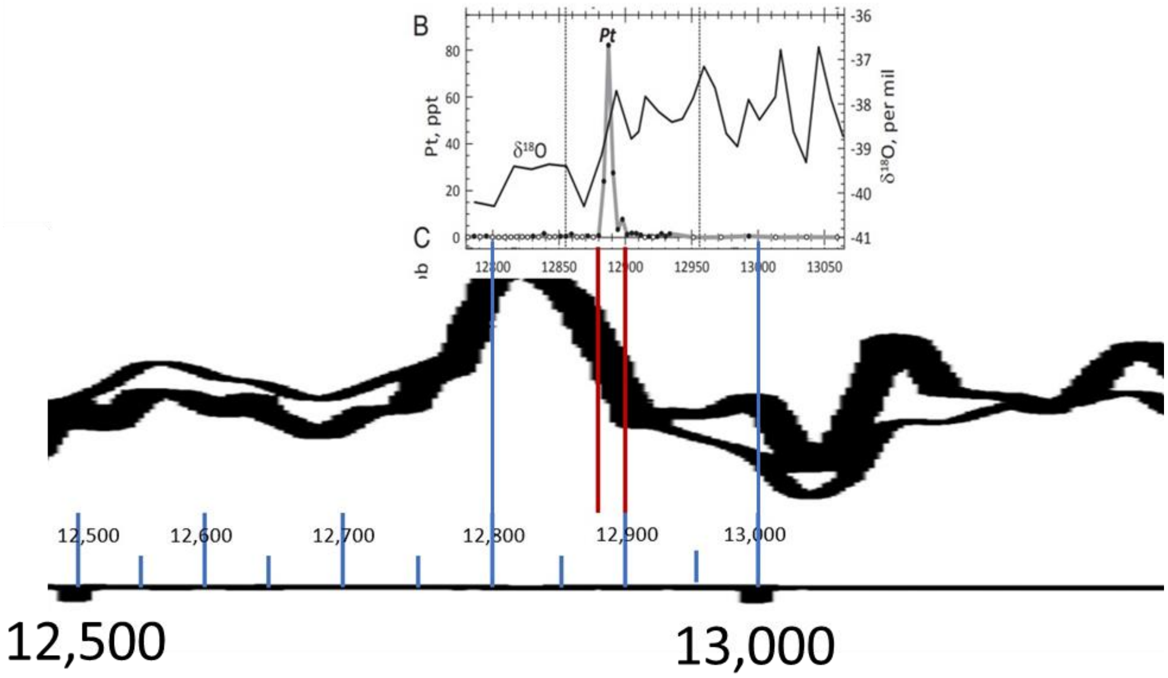


Figure 3b. Extract from Figure 1 of Petaev et al. (2013a) (upper small plot), showing the platinum and oxygen isotope signals in the GISP2 ice core, compared with Figure 2 from Mayewski et al. (1993) (lower plot) showing the ammonium ion signal in the GISP2 ice core (thickest line). The horizontal scales have been stretched to align these plots – indicated by the thin vertical blue lines. The thick vertical red lines bracket the platinum signal, which peaks around 12,890 BP. Clearly, the ammonium ion signal begins around 12,900 BP, coeval with the platinum signal, and not 12,859 BP as stated in the text of Mayewski et al. (1993). Reproduced with permission from the NAS and the AAAS.

Clearly, with correction of this ammonium signal, indicating extensive wildfires, the impactor need not necessarily be local to Greenland. Petaev et al. (2013a) also measured the iridium content of the Greenland ice, finding only a very weak but extended iridium signal coeval with the platinum signal, which is difficult to interpret in terms of known meteorite types. But this combination might be explained by a cometary source.

This Greenland platinum abundance is one of the key pieces of evidence in this debate. Large cosmic impacts and very sudden shifts in climate are extremely rare. If the two most recent events of this type occurred practically simultaneously, or at least within the resolution of current measurements of the GISP2 ice core, it is good evidence, purely on statistical grounds, that the climate shift was triggered by the impact, even in the absence of a clear mechanism.

Despite its importance, Holliday et al. (2014) devoted just two sentences of their 17-page critical review to discussing this evidence. They first comment that that the platinum anomaly is around 30 years too late. Of course, we have just seen that this is incorrect (see above). They next suggest that, in response to Boslough's (2013) comments, ‘*Petaev et al. … accept arguments against the Pt depositing event being the cause of the YD cooling.’* But this misrepresents Petaev et al.'s (2013b) position. In fact, in their response to Boslough (2013), Petaev et al. (2013b) simply acknowledge Boslough’s comments. This is very different to ‘accepting’ them.

Likewise, van Hoesel et al. (2014) devoted very few lines to this platinum discovery in their own critical review, effectively ignoring its apparently coeval timing with the onset of YD cooling and its extended 20-year lifetime indicating a global anomaly should exist. They argued instead that since a platinum anomaly had not yet been found at any other location, it was likely unimportant. However, following Petaev et al.'s (2013a) discovery, several other research groups reported finding platinum anomalies within sediments across the globe using sensitive tests such as fire assay with inductively coupled plasma-mass spectroscopy. But to understand if they are coeval with the Greenland platinum signal, the GISP2 ice core chronology must first be converted into a radiocarbon timescale. This is achieved by the GICC05 chronology. Essentially, according to the radiocarbon-aligned GICC05 chronology we should subtract around 80 years from GISP2 dates in the vicinity of the YD cooling (Svensson et al., 2008). Therefore, on the radiocarbon timeline, a corresponding platinum anomaly is expected around 12,810 cal BP.

For example, Andronikov et al. (2016a) reported high abundances of platinum, other PGEs and rare Earth elements (REEs) within microspherules from the YD black mat at Blackwater Draw, New Mexico, specifically a disconformity known as the ‘Clovis surface’, with concentrations up to 460 ppb. Also, Andronikov et al. (2016b) found elevated levels of platinum, other PGEs and REEs (rare-Earth elements) within a black mat-like feature at several sites in Belgium and the Netherlands, known as the Ussello horizon, thought by many to be the European continuation of the Younger Dryas black mat.

Subsequently, Moore et al. (2017) reported the discovery of a widespread platinum anomaly at the base of the YD black mat in several locations in North America. In many cases, the platinum abundance was found at the same level in the sediment as other impact proxy abundances, such as nanodiamonds and microspherules. In several more cases, the platinum abundance correlated with the last appearance of Clovis tools or with the earliest appearance of later Palaeoindian artefacts such as notched hafted bifaces. For example, at the Flamingo Bay site in South Carolina a platinum abundance nearly 100 times the average crustal value was found in association with the youngest Clovis artefacts.

Conspicuous platinum abundances, around 4 ppb and 10 ppb respectively, were also detected at the YDB at the White Pond site (Moore et al., 2019), South Carolina, radiocarbon dated to 12,785 ± 58 cal BP, and at the Pilauco site in Chile (Pino et al., 2019), radiocarbon dated to 12,770 ± 160 cal BP. More recently, an abundance of platinum measuring around 11 ppb was discovered at the Wonderkrater site in South Africa (Thackeray et al., 2019). Although radiocarbon dating of this site is highly uncertain, it is consistent with a YDB age, and pollen-based measurements indicate it likely corresponds to the onset of the YD period. Recently, Teller et al. (2020) re-examined the Lake Hind site in Manitoba and confirmed platinum and iridium abundances associated with the YDB there. Peak levels for iridium (2.2 ppb) were close to previously reported results by Firestone et al. in 2007 (3.7 ppb) and much larger than reported by Paquay et al. in 2009 (0.1 ppb) and the average crustal abundance (0.02 ppb) suggesting aliquot size and the nugget effect are important at this site. Peak platinum concentrations ranged up to 4.5 ppb, several times larger than measured by Paquay et al. (2009) (1.2 ppb) and the average crustal abundance (0.5 ppb). However, elevated levels of both iridium and especially platinum were found slightly below and significantly above the YDB corresponding to a timespan over 2,000 years, indicating significant dispersion within the sediment. Finally, Moore et al. (2020) analysed debris from the burned layer, thought to represent the YDB, at Abu Hureyra, Syria, dated to 12,825 ± 55 cal BP, finding elevated platinum at 6.2 ppb.

This widespread platinum abundance in bulk sediments near the base of YD-age black mats on at least four continents, confirmed by several independent research groups, is relatively easily measured and unambiguous, since it not found in contact with evidence for volcanism. Its consistent appearance within a distinct layer at dozens of sites, including within Greenland ice within a narrow timeframe of around 20 years, points strongly to a cosmic origin. It is inconsistent with concentration of the background rain of micrometeorites or a sudden but non-catastrophic increase in the influx of micrometeorites because the abundances are far too large (Moore et al., 2017; Petaev et al., 2013a). Moreover, the apparently simultaneous and dramatic onset of the Younger Dryas cooling and extensive wildfires recorded in the Greenland ice points, rather, to a massive impact event (Petaev et al., 2013a). Note that a cooling climate is normally expected to result in fewer wildfires, so the detection of a strong ammonium signal in the Greenland ice coetaneous with the platinum signal is unlikely a direct consequence of the simultaneous onset of cooling. Instead, it is much more likely that cooling and wildfires are a consequence of the impact.

2.2 Iron and Silica-rich impact spherules

Micospherules can be created by cosmic impacts, airbursts, and the non-catastrophic atmospheric burn-up of small meteorites. The extremely high temperatures generated in these processes, over 2,000 °C, melt and vapourize most materials, including those in the incoming meteor and in any impacted surface. Microscopic droplets can nucleate from the vapour phase or are dispersed in the liquid phase as a fine mist. These droplets will typically solidify if launched high into the atmosphere, or splatter on the ground otherwise. Therefore, a range of spherical to sub-spherical microspherules with a composition between that of the target surface and the impacting meteor can be formed and dispersed widely after a cosmic impact event. Rapid quenching causes microspherules typically to be glassy, often with a ‘dendritic’ surface texture. They can be classed generally as either silica-rich or iron-rich. High levels of PGEs suggest mixing with meteoric material, especially if mixing with terrestrial surface features with known high levels of PGEs can be ruled out.

Microspherules can be created through terrestrial mechanisms too. For example, volcanism can generate silica-rich microspherules via dispersal of hot magma (< 1,200 °C) in a volcanic explosion (Lefevre et al., 1986), and iron-rich microspherules can be created by weathering of iron-rich minerals. However, none of these processes involve quenching from extreme temperatures, and therefore microspherules generated via a cosmic source can normally be distinguished through their elemental composition, glassy structure, or a dendritic surface pattern (Wittke et al., 2013b).

As their name suggests, impact microspherules typically have a rounded shape, but they are rarely perfect spheres. They are often found in clusters or aggregates with other materials, and can have a wide range of microscopic sizes. Their identification is, therefore, not straightforward. Detection of any dendritic surface pattern also requires advanced microscopy, such as SEM. Therefore, it is especially important that their existence at any specific YD boundary site is confirmed by independent research groups with expertise in their counting and analysis.

In their original paper, Firestone et al. (2007) describe finding peaks in the abundance of silica and iron-rich microspherules at the YDB at several sites across North America and one in Belgium. The magnetic fraction (i.e. the iron-rich microspherules) often had a high iridium content. Of these sites, Surovell et al. (2009) examined just one where an abundance of magnetic microspherules had previously been found, Blackwater Draw in New Mexico, finding only around 5% (around 35 kg^{-1}) of the number of magnetic microspherules claimed by Firestone et al. (2007) (around 700 kg^{-1}) from slightly above what they considered the YDB. But because of their limited sampling and lack of advanced microscopy to detect quenched surface features, it is not clear whether this represents a peak in abundance of *impact* microspherules with depth in the sediment. Surovell et al. (2009) also found abundance peaks in magnetic microspherules at the YDB at three other sites in N. America, although their peak concentrations were likewise quite small and the existence of other abundance peaks sometimes slightly above or below the boundary layer painted an inconclusive picture. But again, their sampling was quite limited, and they did not use advanced microscopy, like SEM, to look for surface dendritic features or analyse the atomic composition of the spherules. Nevertheless, they concluded against the impact theory.

In 2012, Pigati et al. (2012) examined sediments from 10 sites in California, Arizona and the Atacama Desert in Chile, including one site, Murray Springs, previously examined by Firestone et al. (2007). They confirmed an abundance peak of magnetic microspherules at the YDB at Murray Springs, although they only found about 10% of the number found by Firestone et al. (2007). However, they also found abundance peaks of magnetic microspherules within several other stratigraphic horizons, or 'black mats', dating from older than 40 kyr to 11.5 kyr. Some of these horizons also displayed abundance peaks in iridium. But they did not analyse the surface texture of any of their microspherules or analyse their atomic composition, so it is not clear whether any of these other strata likely relate to other meteorite impacts, volcanism or other potential sources of microspherules such as lightning. On the basis that microspherules appear to be abundant at many stratigraphic boundaries, they concluded that a meteoric origin for the Younger Dryas boundary microspherules is unlikely. However, this argument is flawed, as it is well known that magnetic microspherules can be produced by several routes. Their existence within other stratigraphic horizons actually says nothing about the origin of microspherules at the Younger Dryas boundary. Only more detailed examination, such as microspherule surface texture analysis and elemental abundance, can determine this, which they did not do.

Israde-Alcantara et al. (2012) also found an abundance of magnetic microspherules (nearly 2,000 kg^{-1}) at the YDB at Cuitzeo Lake in Mexico. Under SEM analysis, microspherules were found to have a dendritic surface pattern indicative of rapid quenching from the molten state. Although dating of these lake sediments was inconclusive in this work, later work confirmed a YD age for the black mat at this site (Kinzie et al., 2014).

Later, Bunch et al. (2012) examined the YDB at 18 sites on three continents (N. America, Europe and Asia) and found peaks in both iron and silica-rich microspherules ranging from 5 to 4,900 microspherules/kg. Concentrations above and below the YDB were zero or low. SEM imaging revealed the outer surfaces of most spherules exhibited distinctive dendritic surface textures indicative of rapid quenching. Although most were spherical, a large fraction instead exhibited aerodynamic teardrop shapes with clear surface flow lines (Schleiren).

Further analysis of iron and silica-rich microspherules recovered from the YDB on four continents (including S. America) was provided by Wittke et al. (2013b) the following year. They found many microspherules contained minerals with signs of melting at very high temperatures (see Figure 4). Anthropogenic, volcanic and lightning sources were effectively ruled out. Due to their high abundance, concentration of the background flux of micrometeorites at the boundary could also be ruled out. Elemental analysis shows most microspherules are consistent with a terrestrial source, although some also show elevated levels of PGEs, thus ruling out a brief but non-catastrophic influx of micro-meteorites. Integration of their abundance suggests 10 million tonnes of microspherules were produced, practically confirming a major cosmic impact at the Younger Dryas boundary.

LeCompte et al. (2012) re-examined two sites previously studied by Firestone et al. (2007) and Surovell et al. (2009) and found abundant magnetic microspherules at the YDB. At the Topper site, S. Carolina, they found 260 kg^{-1} where Surovell et al. (2009) found none, while at the Blackwater Draw site, New Mexico, they found over 1,300 kg^{-1} where Firestone et al. (2007) found around half this number and Surovell et al. (2009) found only around 35 kg^{-1}. At a third site, Paw Paw Cove in Maryland, where Surovell et al. (2009) found no magnetic microspherules, LeCompte et al. (2012) instead found 317 kg^{-1}. Typical magnetic spherules displayed dendritic surface textures indicative of rapid quenching from the molten state, and some were found to have significantly raised levels of REEs, which points to mixing with extraterrestrial material. They concluded that there were significant deficiencies in the analytical methods used by Surovell et al. (2009).

van Hoesel et al. (2014) reviewed the microspherule evidence in their critical review, but their arguments against the impact hypothesis are spurious. They suggest the microspherules might have a volcanic origin, given that some of the microspherules at the YDB layer are similar to some marine microspherules thought to have a volcanic origin. But the volcanic origin for these specific marine microspherules is not clear, and a volcanic origin for the YDB microspherules has already been ruled out on the basis that no volcanic signatures are present in the YDB layer. To counter this, van Hoesel et al. (2014) suggest, without evidence, that the microspherules at the YD boundary at *all* YDB sites might have migrated through the sediment from the Laacher See volcanic boundary layer below. However, more recent work (Kletetschka et al., 2018) shows this is clearly not true at a location close to the Laacher See eruption (see Figure 5), and the chemical signatures in the GISP2 ice core of the YD event and volcanic eruptions are also clearly separated (Petaev et al., 2013a). In any case, the range of the Laacher See tephra is limited mainly to Central Europe (Reinig et al., 2020).

Subsequently, abundances of magnetic microspherules at the Younger Dryas boundary were found at several sites in Central and South America, including Patagonia, southern Chile, thus extending the range and mass of the presumed impact ejecta (Pino et al., 2019). Again, typical microspherules exhibited dendritic surface patterns, and abundances ranged from about 200 to 400 kg^{-1}.

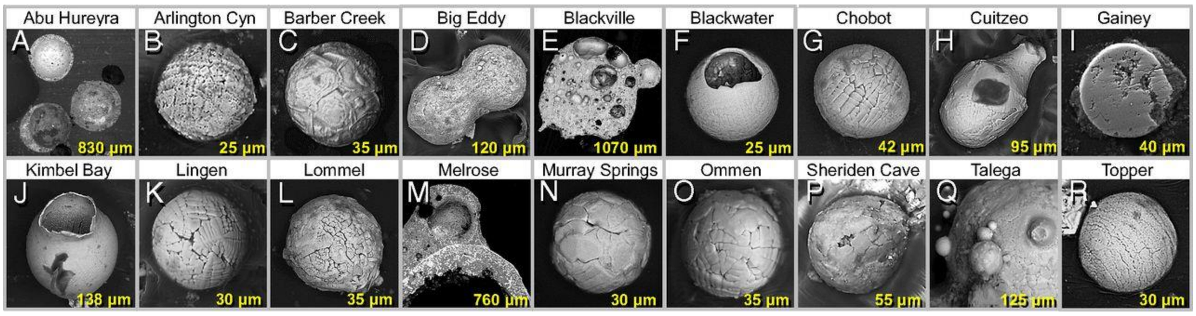


Figure 4. Typical iron-rich and silica-rich microspherules recovered from 18 YDB sites on four continents (Figure 3 from Wittke et al. (2013b)) with dendritic surface patterns indicating quench-melting from extremely high temperature. Some microspherules (from Abu Hureyra (A), Blackville (E) and Melrose (M)) contain lechatelierite inclusions that display flow lines (Schleiren). Reproduced with permission from the NAS.

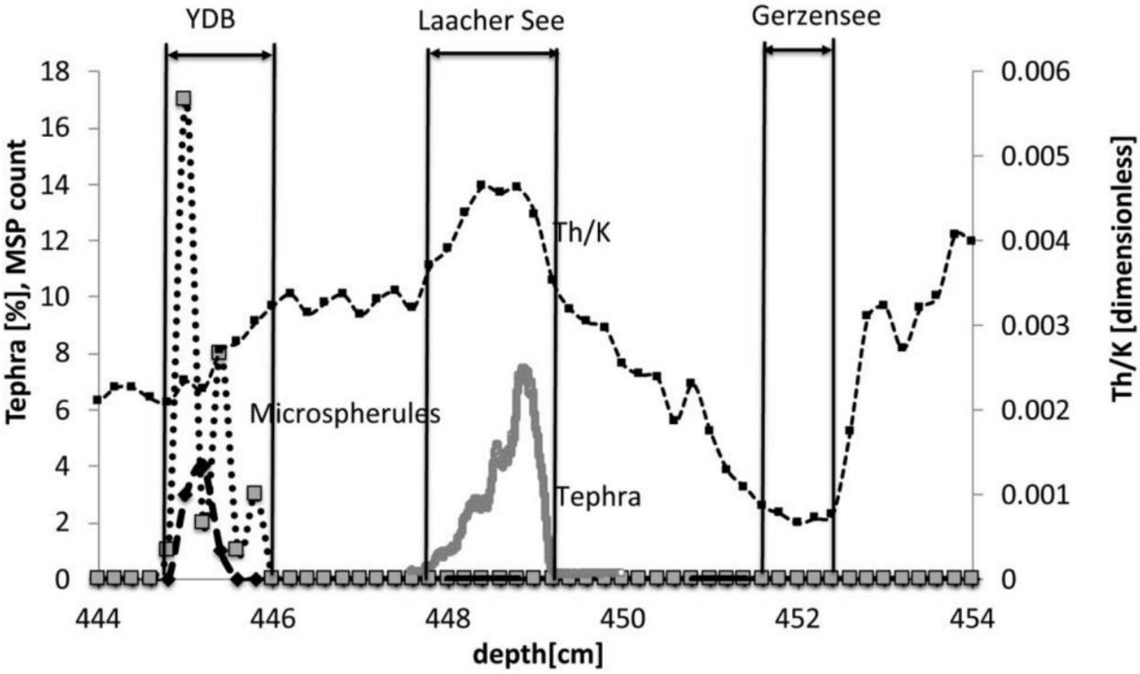


Figure 5. Sediment profile for Stara Jimka, a Palaeolake in the Bohemian Forest, Czech Republic, taken from Kletetschka et al. (2018) showing clear separation between the Laacher See Tephra and Younger Dryas boundary microspherules. The right vertical axis measurement, Th/K, is a proxy for climate. Radiocarbon measurements from the sediment indicate the Laacher See event preceded the Younger Dryas event by around 100 years, which agrees well with evidence from the GISP2 ice core (see Figure 3a). Reproduced with permission from University of Chicago Press.

2.3 Other high temperature melts

Lightening is the only natural process on Earth's surface capable of producing temperatures significantly in excess of 1,500 °C. Volcanism generates temperatures no hotter than magma, around 1,500 °C, while wildfires and building fires are thought to operate typically between 500 and 1000 °C. Therefore, evidence for melted minerals with very high melting temperatures >> 1,500 °C, especially in the absence of volcanism and lightening, strongly indicates production by a cosmic impact.

However, evidence for high temperature melting at Earth's surface is challenging to confirm. First, one has to assess the composition of the mineral and estimate its melting temperature based on thermodynamic models. Then, one should show that the mineral was melted at Earth's surface. Furthermore, the aim of such studies should be to find convincing evidence for the highest temperature attained, i.e. a melted mineral with the highest liquidus temperature, at a specific location. The iron and silica-rich microspherules discussed in the preceding section are a specific class of high temperature melt consisting of rounded microparticles. Here evidence for other high temperature melts is summarized.

Fayek et al. (2012) discovered highly unusual framboidal microspherules embedded in a glassy matrix from the YDB at Murray Springs. The framboids were composed mainly of cubic iron oxide (magnetite) grains, with higher silicon oxide content in the background matrix. They noted that the framboids are similar to ones known to occur in chondrites, and based on the composition of the glassy matrix, they estimated a melting temperature of around 1,500 ^{o}C, consistent with a cosmic impact. Their elemental composition was similar to other known impact particles, but dissimilar to fulguritic minerals (formed via lightning) or particles with a volcanic origin. van Hoesel et al. (2014) commented that the particles did not have a composition consistent with a meteoric origin but this observation is clearly at odds with Fayek et al.'s (2012) data. Specifically, the data points corresponding to the elemental composition of their microspherules, plotted in Figure 4b of their work, are clearly similar to the composition of other impact materials and impact spherules, plotted in Figure 4a of their work.

In their survey of 18 sites across three continents, Bunch et al. (2012) noted the occurrence of large glassy, ‘scoria-like objects’, or SLOs’, at the YDB of three sites, specifically Blackville, North Carolina, Abu Hureyra, Syria, and Melrose, Pennsylvania. The elemental composition of these SLOs was very similar to microspherules recovered in abundance from the boundary layer at all 18 sites, and with known impact ejecta, but dissimilar to known volcanic microparticles or cosmic dust particles. Based on their elemental composition, mainly iron, silicon, calcium, aluminium and magnesium oxides, and by comparison with ternary diagrams (see Figure S9 of their work) they estimated melting temperatures in the range 1,200 to 1,900 ^{o}C for a selection of these particles. Bunch et al. (2012) also claim to find suessite crystallites within some SLOs from the Melrose site, a mineral sometimes formed in meteoric impacts with a crystallisation temperature over 2,300 ^{o}C. Moreover, given the large size of the SLO particles, some in excess of several millimetres, they could not have been transported far from the centre of any putative impact event, indicating multiple widely separated local impacts.

However, Bunch et al. (2012) provided detailed chemical compositions only as an average over an assemblage, and not for any specific particle. And, moreover, their melting temperature estimates were mainly based on interpolation of ternary oxide diagrams, which for particles with more than three major components can lead to significant error. Therefore, their estimated melting temperatures cannot be accurately confirmed.

Nevertheless, some SLOs at Abu Hureyra were noted to contain regions of what appeared to be relatively pure (94%) silica oxide (Lechatelierite), with clear flow lines (Schlieren) and surface imprints, for which melt temperatures in excess of 2,000 ^{o}C were estimated. This is good evidence for either lightning or a cosmic impact. Lightning at Abu Hureyra as the trigger of the fire could, however, be ruled out, leaving a cosmic impact as the only viable explanation for this material.

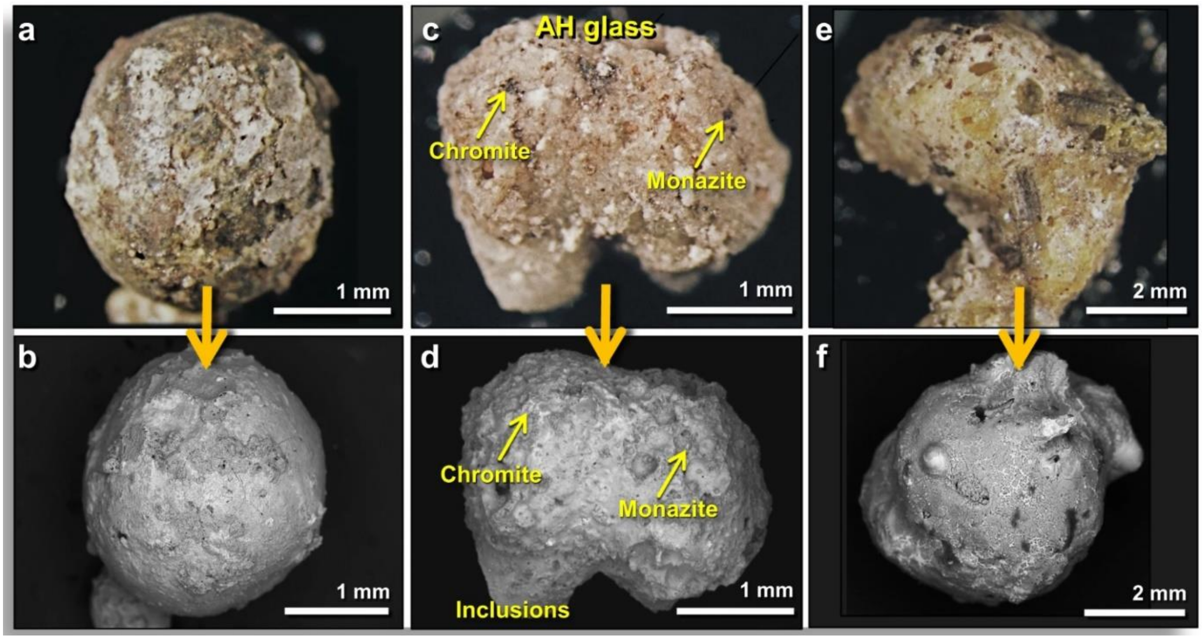


Figure 6. Typical examples of Abu Hureyra meltglass (Figure 2 from Moore et al. (2020)). Reproduced under the terms of the CCA 4.0 International License.

In their critical review, van Hoesel et al. (2014) essentially agree with this line of reasoning, but they question an impact origin on the basis of the lack of shocked quartz or other shocked minerals acceptable to them. But this is a fallacious argument, as a ground impact has not been proposed for the destruction at Abu Hureyra. Instead, a local airburst is the proposed mechanism.

Following this work, Thy et al. (2015) selected a few SLO particles for further analysis from the Abu Hureyra site, although only one of these particles was from the burned 'Level II' layer examined by Bunch et al. (2012) thought to represent the YDB. On the basis of this single particle they estimated a melting temperature close to 1,200 °C, consistent with the lower end of the temperature range in Bunch et al. (2012). Moreover, they found similar particles at other levels at Abu Hureyra and at other archaeological sites across Syria with similar radiocarbon ages. From this they argued in favour of a series of very high-temperature building fires at all these sites. But, clearly, their search at Abu Hureyra was not very exhaustive. The aim of such research is to find evidence for maximum temperatures, but analysis of a single particle does not fulfil this aim. Nor does evidence of building fires at these sites preclude the possibility of a cosmic impact event being the ultimate trigger for any of these fires. And, in any case, their conclusions ignore Bunch et al.'s (2012) findings concerning 94% pure Lechatelierite with Schleiren, which cannot be explained by building fires.

Later, Moore et al. (2020) re-examined SLOs from around the burned layer, Level II, at Abu Hureyra, confirming Bunch et al.'s (2012) original findings. They document a wide range of silica-rich particles with melted pure Lechatelierite inclusions showing signs of bubbling indicating temperatures in excess of 2,200 °C. Some silica particles contained melted inclusions of monazite and chromite, which melt at around 2,100 and 2,200 °C respectively (see Figure 6). Several particles also showed imprints from plant leaves, which melted around 1,300 °C in laboratory experiments, showing that the destruction and melting occurred at Earth's surface. This effectively confirms a cosmic impact at Abu Hureyra, recorded in the level II burned layer.

2.4 Nanodiamonds

Diamonds are relatively abundant at Earth's surface. Their formation mechanisms continue to be debated, but generally extreme pressures and high temperatures are thought to act on carbon-rich materials deep within the Earth to create cubic diamond crystals via phase transformation, typically micrometres or more in size. Volcanic and tectonic activity then bring them to the surface. All diamonds formed through this route have pure sp3 bonding and nearly all also have a cubic structure, i.e. a repeating ABC pattern of hexagonal carbon layers. There are some reports of a repeating AB pattern of hexagonal carbon layers, corresponding to hexagonal diamond, also known as Lonsdaleite, but the natural existence of this structure is questioned (Daulton et al., 2017).

Nanodiamonds, i.e. nanometre through to sub-micron sized carbon crystals dominated by sp3 bonding, are known to occur within meteorites and cosmic impact structures (Daulton et al., 2010). They are also known to be produced via shock metamorphism by high energy explosions acting on carbon-rich precursor materials. Debate continues regarding the existence and proper identification of different nanodiamond structures, particularly the 'new' forms, n-diamond and i-carbon (Wen et al., 2007). In terms of static pressures, the new-diamond forms are thought to form at lower pressures than cubic diamond, which in turn is thought to form at lower pressures than hexagonal diamond (see Kinzie et al. (2014) and references therein). The new forms, n-diamond and i-carbon, are apparently also generated routinely within commercial activated carbons, such as Norit, produced through superheated stream treatment of charcoal in an anoxic atmosphere. They are not found in the precursor charcoals, showing that it is the anoxic superheated steam treatment that is responsible for their production in this case (Kinzie et al., 2014). These new nanodiamond forms are distinguished from cubic and hexagonal diamond by their diffraction spacings.

Cubic and hexagonal diamond can be produced synthetically via high pressure compression of graphite or by CVD processes, i.e. condensation of carbon ions onto a clean surface from the vapour phase at low pressure. A range of methods are available for energising a carbon source, such as methane, to generate carbon ions in the vapour phase. Diamond films have also been formed via heating very specific polymers under argon on suitably smooth surfaces at normal atmospheric pressure (Bianconi et al., 2004). However, none of these synthetic methods can be expected to occur naturally at Earth's surface.

Almost all terrestrially formed diamond is microscopic or larger, > 1 μm, and of cubic form. Naturally formed terrestrial nanodiamonds, 2 nm to 100 nm, are extremely rare and have never been found in association with wildfires, volcanic explosions or any other natural surface process. A coetaneous abundance of nanodiamonds dispersed across a large area at Earth's surface, therefore, is an excellent proxy for a cosmic impact, especially in the absence of evidence for volcanism, such as sulphate and tephra abundances.

It is odd, therefore, that in a major critical review of the nanodiamond evidence Daulton et al. (2017) refuse to admit nanodiamonds as an impact proxy. Their counter-argument, relating specifically to cubic nanodiamonds, is that '*shock metamorphism does not appear to be the predominant formation mechanism of diamonds of that size found in the crust*'.

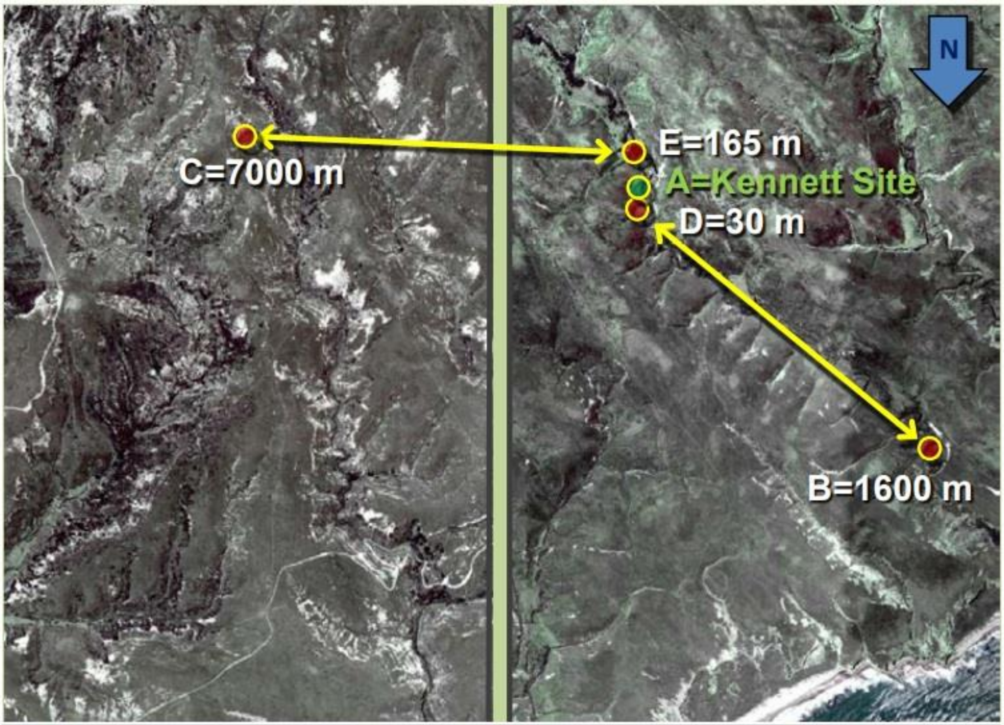
Let's just analyse the logic of this statement. First, Daulton et al. (2017) claim to know the dominant formation mechanism of cubic nanodiamonds within Earth's crust is not via shock, i.e. they are created by longer-term extreme pressure processes. Second, they claim this reveals the formation mechanism for cubic nanodiamonds at the Younger Dryas boundary, i.e. they must also be formed by longer-term extreme pressure processes, and therefore are not formed by a cosmic impact. But neither of these statements is supported by the evidence. Regarding their first claim, nearly all the evidence they provide for terrestrial formation of cubic diamond relates to micron-sized diamonds or larger, or their aggregates. The only clear instance of terrestrial nanodiamond generation they mention refers to nanodiamond inclusions found within rare garnets. But as garnet is not rich in carbon, the limited size of cubic diamond domains within these specific garnets is more likely related to a limited carbon feed. Moreover, it is clear that nanodiamonds at the Younger Dryas boundary are not found in association with any garnets. Other claims by Daulton et al. (2017) for the natural occurrence of cubic nanodiamonds on Earth relate to, i) cubic nanodiamonds discovered within surface soils in Belgium and Germany (Yang et al., 2008), and ii) cubic nanodiamonds found at the Ussello horizon in the Netherlands (van Hoesel et al., 2012). But in the former case, Yang et al. (2008) suggest these nanodiamonds are likely to have been produced either by another cosmic impact or detonation of explosives during modern wars, and in the latter case the Ussello horizon is regarded by many as a continuation of the Younger Dryas boundary. Either way, these are not clear examples of natural cubic nanodiamond formation on Earth.

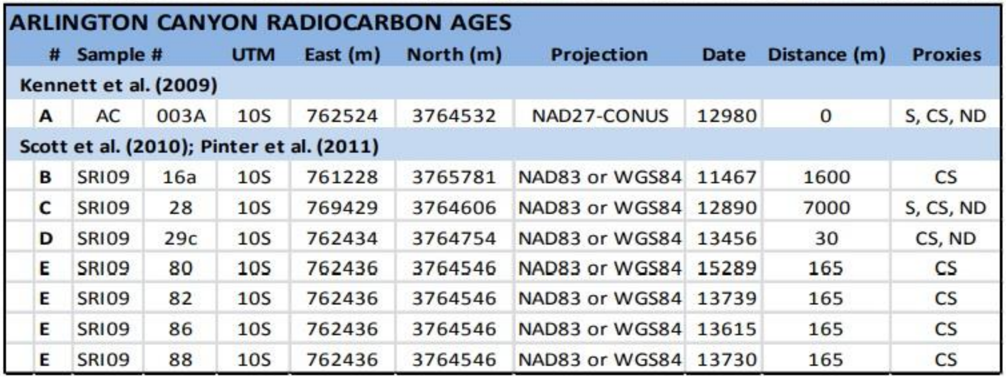
Regarding their second claim, even if terrestrial nanodiamond formation was generally via a longer-term high pressure process than shock, the presence of a coetaneous layer of nanodiamonds of Younger Dryas age across a large fraction of Earth's surface in the absence of other clear volcanic markers, such as tephra and sulphates, clearly points to a cosmic origin. This is because we would not expect geological and weathering processes to be so uniform that they generate a coetaneous layer of extremely rare minerals across several continents. Only a volcanic eruption or cosmic explosion can explain this. But, in any case, volcanism is not known to create nanodiamonds. For all these reasons, Daulton et al.'s (2017) statement is clearly incorrect.

Kennett et al. (2009a) first reported the recovery of abundant nanodiamonds at the YDB at six sites across North America, including at the Murray Springs site (see Figure 1), Arizona. Crystal sizes ranged from 2 to 300 nm, and peak abundances were up to a few hundred ppb in bulk sediments. Selected area diffraction patterns are claimed to be consistent with cubic diamond and n-diamond. Abundant nanodiamonds were found to occur inside amorphous carbon particles, suggesting shock metamorphism of the carbon precursor, and as isolated crystallites. Kennett et al. (2009b) further reported finding abundant cubic nanodiamonds, n-diamonds and hexagonal nanodiamonds (Lonsdaleite) at the YDB at Arlington Canyon, Santa Rosa Island.

Daulton et al. (2010) were unable to reproduce these results but this was very likely due to collection of incorrect samples. Kennett et al. (2009b) reported nanodiamonds inside or adhered to specific kinds of impact-related glassy carbon particles, such as carbon spherules and glassy carbon 'elongates'. However, Daulton et al. (2010) analysed microcharcoal aggregates from Murray Springs, which are not expected to contain any nanodiamonds. From Arlington Canyon, Daulton et al. (2010) selected carbon microspherules for analysis from the lowest metre of a 5-metre sediment bank claimed to be the same one examined by Kennett et al. (2009b). However, Wittke et al. (2013b) and Kinzie et al. (2014) show (see Figure 7) that Daulton et al. (2010) did not, in fact, sample the same site as Kennett et al. (2009b) at Arlington Canyon – instead their samples with labels SRI-09 were obtained from several different locations separated by up to 7,000 m from the site sampled by Kennett et al. (2009b). Scott et al. (2017), with Daulton as co-author, later refuse to admit this error, pointing to photographs that show that they did indeed sample the same sediment bank as Kennett et al. (2009b). But this is misleading, as the site and samples depicted in these photos are all labelled SRI-10 to SRI-13, whereas the relevant samples in Daulton et al. (2010) all have labels SRI-09. So it is quite clear the nanodiamond samples in Daulton et al. (2010) did not, in fact, come from the same sediment bank sampled by Kennett et al. (2009b). Daulton et al. (2010) also analysed glassy carbon elongates and carbon microspherules from another site on Santa Cruz Island, another Californian

Channel Island close to Santa Rosa Island. However, radiocarbon dating of these sediments indicates they are around 5,000 years too old to be relevant. Nevertheless, in a series of papers based on the same samples, Daulton and co-workers cast doubt on the identification of Lonsdaleite by Kennett et al. (2009b) at Arlington Canyon (Daulton, 2012; Daulton et al., 2017; Daulton et al., 2010). Expected diffraction signatures are said to be missing, and they conclude in favour of an assembly of graphene/graphene layers.





ARLINGTON CANYON RADIOCARBON AGES

#	Sample #		UTM	East (m)	North (m)	Projection	Date	Distance (m)	Proxies
Kennett et al. (2009)									
A	AC	003A	10S	762524	3764532	NAD27-CONUS	12980	0	S, CS, ND
Scott et al. (2010); Pinter et al. (2011)									
B	SRI09	16a	10S	761228	3765781	NAD83 or WGS84	11467	1600	CS
C	SRI09	28	10S	769429	3764606	NAD83 or WGS84	12890	7000	S, CS, ND
D	SRI09	29c	10S	762434	3764754	NAD83 or WGS84	13456	30	CS, ND
E	SRI09	80	10S	762436	3764546	NAD83 or WGS84	15289	165	CS
E	SRI09	82	10S	762436	3764546	NAD83 or WGS84	13739	165	CS
E	SRI09	86	10S	762436	3764546	NAD83 or WGS84	13615	165	CS
E	SRI09	88	10S	762436	3764546	NAD83 or WGS84	13730	165	CS

Figure 7. Figure S1 and table from the appendix to Wittke et al. (2013b) showing a Landsat image of Santa Rosa Island. The green dot is the location of the YDB sampling location from Kennett et al. (2009b). Red dots are sampling sites used by Daulton et al. (2010), documented by Scott et al. (2010), with distances in meters from the original site (see also the table above). Reproduced with permission from the NAS.

The following year Kurbatov et al. (2010) claimed to find abundant nanodiamonds, including Lonsdaleite, at the Younger Dryas boundary at Kangerlussuaq, on the margin of the Greenland ice sheet. Although their nanodiamond abundance is over 1 million times the background level, dating of the site is problematic. Expert opinion of the stratigraphy and limited correlation of a series of oxygen isotope measurements indicate that the Younger Dryas boundary is very likely to be correctly identified, but nevertheless more robust dating of the site is required to firmly associate these findings with the YDB.

However, Tian et al. (2011) confirmed the existence of abundant cubic nanodiamonds at the Ussello horizon, often thought to be the continuation of the YDB, at Lommel, Belgium. Through analysis of the crystal structure of particles found within larger amorphous carbon materials using SAED, HRTEM and ELNES, they find '*undisputable proof*' for the existence of cubic nanodiamonds with size ranging from a few nm to 20 nm, and larger flakes up to 100 nm in lateral dimension. Furthermore, Israde-Alcantara et al. (2012) also found abundant nanodiamonds at the YDB at Lake Cuitzeo, Mexico. Diamond nanocrystals in the range of a few nm to 10 nm were identified, with a peak concentration of 100 ± 50 ppb. Crystal structure, bonding and elemental analysis performed with HRTEM, STEM, FFT, EDS, SAD, and EELS indicate the presence of abundant n-diamond with smaller amounts of i-diamond and Lonsdaleite. Cubic nanodiamonds were not definitively identified, although they might have been masked by n-diamond.

Note that all authors so far have been careful to explain that they discovered clear nanodiamond peaks in bulk sediment at the purported YDB, and that few or no nanodiamonds were found either above or below this layer within a reasonable timeframe. Kennett et al. (2009b) showed explicit plots of nanodiamond abundance with depth in the sediment for each site examined, typically peaking at a few hundred ppb for most sites, while Tian et al. (2011) state this explicitly in their text. It is therefore odd that Daulton (2012) claims the contrary in his rebuttal. Daulton (2012) also pointed to the existence of cubic nanodiamonds in surface soils at sites across Germany and Belgium (Yang et al., 2008), claiming this contradicts the impact theory. But, as already stated, this is likely incorrect as their existence might indicate another cosmic impact, probably an airburst since no impact crater is known at this location. Such an event, like the Tunguska event of 1908, Siberia, where nanodiamonds in surface soils have also been found (Kvasnytsya et al., 2013), is not unexpected. Alternatively, these surface nanodiamonds cited by Daulton (2012) might signal the fall-out from explosive detonations carried out during modern wars, as suggested by the authors (Yang et al., 2008). Finally, Daulton (2012) again refutes the identification of the Lonsdaleite form by Kurbatov et al. (2010) citing diffraction peaks inconsistent with this structure, and questions the identification of Lonsdaleite by Israde-Alcantara et al. (2012), citing their HRTEM image as insufficient.

However, van Hoesel et al. (2012) later confirmed an abundance of cubic nanodiamonds within glassy carbon particles at the Ussello horizon, thought to be the YDB by many, at Geldrop-Aalsterhut, Netherlands. Then in 2014, Bement et al. (2014) confirmed an abundance of n-diamonds, typically of size less than 15 nm with concentrations of around 200 ppb, similar to Kennett et al. (2009a), at the YDB at Bull Creek, Oklahoma. They also found a similar abundance in surface soils, potentially indicating an airburst in more recent times near this location, or perhaps fall out from modern explosive, as for the Belgian soils. Only background levels of nanodiamond were found in the remainder of their sediment profile, covering a timeframe of around 20,000 years.

Kinzie et al. (2014) then produced an extensive report concerning nanodiamond abundances at 22 YDB sites across three continents. Using nine different analytical techniques, including electron microscopy and diffraction, they find cubic nanodiamonds, n-diamond and i-carbon across these 22 sites. They also claim to find Lonsdaleite-like nanodiamonds at some sites. Nanodiamond sizes typically range between 1 and 20 nm, with peak abundances in bulk sediments in the range 11 to 494 ppb across these 22 sites. Their measurement protocol relies on counting rounded to sub-rounded particles within electron microscope images of treated sediment samples. Random sampling of these particles with their suite of analytical techniques shows that over 99% of such particles are indeed nanodiamonds.

However, Daulton et al. (2017) later questioned all these results. While accepting that cubic nanodiamonds have been correctly identified at 8 YDB sites, Daulton et al. (2017) disputes, i) the use of any nanodiamond type as an impact marker, ii) the identification of Lonsdaleite at any site, suggesting instead they are graphene/graphite complexes, iii) the identification of n-diamond and i-carbon at any site, suggesting instead that such particles are typically Cu, Zn or other non-carbon crystals, iv) the existence of a nanodiamond abundance at any YDB site, citing severe problems with the measurement protocols of all such claims, and v) the synchronicity of any claimed YDB site at which nanodiamonds are found. Their final counter-claim is an important issue that will be dealt with separately in section 2.6.

Daulton et al.'s (2017) first counter-claim, regarding the use of nanodiamonds as an impact proxy, has already been dealt with above. Regarding the identification of Lonsdaleite, the key issue identified by Daulton et al. (2017) is that the diffraction patterns of Kennett et al. (2009b), Kurbatov et al. (2010) and Kinzie et al. (2014) appear to be missing diffraction rings at 0.15 nm expected for Lonsdsaleite. By scaling these diffraction patterns by a factor of 1.054, Daulton et al. (2017) claim a better match is obtained to an assembly of graphene/graphene layers. But this is a matter of judgement based on a rather fuzzy diffraction image (see Figure 8). However, Kinzie et al. (2014) are clear that their diffraction spacing measurements are accurate, since they have been calibrated with reference to a known graphene sample. They therefore rule out the possibility they have mis-identified the material. Moreover, Kinzie et al. (2014) provide further evidence of Lonsdaleite-like crystals from two caves, Sheriden and Daisy, in North America, and this data is not contested by Daulton et al. (2017). Considering this dataset as a whole, the diffraction patterns of the Lonsdaleite-like samples from Arlington Canyon (Kennett et al., 2009b), Greenland (Kurbatov et al., 2010), and the two North American caves (Kinzie et al., 2014) appear to be identical, and an EDS map of the Arlington Canyon particle shows it is pure carbon. Given Kinzie et al. (2014) claim that their diffraction spacing measurements are accurate, and given their consistency with HRTEM images of the lattice planes and FFTs of these images, it is highly likely that at least some of the nanodiamonds presented by Kinzie et al. (2014) are Lonsdaleite or Lonsdaleite-like. However, this debate would benefit from EELS spectra of these crystals that would show the proportion of sp2 (indicating graphite or graphene) versus sp3 bonding (indicating diamond), enabling a definitive decision.

Given that Lonsdaleite consists of sp3 bonded layers of carbon with a repeating AB pattern, while cubic diamond consists of sp3 bonded layers of carbon with a repeating ABC pattern, one potential resolution of this data is that the Lonsdaleite-like crystals in question have a disordered sequence of AB and ABC layers. Such stacking faults can be expected in a mineral formed through shock.

Regarding Daulton et al.'s (2017) third point, that the n-diamonds and i-carbons identified are likely to be other minerals, this possibility is effectively eliminated. Kinzie et al. (2014) randomly sample the rounded particles they identify as nanodiamond with SEM, and using a suite of experimental techniques find that 99% of them are nanodiamonds and not other kinds of crystal, such as quartz, zircon and rutile.

Regarding their fourth point, Daulton et al. 92017) claim that Kinzie et al. (2014) and all other researchers cannot reliably identify nanodiamond abundances. As already discussed, in the case of Kinzie et al. (2014) their counting method relies on analysis of SEM microscope images where every rounded to sub-rounded particle is counted as a nanodiamond. Daulton et al. (2017) claim insufficient calibration of this counting method has been performed. However, for the same reason as above, this is clearly incorrect.

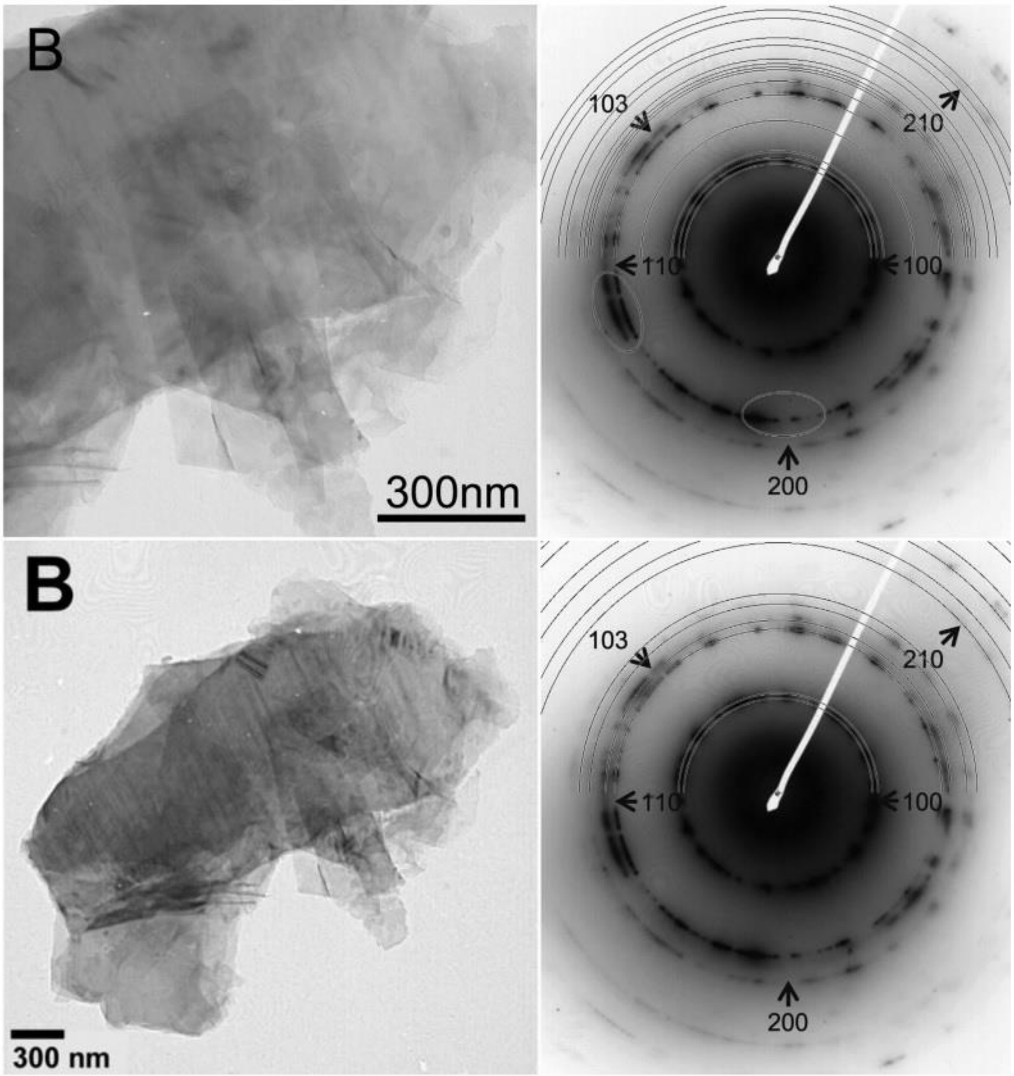


Figure 8. Identification of Lonsdaleite-like crystals with SEM and x-ray diffraction (from Daulton et al. (2017)). The same diffraction pattern on the right, from Arlington Canyon and purported to be Lonsdaleite-like (Kennett et al., 2009b), is compared with computed diffraction rings for Lonsdaleite (top) and a graphite/graphene assembly (bottom). However, the bottom image has been scaled by a factor of 1.054. Daulton et al. (2017) focus on the single missing diffraction ring between the 100 and 110 rings in the top image. The axial asymmetry in this diffraction pattern, highlighted by the ellipses, can be explained by a non-uniform distribution of crystal grain orientations. Reproduced with permission from the publisher (John Wiley and Sons).

The issue of synchronicity is dealt with later. However, if the 24 boundary layers now positively identified to display nanodiamond abundances are indeed synchronous, then the only reasonable explanation for this evidence is a cosmic event. Other mechanisms are effectively ruled out by Kinzie et al. (2014). Indeed, isotopic abundances measured by Kinzie et al. (2014) indicate the carbon in these nanodiamonds is predominantly terrestrial, strongly indicating a major cosmic impact event.

2.5 Charcoal, soot and wildfires

Intense thermal radiation resulting from cosmic impacts, whether ground impacts or airbursts, is sufficient to ignite wildfires on the ground (Matthias et al., 2017; Napier, 2010). Added to this, a ground impact can disperse debris with high altitude trajectories that can, in turn, ignite wildfires around secondary impact sites. Moreover, in addition to thermal radiation, airbursts can cause extensive burning on the ground due to the downward momentum of the resulting fireball. Therefore, evidence for extensive wildfires is an essential component of the Younger Dryas impact hypothesis. Of course, key difficulties with this line of evidence are i) distinguishing between evidence for impact-related wildfires and natural wildfires, and ii) precise dating of this evidence. For these reasons, charcoal and other evidence of intense wildfires cannot be viewed in the same sense as the other proxies already described. All we can expect is that, if the impact occurred, we should find a coetaneous abundance of charcoal, soot, and other wildfire indicators, such as carbon-rich microspherules, widely distributed across a large fraction of Earth's surface. It is not necessary to demonstrate they were produced by a cosmic impact, because charcoal and soot are not, by themselves, diagnostic of an impact.

Charcoal was highlighted as an impact proxy for the Younger Dryas impact event by Firestone et al. (2007) in their original paper. A charcoal abundance was claimed at the Younger Dryas boundary at nearly all the sites investigated, although it is not possible to verify this claim with the data provided. Later work by similar groups of researchers extended these claims to Arlington Canyon on Santa Rosa Island (Kennett et al., 2008) and Lake Cuitzeo, Mexico (Israde-Alcantara et al., 2012).

Power et al. (2008), working with the World Charcoal Database (WCD), find conspicuous peaks in charcoal abundance between around 13 and 11 kyr (their Figure 2), the highest over the entire duration of their record (24 kyr). However, after application of several data transformation techniques, these peak abundances are no longer apparent in their regional plots of charcoal anomaly (their Figure 5). Instead, we see a weak signal in the period 13.5 to 12.5 kyr in most regions of the world, except for south and central America and East Asia. Probably, the weakness of this signal, given the abundances evident in the original database, indicates their data analysis methods are not suited to isolating and highlighting the main charcoal anomalies over the last 24 kyr. Using the WCD again, Marlon et al. (2009) examine 35 high resolution charcoal records for North American lake sediments, finding a strong signal for anomalous fire frequency in the range 13,100 to 12,700 cal BP, described as '… *the largest and most rapid change in biomass burning during deglaciation'.*

However, they attribute this anomaly to changes in climate, rather than a cosmic impact, largely because of the breadth of this anomaly and because similar charcoal signal peaks are observed at other times, including near the end of the Younger Dryas period.

Nevertheless, a conspicuous layer of charcoal within the Ussello horizon that spans north west Europe, often considered to be an extension of the YDB, was later confirmed by Kaiser et al. (2009). However, they attributed this charcoal-laden stratigraphic boundary to non-impact causes essentially on the basis of a wide spread of individual radiocarbon dates across multiple sites, which they claimed were inconsistent with a synchronous event. The issue of dating is an important one to which we will return later, but a consistent finding is that the uncertainty in the age of YDB sediments is rarely captured by a single radiocarbon measurement at a specific site. Indeed, it is standard practice to take in the region of 10 measurements at any site to create proper age-depth models so that the true age uncertainty in a boundary layer can be reliably reported. Reliance on single measurements from any site is unwise, as we can expect such an approach to give the false impression of asynchronous local events for a synchronous widespread event across all sites.

Therefore, although Kaiser et al.'s (2009) observation of this charcoal-laden layer is useful, their conclusion that these sites are not synchronous should be considered inconclusive.

Gill et al. (2009) also found a conspicuous charcoal abundance at what appears to be the Younger Dryas boundary within lake sediments at Appleman Lake, Indiana. However, on the basis of their radiocarbon age-depth model for these sediments, they conclude this layer at around 850 cm (see Figure 9a) precedes Younger Dryas cooling by nearly 1,000 years. But, again, their reasoning is flawed because they fail to properly account for the uncertainty in their age-depth model. Even casual inspection of their radiocarbon measurements in their supplementary information (see Figure 9b) suggests this charcoal layer is **not** inconsistent with a Younger Dyas age, and, moreover, it appears coeval with the onset of a period of dramatic change in vegetation around the lake apparent between 850 and 780 cms whose duration correlates well with the Younger Dryas period. Gill et al. (2009) essentially ignore this strong correlation, as well as the inherent uncertainty in their radiocarbon measurements, in determining their age-depth model. This is an important observation because their highly-cited work is often used to refute the impact theory. Rather, this work could be viewed as strongly supporting it.

Melott et al. (2010) showed that ammonium and nitrate ion data from Greenland ice cores also indicate extensive wildfires at the onset of Younger Dryas cooling. However, the magnitudes of the abundances are unexpectedly small when calibrated against the Tunguska event of 1908. This inconsistency was explained by Melott et al. (2010) in terms of under-sampling the Greenland ice cores, i.e. the sampling intervals used across the Younger Dryas period, which are greater than several years, are inadequate for sampling signal peaks with durations at most a few months. Possibly, then, the measured Greenland ice core data exhibits only the longer-term decay of these ammonium and nitrate signals due to re-dispersion within the environment, rather than the peak response immediately following the putative impact.

Andronikov and Andronikova (2016) later studied trace element abundances in the YDB at Murray Springs. They concluded that the base of the black mat at that site likely contains an abundance of microscopic charcoal particles with a similar trace element signature, with elevated levels of REEs, to macroscopic charcoal particles from the same location and from the Ussello horizon in Europe, but distinct from modern charcoal particles. This might explain why macroscopic charcoal pieces are not often observed within the boundary layer at Murray Springs – an observation used by Haynes et al. (2010b) to dispute the impact theory. Instead, the charcoal expected at this site is, it appears, mostly dispersed as microscopic dust.

In a pair of papers, Wolbach et al. (2018a; 2018b) present a detailed examination of a wide variety of evidence that supports the global occurrence of extensive wildfires coeval with the estimated date of the Younger Dryas impact event. In their first paper, they correct the mis-plotted GISP2 ammonium signal in Petaev et al. (2013a), showing that the onset of a pulse in ammonium ions, lasting around 100 years, is coeval with the GISP2 platinum signal and the onset of Younger Dryas cooling at around 12,825 cal BP according to the corrected GICC05 Greenland ice core chronology. They also show this peak in ammonium is consistent with significant isolated peaks in other indicators for biomass burning, such as acetate, oxalate and formate ions, apparent at an equivalent depth in the GRIP ice core.

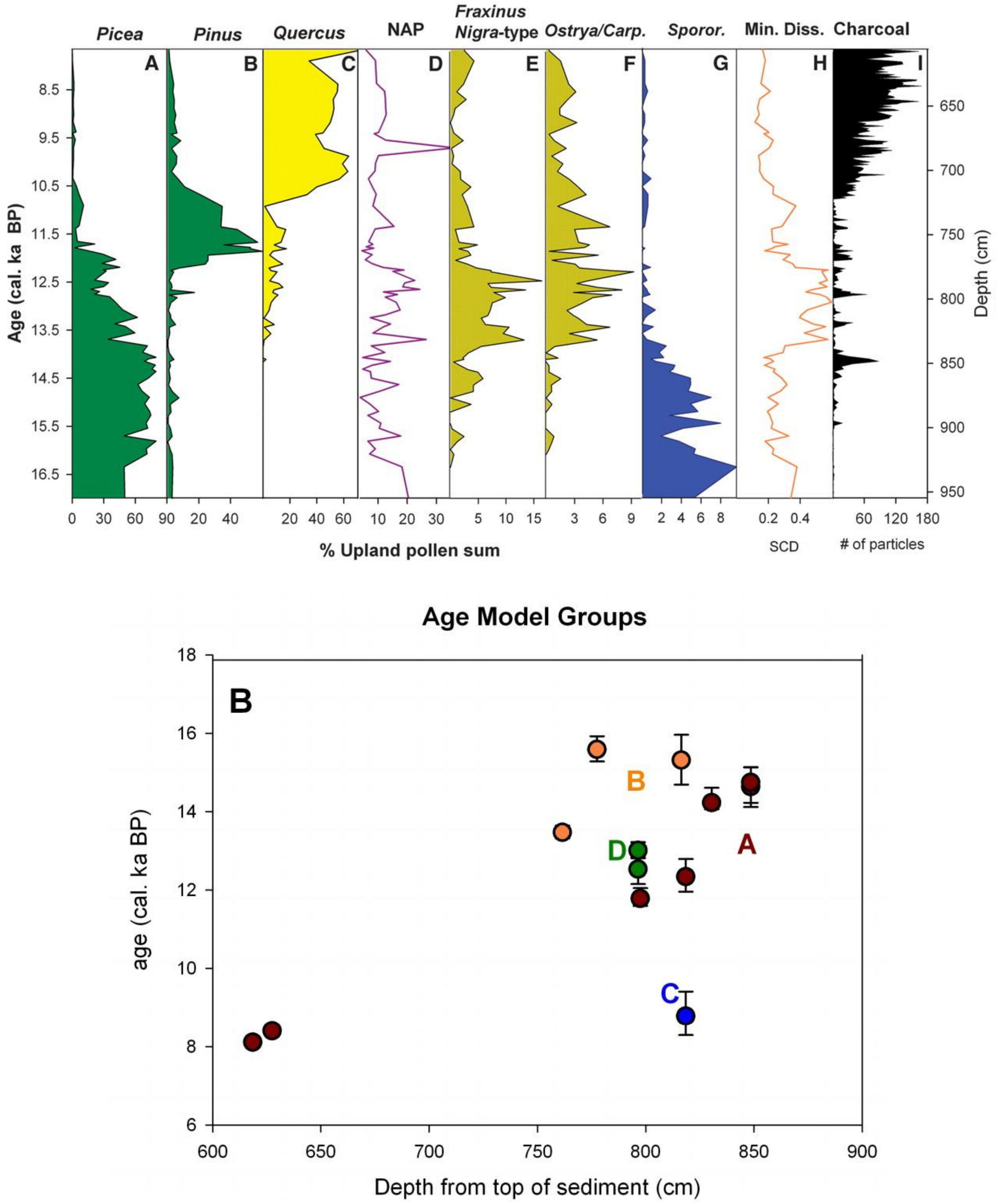


Figure 9. a) Figure 2 from Gill et al. (2009) showing the variation with sediment depth of a range of markers (upper plot). Note the prominent charcoal spike at 850 cm, which just precedes the onset of a dramatic change in pollen (signalled by the 'minimum dissimilarity', or Min. Diss.), and therefore climate lasting around 1,500 years. This is likely the onset of the Younger Dryas period. b) Radiocarbon measurements from which Gill et al. (2009) constructed their age-depth model. Clearly, there is sufficient uncertainty in this data such that 850 cm might correspond to the onset of Younger Dryas cooling, circa 12,800 cal BP. Gill et al. (2009) construct their age-depth model by linear regression through the data points in groups A and D only, and they fail to report the uncertainty in the coefficients of their fitted line. Reproduced with permission from the AAAS.

In their second paper, Wolbach et al. (2018b) re-examine the WCD for peaks in charcoal near the onset of the Younger Dryas period, and attempt to measure the abundance of a specific form of soot, known as aciniform soot, at the Younger Dryas boundary. Regarding the first issue, they first note that the radiocarbon dates of many entries in the WCD are inconsistent because they are based on several different radiocarbon calibration curves. This will tend to blur any strong signal. After correcting this issue, and after expanding the dataset used by Marlon et al. (2009) to cover 65 North American Lakes, Wolbach et al. (2018b) find a strong charcoal signal centred on 12,900 cal BP, consistent with the expected date of the YD event. Repeating their analysis for other regions, they find conspicuous peaks in the charcoal signal for Europe, South and Central America and Asia at around the same time.

Regarding the second issue, Wolbach et al. (2018b) find conspicuous peaks in aciniform soot at the YDB at 8 out of 10 sites investigated across North America. Aciniform soot is a particular kind of soot composed of aggregates of spherical amorphous carbon particles whose morphology resembles a 'bunch of grapes'. Their justification for searching for aciniform soot is that '*AC/soot from nonimpact wildfires is rarely preserved*'. Isolation of this form of soot from sediment samples is an arduous task with many treatment steps. Nevertheless, Wolbach et al. (2018b) document abundance peaks in this form of soot coeval with peaks in other impact proxies, mainly platinum. Averaging over the 10 sites selected, they estimate that around 9% of Earth's biomass was set alight, apparently within the short span of a single day. This amount of soot, they estimate, would have generated an optical depth of 600, essentially producing complete darkness. They further claim this 'impact winter' could have lasted 6 to 7 weeks, and was therefore global, essentially providing a trigger for Younger Dryas cooling as well as contributing to human population and culture changes and the late Quaternary megafaunal extinctions.

Many assumptions are made in arriving at this estimate. Most obviously, it is assumed that aciniform soot at the YDB originated entirely from the impact event, and not from other sources such as local campfires. This seems like a reasonable assumption given the assumed scale of the event. Second, their calculations assume all the biomass burned was converted entirely to aciniform soot and not converted to other forms of carbon, such as charcoal or CO_2. Clearly, this assumption is conservative, tending to vastly underestimate the true amount of burned biomass. On the other hand, several of the sites sampled are ancient freshwater collection locations, such as lakes, where soot would tend to concentrate. As such, their small sample of sites will tend to produce an overestimate. The extent to which these competing assumptions will cancel is unknown, and therefore their estimate should be viewed as being very approximate. Nevertheless, even if they overestimate the mass of burned biomass by a factor of 10, an optical depth of 60 still corresponds to complete darkness.

Holliday et al. (2020a) present a strongly worded and wide-ranging rebuttal to Wolbach et al.'s (2018a; 2018b) claims. Many of their comments apply to earlier work and were already addressed by those authors. If we focus specifically on the evidence presented by Wolbach et al. (2018a; 2018b) in their two papers, Holliday et al. (2020b) suggest first that Wolbach et al. (2018a) mis-plotted the GISP2 and NGRIP ammonium ion data. But this appears mainly to be a simple misunderstanding concerning conversion between appropriate age scales. And while Wolbach et al.'s (2018a) ammonium ion data plots (Figures 3 and 4 of their work) do appear to have been smoothed from the raw data for both ice cores, this is consistent with the smoothing applied by Fischer et al. (2015) used to highlight prominent peaks in ammonium abundance in the GRIP and NGRIP ice cores (see Figure 4 of Fischer et al. (2015)). In any case, the close timing of the ammonium ion pulse at the onset of YD cooling recorded in both ice cores with the GISP2 platinum signal identified by Petaev et al. (2013a) is apparently correct. Holliday et al. (2020b) further argue that this ammonium ion pulse is not very special, and that many other pulses recorded in the ice cores are at least as significant. But when we discount the Holocene period, which will be affected by anthropogenic biomass burning and a much warmer climate (and is therefore not a fair comparison), there are few other major peaks in ammonium ion concentration observed in these ice cores over the last ice age, and it is clear none are as significant as that at the YD onset (see Figures 2 to 4 of Fischer et al. (2015)). In this sense, the YD ammonium signal does appear to be quite special. In any case, arguments about the magnitude of peaks in ammonium ion concentration present in these ice core samples must be made cautiously, since, as pointed out by Melott et al. (2010), these ice cores are likely under-sampled relative to the few-month duration of the expected peak in the ammonium signal resulting directly from an impact event.

In their criticism of paper 2 by Wolbach et al. (2018b), Holliday et al. (2020b) begin by suggesting that large cosmic impacts are not known to generate extensive wildfires and that, in any case, evidence for such wildfires cannot be sought in the charcoal record. These views are self-evidently incorrect and rebutted by Wolbach et al. (2020) in their counter-response. Turning to more substantive issues, Holliday et al. (2020b) first question the selection by Wolbach et al. (2018b) of 30 additional North American lake records, implying their choice might be biased. But this accusation is not substantiated. For example, Holliday et al. (2020b) do not provide examples of any North American lake records without a charcoal abundance at the required time. They also argue that the radiocarbon dating results of Kaiser et al. (2009) concerning the Usselo Horizon effectively refutes the impact theory. But as pointed out above, this misunderstands the nature of variance in the radiocarbon dating of sediments. They further suggest that the peak in charcoal abundance identified by Wolbach et al. (2018b) spanning the onset of the Younger Dryas period identified in 65 North American lake sediment records might instead reflect the improved climate that peaked during the Bolling-Allerod period several hundred years earlier. Certainly, this is a possibility, but as has already been argued, it is a moot point since charcoal is not by itself an impact proxy. All Wolbach et al. (2018b) need to show is that a widespread abundance of charcoal near the onset of Younger Dryas cooling, within dating uncertainty, exists, and this is clearly accomplished. Finally, Holliday et al. (2020b) argue that the abundance of charcoal identified by Wolbach et al. (2018b) near the onset of YD cooling is not special, as other similar abundances occur at other times, including at the onset of significant climate warming events such as the end of the Younger Dryas period. But this is an unfair complaint because the rate of biomass burning on Earth during these periods is so high. Indeed, the annual rate of biomass burning at these times is around 2 % per year. Considering the uncertainty in radiocarbon dates is of the order of a few hundred years, and that an impact event cannot burn more than 100% of Earth's biomass, it will obviously not be possible to distinguish burning events on this basis. Indeed, this is precisely why ammonium ion records in ice cores are valuable. They are sampled with much higher resolution than is possible with radiocarbon dating. And it is clear from Figures 2 to 4 of Fischer et al. (2015) that the burning event at the onset of YD cooling is special.

As it is clearly difficult to distinguish charcoal burned by natural wildfires from those incinerated by a cosmic impact, Wolbach et al.'s (2018b) analysis of aciniform soot abundances at the YDB, usually identified by its co-location with an abundance of platinum, is important. But Holliday et al. (2020b) do not contest this aspect of their work.

Subsequently, abundances of soot and charcoal were discovered at the YDB at White Pond, a Carolina Bay (Moore et al., 2019), and Pilauco, Chile (Pino et al., 2019).

2.6 Synchroneity

The Younger Dryas impact hypothesis posits Earth's collision with a swarm of comet debris. As we shall see in the next section, this collision is suggested to be with debris from the Taurid meteor stream. The event is envisaged to have occurred within the span of a single day across an entire hemisphere. After the impact, a wide range of longer-term effects could have occurred. Indeed, climate change, megafaunal extinctions and human population and cultural changes are proposed as part of the theory. But the timescale for creation of the geochemical evidence reviewed here is generally much shorter. It follows that synchroneity is a crucial issue for the Younger Dryas impact hypothesis.

We can expect the bulk of the macroscopic impact-generated particles to have settled in place on the same day as the collision event, although smaller numbers of these particles ejected into high altitude orbits could have taken much longer to fall back to Earth. Smaller particles suspended in the atmosphere can take longer to settle. For example, the platinum signal observed in the GISP2 ice core has a width of about 20 years (Petaev et al., 2013a). Gases generated by explosions and wildfires will have different lifetimes depending on a number of factors, including solubility. Even once in place, the dynamic environment can disturb initial placements, creating the illusion of continuing emplacement. Bioturbation and disturbance by weathering, flooding and run-off could all be in play, depending on the specific characteristics of the location.

Unfortunately, radiocarbon dating is not sufficiently precise to determine synchroneity because measurement uncertainties are typically of the order of 100 years at this time. Radiocarbon calibration uncertainties are somewhat larger again. Nevertheless, any geochemical evidence for a cosmic impact which is clearly not synchronous must either indicate more than one such event or disturbance by the environment. Ice core evidence has much greater precision; sub-annual resolution is possible. But ice layer counting errors lead to difficulties when comparing with other ice cores or with a radiocarbon chronology.

For these reasons, tests for synchroneity of the geochemical evidence are very challenging. The details of each specific site are crucial. In general, though, we can expect that once all mitigating factors (i.e. physical processes likely to lead to variation in the radiocarbon date) are taken into account, the geochemical evidence at different sites should not be obviously asynchronous. The problem, then, is knowing what all these mitigating factors are. In many cases, they cannot all be determined, and therefore one is often faced with seemingly inconsistent radiocarbon data even from within the same site. For this reason, it is essential to take many radiocarbon measurements for each site and generate an age-depth model for the sediment that includes the suspected Younger Dryas boundary layer. The key point here is that individual radiocarbon measurements rarely account for all the age uncertainty of a sediment. Multiple measurements are needed to properly quantify this uncertainty.

The geochemical dating problem, then, becomes one of statistical modelling. In general, two approaches are often employed to create such age-depth models. First, the data can be 'cleaned' to remove obvious outliers that are inconsistent with the bulk of the data and the stratigraphy. Then a linear or other regression is attempted. In such cases it is vital that the uncertainty in the model parameters is reported and taken into consideration when making conclusions. As has already been discussed, Gill et al. (2009) failed to do this.

Alternatively, a Bayesian modelling approach can be attempted. Here, decisions about how each data point are treated within the model are required in advance. In other words, insight into the physical processes affecting each data point is needed. For example, the model can allow for the 'old wood' effect for specific data points. Once all such mitigating factors have been included, the model assumes that all the remaining variance is due either to random sampling from a statistical distribution or to the change in age with depth in the sediment. The Bayesian software then samples these statistical distributions to determine the best fit to the age-depth model.

The Bayesian approach has advantages and disadvantages. If all mitigating factors are known *a priori* (these are among the 'priors' in Bayesian modelling terminology) then it will create the best possible age-depth model according to the chosen regression type. On the other hand, if any mitigating factors remain unknown, i.e. if the model does not accurately account for all the physical process at play in the sediment that can lead to dispersion of the data (like the old wood effect), then an over-constrained age-depth model can be generated that does not reflect the true uncertainty in the data. In such cases, which are frequent, a simple regression of the data is the better option.

Given these difficulties, it is not surprising that synchroneity is among the most contentious issues in this debate.

In their original paper, Firestone et al. (2007) suggested an initial estimate for the impact event around 10,900 ± 100 cal BCE (1 sd), in broad agreement with a range of studies. At this time, the IntCal04 radiocarbon calibration curve was in standard use.

As has already been mentioned, Kaiser et al. (2009) presented radiocarbon dates for the charcoal boundary layer at multiple Ussello horizon sites across northern Europe, finding around half of them were inconsistent with synchroneity and the date range in Firestone et al. (2007). However, only single measurements were made at each site. Proper age-depth models that intersect the boundary were not generated for any of them, leaving open the possibility that the sites are synchronous and the dispersion in dates they found was due to natural processes. Moreover, the precise boundary layer at each site corresponding to the depth of geochemical markers, rather than charcoal which is not diagnostic for the impact event, was not determined for any site studied, and therefore it is not possible to know if any charcoal samples were taken directly from the Younger Dryas boundary. Their results are therefore not strictly valid.

van Hoesel et al. (2012) later analysed the Geldrop-Aalsterhut boundary layer in the Netherlands, one of the Ussello sites investigated by Kaiser et al. (2009), finding nanodiamonds within it. They also claimed it was inconsistent with a Younger Dryas impact age. Their conclusion was based on comparison of the radiocarbon date of a single piece of charcoal taken from 5 cm above the boundary layer at Geldrop-Aalsterhut with their own determination of the age of one other proposed YDB site, Arlington Canyon, Santa Rosa Island. But neither age in this comparison is supportable. All 14 radiocarbon measurements made by van Hoesel et al. (2012) at Geldrop-Aalsterhut clearly are consistent with the impact age estimate in Firestone et al. (2007). Therefore, any age-depth model for the site must also be consistent. The inconsistency they identified is instead caused by their own age-depth model for Arlington Canyon, which is a particularly difficult site to analyse. Radiocarbon measurements at this site through the boundary layer, or layers, containing impact markers have a wide dispersion of dates. We will consider this interesting site again later.

Wittke et al. (2013b) later updated the impact age estimate to 10,850 ± 150 cal BCE (1 sd). This difference was explained in terms of a change to the standard radiocarbon calibration curve to IntCal09 which has greater uncertainty around this time than the earlier IntCal04 curve. In terms of radiocarbon years, the age estimate is unchanged at 10,900 ± 100 BP (1 sd). Their age estimate was based on the age-depth models for 18 YDB sites across four continents at which impact markers, such as nanodiamonds, had been found. van Hoesel et al. (2013) complained that the age estimate for the Geldrop-Aasterlehut site in Wittke et al. (2013b) is inconsistent with their own (10,735 ± 45 BP (1 sd)), but this is clearly incorrect at the level of 2 sd, or 95% confidence.

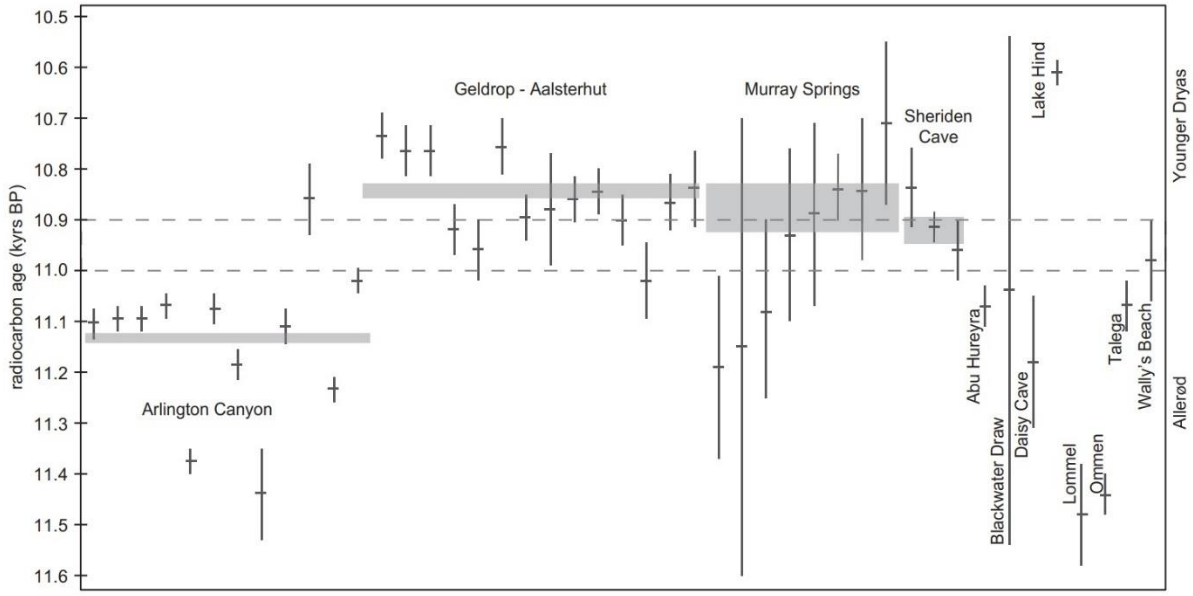


Figure 10. The 12 YDB sites directly dated with radiocarbon measurements discussed in van Hoesel et al. (2014). Horizontal grey bars are weighted averages (1 sd) of the measurements at each site. The horizontal dashed lines indicate the estimated date of the YD impact event (1 sd), although they are incorrectly plotted (see text). Reproduced with permission from Elsevier.

Later, in their critical review, van Hoesel et al. (2014) identified several issues with age-depth models created by a range of impact theory proponents, including those in Wittke et al. (2013b). For example, some of them inferred the date of the boundary layer from the presence of Clovis tools underneath it (Ives and Froese, 2013; Wittke et al., 2013a), instead of using radiocarbon methods. The sudden ending of the Clovis culture in North America is one of the claims of the impact theory, therefore the use of Clovis tools as a boundary marker is circular reasoning. After eliminating sites where the boundary layer was not dated directly, van Hoesel et al. (2014) produced Figure 10, which shows radiocarbon measurements for 12 remaining sites. The horizontal grey bars are weighted averages for the measurements at each site, with widths equal to the standard error (1 sd), while the dashed lines supposedly show the estimated age of the impact event. However, there are several problems with this plot. First, the estimated age of the impact event in radiocarbon years specified in Wittke et al. (2013b) is 10,900 ± 100 BP (1 sd), not 10,950 ± 50 BP (1 sd) as plotted. Second the uncertainty in the weighted average for the Arlington Canyon data is incorrect. It is about 3 times too narrow. Possibly, van Hoesel et al. (2014) divided their standard error calculation by 12 instead of $12^{1/2}$. Once this correction is made, we see that three of the sites, namely Lake Hind in Manitoba, Lommel in Belgium, and Ommen in the Netherlands, are inconsistent with Wittke et al.'s (2013b) age estimate at the level of 2 standard deviations. Moreover, several of the sites are mutually inconsistent. For example, Arlington Canyon is inconsistent with Geldrop-Aastelehut at 2 standard deviations.

However, all of the problems identified by van Hoesel et al. (2014) could be caused by inadequate age-depth modelling, including the use of single measurements for some sites. As already discussed, it is well known that radiocarbon measurements can contain many sources of error, and therefore proper age-depth models are preferred. For example, Wittke et al. (2013b) followed Kennett et al.

(2008) in allowing for the ‘old wood’ effect at Arlington Canyon, but van Hoesel et al. (2014) did not take this effect into account.

Meltzer et al. (2014) then produced their own analysis of the synchroneity of all purported YDB sites. Where data allowed, they attempted to reproduce the age-depth models of impact theory proponents for a range of sites. They found large differences for many sites, up to several thousand years in some cases. However, no standard errors were provided for their calculations. It is therefore not possible to determine if any of these age differences are significant. In a technical sense, therefore, their data is meaningless and their conclusions cannot be supported.

The same error is repeated in Holliday et al.'s (2014) critical review of the impact theory, which essentially reproduces the data and arguments of Meltzer et al. (2014). This review also repeats a view (illustrated with a box-plot) originally presented in earlier work by Holliday and Meltzer (2010) which claims the Younger Dryas black mat seen widely across North America does not represent a synchronous event. Specifically, Figure 2 of Holliday et al. (2014) apparently shows that the measured radiocarbon dates of supposed YD black mat sections from over 50 sites are not synchronous. However, tracing this data back to its source, Haynes (2008) instead argues, on the basis of this same data, in favour of a widespread synchronous event at the beginning of the Younger Dryas period. In any case, much of the data in this plot is considered unreliable or is unpublished. For example, from Figure 2 in Holliday et al. (2014) the Naco site, Arizona, is dated around 10,400 ± 800 cal BP (1sd), yet in Haynes (2008) we find the comment that this measurement is an ‘*inaccurate bone date (unpublished)*’. Likewise, for the Wilcox Playa site, Arizona, the datapoint in Figure 2 of Holliday et al. (2014) at 10,000 ± 700 cal BP (1 sd) corresponds to a minimum age for the black mat, and not the age of its base where, presumably, the geochemical signals of the impact are likely to be found.

Kennett et al. (2015a) later provided an extensive and detailed report for 29 YDB sites, determining a new date for the impact event. Using Bayesian chronological modelling applied to 354 dates from 23 stratigraphic sections in 12 countries on four continents, they found an age range for this event of 12,835–12,735 cal BP at 95% probability. This range overlaps that of a peak in extraterrestrial platinum in the Greenland Ice Sheet and of the earliest age of the Younger Dryas climate episode in six proxy records, suggesting a causal connection between the YDB impact event and the Younger Dryas.

They separate the 29 sites into high, medium, and low-quality sites based on an evaluation of each site’s characteristics. Arlington Canyon is considered high quality even though it is modelled allowing for the ‘old wood’ effect. An old wood model for this site is justified by its pollen record, which suggests the island was partly forested by several species of long-lived conifers.

The eight high-quality sites span N. America, western Europe and south west Asia, and each is consistent with a synchronous event, which suggests all YDB sites are likely synchronous. Confusingly, Lake Hind, Manitoba, is listed as both high and medium-quality in different lists. To assess synchroneity, Kennett et al. (2015a) compare the unmodelled age of 23 higher-quality sites with their modelled ages. They find that, of the 23 dates, 22 (96%) fall within the YDB range at a 99% confidence interval, and 19 (83%) overlap from 12,840–12,805 cal BP, a 35-year interval.

In other words, of 23 sites, Kennett et al. conclude that only one falls outside a 3 sd confidence interval. However, this assessment is based on *calibrated* radiocarbon dates. Synchroneity is better assessed using uncalibrated radiocarbon dates because the radiocarbon calibration curve itself can contribute considerable uncertainty. In this case, a quick inspection of the uncalibrated radiocarbon data for each site shows there are actually at least three sites that are inconsistent with a synchronous event at the level of 4 sd, namely Lake Hind in Manitoba, Lommel in Belgium and Barber Creek in N. Carolina (new radiocarbon measurements for Ommen in the Netherlands show that it is consistent with a synchronous event). This is a concern, as only one or two of these 23 sites are expected to fall outside a 2 sd confidence interval, and none are expected to fall outside a 3 sd confidence interval. However, in each case, these three 'medium-quality' sites are characterised by only a single radiocarbon measurement. And it is well-known that the uncertainty in the age of a site can often be far larger than the statistical error in individual measurements. Clearly, it would be very helpful if further radiocarbon measurements were made for these specific three sites so that proper age-depth models can be created, and the true age uncertainty of each site determined reliably.

Ultimately, we should conclude that the data presented by Kennett et al. (2015a) are not obviously inconsistent with a synchronous event, but more radiocarbon data is needed for the three troublesome sites highlighted to confirm they are not obviously asynchronous. Given the apparent synchronicity of the high-quality sites that span three continents, it would be surprising if the others were not all eventually found to also be consistent.

Separately, Holliday (2015) and Boslough et al. (2015) raise concerns with Kennett et al.'s (2015b) Bayesian modelling, but their generally weak arguments are effectively rebutted (Kennett et al., 2015b). Nevertheless, the important issue raised above concerning synchroneity, i.e. that a few sites with only single radiocarbon measurements currently appear inconsistent, remains to be resolved.

Later, Moore et al. (2017) reported on the discovery of a platinum anomaly across N. America. This anomaly was expected given Petaev et al.'s (2013a) discovery of a platinum signal in the GISP2 ice core at the onset of Younger Dryas cooling. In that work, noting the 20-year width of the platinum signal, Petaev et al. (2013a) concluded the platinum was airborne, and therefore should create a global anomaly. But, as they only found one isolated platinum signal in the GISP2 ice core within a period of over 250 years, Moore et al. (2017) conclude the platinum anomaly can be used as a convenient datum for global identification of the Younger Dryas boundary. This is because this timespan, around 250 years, is generally larger than the typical level of uncertainty in radiocarbon measurements corresponding to this time. Therefore, it should be possible to unambiguously identify the Younger Dryas boundary at many locations around the globe.

Teller et al. (2020) further investigated the Lake Hind site, taking additional radiocarbon measurements from within the YDB layer. Their Bayesian age-depth model for this site suggests it is indeed consistent with the estimated date of the impact event. Only two sites therefore remain a concern, Barber Creek and Lommel.

Finally, Jorgeson et al. (2020) find the dispersion in radiocarbon dates from measurements from within the YDB layer only is greater than those from within the Laacher See boundary layer (the Laacher See volcanic eruption occurred in the region of modern Germany, probably around 100 years earlier than the Younger Dryas event (Kletetschka et al., 2018)). However, they don't include the new measurements taken from the YDB at Lake Hind by Teller et al. (2020),and they only allow for 'old wood' at Arlington Canyon on Santa Rosa Island up to 100 years old, which seems inadequate given the likely age of trees that grew there. In any case, their conclusion that YDB sites are not synchronous, because the dispersion in radiocarbon dates from within the YDB layer is greater than from within the Laacher See boundary layer, is not supportable. Instead, their conclusion should have been that the Younger Dryas and Laacher See events are not equivalent, which is an obvious result.

Ultimately, the Bayesian age-depth modelling of Kennett et al. (2015a) suggests the YD boundary is synchronous across four continents. The two remaining YDB sites, Barber Creek and Lommel, where that is not currently apparent both involve only single radiocarbon measurements, and therefore their true age uncertainty is unknown. Further efforts should be made to resolve the ages of these specific sites, as for Lake Hind previously. Nevertheless, as things stand, no Younger Dryas boundary site is obviously inconsistent with a synchronous event.

3 YD event scenarios

Firestone et al. (2007) originally proposed the impact was caused by one or more low density ET objects falling onto the Laurentide ice sheet. They went further to suggest the YD event resulted from a combination of airbursts and surface impacts, and that the impactor was very different from well-studied iron, stony, or chondritic impactors, and was, therefore, most likely a comet.

This implies an encounter with fragmented comet debris. Such debris is routinely generated by comets orbiting within the inner solar system where the sun's heat is sufficient to cause cometary decay (di Sisto et al., 2009; Fernandez, 2009). We observe these decay products as meteor streams. Firestone et al. (2007) suggested the well-known Tunguska event provides a model for one such airburst. But they also speculated on the possibility of an ET impactor up to 4 km in diameter, noting that such an object would leave an obvious and very large crater, and none is known of the required age. They further suggested that objects up to 2 km in diameter might leave little trace on the ground below if they impacted the 2 km thick Laurentide ice sheet at angles < 30 degrees from horizontal.

Based on 30 years prior research into the Taurid meteor stream and comet Encke, and the theory of 'coherent catastrophism' (Asher et al., 1994; Clube and Napier, 1984; Napier, 2001), Napier (2010) proposed this meteor stream as a potential culprit, citing an encounter with the equivalent of 2000 – 10,000 Tunguska-like objects over about an hour was a '*reasonably probable event*'. In other words, a distributed event up to 10^5 Mtonnes is reasonably likely over the last 20-30 kyr. This scenario requires the existence of a giant progenitor comet, with diameter 50 to 100 km, within near-Earth orbit on this timescale. Evidence for such a large comet in Earth's recent history is provided in the form of the current mass of the zodiacal dust cloud and correlations in the orbits of the largest Encke-like asteroids. Napier (2010) further suggests thermal radiation from passage through the atmosphere of such a swarm is expected to lead to a conflagration over at least continental scales.

He concludes by pointing out that current assessments of impact hazard do not take into account the possibility that the population of near-Earth asteroids could have changed significantly over the last 20-30 kyr, and therefore they are not useful for assessing the impact risk over this time period. More succinctly, looking at today's skies (in terms of the near-Earth asteroid population) is no guide to the historic impact hazard (or the future one, for that matter).

In their 'requiem' review, Pinter et al. (2011) focus on the possibility of a very large impactor. They essentially agree with Firestone et al. (2007) that this scenario is unlikely given no large young crater is known. However, they ignore entirely the possibility of a distributed event caused by a fragmented comet.

The YD impact scenario was later updated by Israde-Alcantara et al. (2012), with Firestone as one of many co-authors, who suggest the object must originally have been at least several hundred meters in diameter, and probably entered the atmosphere at a relatively shallow angle (>5° and <30°). Thermal radiation from the air shock reaching Earth's surface from such an encounter would be sufficient, they suggest, to pyrolyze biomass and melt silicate minerals below the flight path of the impactor(s).

However, Boslough (2012) argues that an object of the minimum size quoted above would be insufficient to cause the continental-scale devastation suggested originally by Firestone et al. (2007), and that if any single fragment was larger than 120 m, it would likely leave a crater. But neither of these statements is inconsistent with the impact scenario proposed. Moreover, the quoted value of 120 m applies to an impact trajectory perpendicular to the ground only. It is not known how this value varies with impact trajectory, impactor type or surface characteristics.

As has already been mentioned, Petaev et al. (2013a) concluded in favour of a large dense object, around 0.8 km in diameter, for the Younger Dryas impactor. But, they did not consider a low-density cometary source. Their dense object equates roughly to a 1.5 km diameter low-density source, which itself might be highly fragmented.

The following year, Wittke et al. (2013b) added to the impact scenario by suggesting the impactor most likely broke apart in solar orbit before encountering Earth, as do most comets, including Comet Shoemaker–Levy 9 which impacted Jupiter as multiple fragments, the largest of which was ~1 km in diameter.

Boslough et al. (2013) objected to this attempt to clarify the impact scenario, largely because it is generally thought Shoemaker-Levy 9 fragmented due to tidal interaction with Jupiter, not the Sun. Nevertheless, comets in solar orbit do routinely break up (di Sisto et al., 2009; Fernandez, 2009). But Boslough et al. (2013) consider the likelihood of such an event to be extremely low. They suggest '*exquisite timing'* is needed if multiple large fragments are to strike Earth after a comet breaks up in solar orbit.

However, these arguments are rejected by Napier et al. (2013). He re-asserted that, given the known size-population of Centaurs in the outer solar system, their leakage rate into the inner solar system, the current mass of the zodiacal dust cloud and correlations in the orbits of the largest Taurid meteor stream objects, an event of the type described by Wittke et al. (2013b) is a reasonably probable event over the last 20-30 kyr. No exquisite timing is needed. Essentially, Boslough et al. (2013) are assuming the near-Earth asteroid population is a steady-state system, rather than one that can vary dramatically on the timescale of millennia with the addition of new mass from the Centaur population.

van Hoesel et al. (2014) further suggest the evidence might be explained by several smaller unrelated impact events occurring over a timeframe of a few hundred years. However, this is at odds with the platinum signal in the GISP2 ice core which effectively limits a multiple-impact scenario to a timespan of only 20 years. No other platinum signals are evident in the GISP2 ice core over a timespan of 250 years. Moreover, Petaev et al. (2013a) propose an impactor equivalent to a 1.5 km comet, which is inconsistent with van Hoesel et al.'s (2014) suggestion.

In their critical review, Holliday et al. (2014), with Boslough as co-author, once again criticise the impact scenario. However, their criticism is a series of spurious arguments. For example, they argue that 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. But neither statement reflects the updated impact scenario (Wittke et al., 2013b).

Likewise, Holliday et al. (2014), as for other critics, point out that no large crater of YD age is known sufficient to explain the evidence in terms of a single impact body. But again, this argument does not reflect the proposed impact scenario. Furthermore, they argue that the probability of the fragmented comet impact event specified by the hypothesis is infinitesimal, about one in 10^{15}, and that 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. But this statement is at odds with that of Napier (2010), who finds it to be a '*reasonably probable event'*. Indeed, Holliday et al. (2014) completely ignore the 'coherent catastrophism' scenario of a giant comet decaying within the inner solar system (Napier et al., 2013).

Holliday et al. (2014) present further spurious arguments by describing the impact scenario completely in terms of either Tunguska-sized impactors (which is considered a 15 Mtonne event) or in terms of 5,000 Mtonne impactors. The former is considered insufficient to generate surface melting (which is required by the observed abundance of quench-melted microspherules with terrestrial composition at the YDB) while the latter would likely create a large crater. And yet no YD-age crater is known. But Holliday et al. (2014) do not consider a scenario consisting of a range of impactor sizes and impact locations, some of which might be capable of producing surface melting without producing an obvious crater. Indeed, they even provide a counter-example in terms of the existence of Libyan desert glass (Boslough, 2013), for which surface melting is clear and yet no crater is known. In any case, a YDB-age crater might yet be found. Nor do they address the possibility that an ice sheet might partially shield Earth's surface, thereby reducing the likelihood of a typical impact crater.

Napier's 'coherent catastrophism' scenario is later boosted by Hagstrum et al. (2017) who searched the Fairbanks and Klondike mining districts of Alaska, USA, and the Yukon Territory, Canada, and found large quantities of impact-related microspherules in fine-grained sediments retained within late Pleistocene mammoth (Mammuthus primigenius) and bison (Bison priscus) skull fragments. Raised levels of platinum were also found. These deposits are then reinterpreted partly as blast debris that resulted from several episodes of airbursts and ground/ice impacts within the northern hemisphere during the Late Pleistocene epoch (~46–11 ka BP).

This result supports earlier observations by Pigati et al. (2012) who investigated black mats ranging in age from approximately 6 to more than 40 ka in the southwestern United States and the Atacama Desert of northern Chile. At 10 of 13 sites, they found elevated concentrations of iridium in bulk sediments or within magnetic spherules or grains within, or at the base of, various black mats, regardless of their age or location. Pigati et al. (2012) concluded their data was inconsistent with a cosmic impact origin, but their implicit assumption is that multiple cosmic impacts over this time are extremely unlikely. Clearly, they did not consider coherent catastrophism, which might partially explain their data, as a potential scenario.

Following this, Kjaer et al. (2018) report the discovery of a large impact crater beneath Hiawatha Glacier in northwest Greenland. From airborne radar surveys, they identify a 31-kilometer-wide, circular bedrock depression beneath up to a kilometre of ice. They further suggest the impactor was over 1 km wide and unlikely to predate the Pleistocene, i.e. it is less than a few million years old (see Figure 11). This maximum age is confirmed a year later (Garde et al., 2020). Clearly, this crater is a candidate YD-age impact structure.

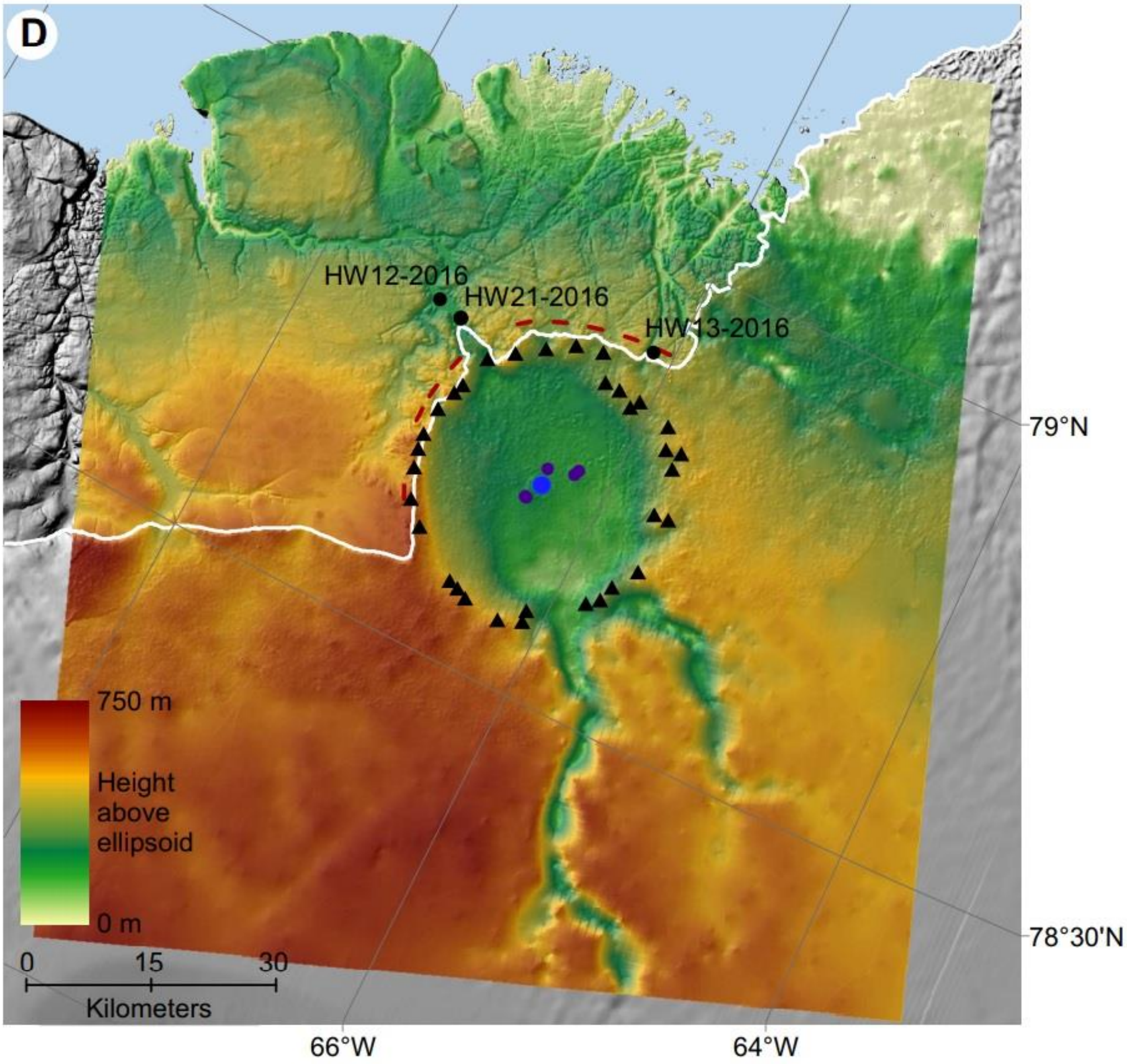


Figure 11. Bed topography of the Hiawatha crater (Figure 1D in Kjaer et al. (2018)), north west Greenland. Black triangles denote the elevated rim, while dark purple circles represent peaks in the central uplift. Reproduced under the terms of the CCA 4.0 International License.

The following year, MacGregor et al. (2019) report the discovery of a possible second subglacial impact crater around 36.5-km wide and 183 km southeast of the Hiawatha impact crater. Based on satellite and aerogeophysical data, they suggest the identified structure is likely an impact crater, although this is not yet confirmed by direct geochemical measurements from the vicinity of the structure. Nevertheless, they conclude that if it is an impact crater it is unlikely to be a twin of the Hiawatha impact crater. However, this conclusion is incorrect because their discussion about the possibility of this second structure being a twin of the Hiawatha crater is internally inconsistent. On the one hand, they argue that, like the Hiawatha crater, this sub-glacial structure is unlikely to predate the Pleistocene (< 3 million years old). However, the statistical calculation by which they evaluate its 'twinness' with the Hiawatha crater, (their second calculation, the 'birthday problem', described in the second paragraph of section 3.3 of their paper on which their conclusions are based) allows both structures to be up to 650 million years old. If, instead, their age difference is limited to less than 3 million years, as they themselves argue earlier in their paper, they should have concluded in favour of the twin hypothesis (in agreement with their first statistical calculation in the first paragraph of section 3.3, which they ignore in making their conclusions). That is, if the second structure is eventually confirmed to be a crater, then the corrected statistical calculation suggests it is very likely a twin of Hiawatha.

If the second structure is indeed a twin of the Hiawatha crater, then it was likely created by a fragmented comet impact, since fragmented asteroids consisting of large similarly-sized pieces are extremely rare. This then increases the probability that the Hiawatha crater, and its potential twin, are YD impact structures. Later work that analysed the gravity field around both these structures supports their identification as impact craters (Klokocnik et al., 2020).

The same year as this second structure was discovered, Napier (2019) explores the possibility of YD meteor 'hurricanes' with intensities far beyond modern experience. Enough meteoric smoke might be created during such encounters to generate dramatic coolings lasting several years, along with widespread wildfires. Therefore, the YD impact event need not involve any fragments large enough to create a crater, yet it could still produce the geochemical evidence observed as well as a mechanism for the YD cooling.

Finally, Sun et al. (2020) propose a volcanic origin for the geochemical signals at the YDB. In their work focussed on Hall's Cave, Texas, they examine the osmium isotope record of the cave's sediment and find that, at the YDB, sediment samples with osmium isotope anomalies don't appear to have corresponding anomalies in other PGEs. Despite all the preceding evidence in this debate to the contrary, they interpret this as evidence for a volcanic trigger for the YD climate event. However, in their table S1 there are five sediment records at 151 cm corresponding to the depth of the YDB, one with a platinum anomaly (435.1 ppt) but no osmium anomaly, and one with an osmium anomaly ($^{187}Os/^{188}Os$ ratio of 0.41) and no platinum anomaly. Probably, as these five measurements were all taken laterally at the depth of 151 cm, this variation in the data reflects the slowly undulating nature of the stratigraphy of the Hall's Cave sediments and/or the 'nugget' effect. Clearly, Sun et al.'s (2020) decision to focus on the sample with the osmium anomaly is selective and unjustified.

4. Summary

Considering that the GISP2 ice core shows the platinum anomaly is contemporaneous with an ammonium anomaly, but not a sulphate signal, the only viable explanation for its occurrence is a cosmic event. A short-lived but non catastrophic burst of micrometeorites can explain the occurrence of the platinum peak in the ice, but not its magnitude or its apparent synchroneity with the ammonium signal and the Younger Dryas climate change. Although it is possible both these latter effects can have other causes, their extremely close timing with the platinum signal points strongly towards a major cosmic impact, as suggested by Petaev et al. (2013a). This is supported by the presence of the platinum signal on at least four continents coetaneous with other impact proxies, as discussed next.

Impact spherule abundances, amounting to approximately 10 million tonnes, have been found at over 20 sites on four continents by several independent research groups. Surface dendritic patterns suggest quenching from very high temperatures. Elemental compositions are consistent with mainly terrestrial material, although some display raised levels of PGEs or REEs indicating mixing with ET material. There is no evidence for production via volcanism. The only reasonable explanation for their occurrence is a major cosmic impact event. They are found together with other high temperature melts with similar compositions at three sites. Those at Abu Hureyra, Syria, can only be explained by a cosmic impact.

Nanodiamond abundances have also been found at over 20 sites on three continents by several independent research groups. Mostly they are n-diamond and i-carbon, but cubic diamond has been found at eight YDB sites. Nanocrystals of what are very likely Lonsdaleite-like nanodiamonds have been found at four YDB sites across North America, but further EELS measurements are needed to confirm this. The widespread existence of all these nanodiamond forms can only be reasonably explained by a cosmic impact. There is no evidence for nanodiamond production via wildfires or volcanism. Abundances of PGEs, microspherules and nanodiamonds in a continental-scale layer has only ever previously been observed at the K-T boundary.

Charcoal and soot abundances at the YDB are found across four continents consistent with a major cosmic impact. The abundance of soot, if generated within a single day, is consistent with an impact winter lasting several weeks. Together with the release of vast amounts of icy salt-free meltwater into norther oceans, and smoke from meteorite ablation, a potential mechanism for the Younger Dryas cooling is provided.

No YDB site has yet been found to be obviously inconsistent with a synchronous event circa 10,785 ± 50 cal BP (2 sd). The only reasonable conclusion is that a major cosmic impact event occurred at this time. Its timing is so close to the onset of YD cooling that a causal link is highly likely. Such an event might plausibly lead to human culture changes and megafaunal extinctions as proposed, but more detailed research is needed to investigate this. Certainly, the latest assessment of the end-Pleistocene megafaunal extinction in N. America, which concludes that the onset of Younger Dyas cooling is pivotal, is consistent with a cosmic impact playing a major role (Stewart et al., 2021).

A pair of impact-like structures, each over 30 km across and < 3 million years old, has been found under the Greenland ice. Statistically, if they are both indeed impact structures, they are very likely twins, indicating a comet impact. Clearly, they are good candidates for the YD impact event, although in principle no craters are required by the theory. We will need to wait for further research to determine their true age.

No other mechanism is known to simultaneously produce the geochemical signals reviewed here. Volcanism is not known to generate nanodiamonds or iron-rich microspherules, let alone over a continental-scale area in the absence of tephra and sulphates. A non-impact cosmic origin, such as an enhanced influx of cosmic dust, might account for raised levels of PGEs and nanodiamonds, but the peak magnitudes measured at the YDB are far too high and the co-occurrence of iron and silica-rich microspherules and other quench-melt materials, including SLOs with surface imprints, and the co-occurrence of the GISP2 ammonia signal points securely to an impact origin. Of course, there remains the possibility that the geochemical signals reviewed here were not generated by a single event. However, the probability of multiple unrelated major impact events over this timeframe is tiny, and contra-indicated by the GISP2 ice core record which displays only one platinum anomaly at this time. The possibility instead of a major solar event has also been suggested (LaViolette, 2011), but it is not clear how this mechanism could account for any of the geochemical signals observed at the YDB, i.e. solar events in the current solar epoch are not known to generate extensive nanodiamonds, PGEs or quench-melted materials and wildfires at ground level.

5. Conclusions

Among all the research published concerning the YD impact hypothesis involving the impact indicators discussed in this review, only one paper so far is apparently inconsistent with it (Holliday et al., 2016). This is the so-called ‘blind test’ in 2016 that analysed YDB sediments from the Lubbock Lake site in Texas, not far from the Blackwater Draw Clovis site in New Mexico. It discusses results for the abundance of magnetic grains and microspherules reported earlier by Surovell et al. (2009) together with additional previously unreported measurements for nanodiamonds and magnetic microspherules from Jim Kennett’s (JK) lab. The magnetic grain data do not concern us, as they are not diagnostic of an impact, and the microspherule data of Surrovell et al. has been found to be inadequate by LeCompte et al. (2012). However, the nanodiamond and magnetic microspherules evidence from JK’s lab is new and, given the strength of the impact hypothesis, we can expect it to be consistent with other YDB sites. Instead, an abundance of nanodiamonds and magnetic spherules is reported at a level in the Lubbock Lake sediments corresponding, according to the stratigraphy, to near the end of the Younger Dryas period, and not its onset. These results can be considered inconsistent with the impact hypothesis. Considering the uniqueness of these results, this work should be repeated, taking care to make direct radiocarbon measurements of the sediments rather than relying on the similarity of stratigraphy to other sites.

Apart from this one research paper, the overwhelming consensus of the evidence from scores of YDB sites across nearly half the world’s surface is that a major cosmic impact occurred around 10,785 ± 50 BP (2 sd). Even work purported to contradict the impact hypothesis, when examined closely, actually supports it (Gill et al., 2009; Haynes et al., 2010a; MacGregor et al., 2019; Pigati et al., 2012; Sun et al., 2020; van Hoesel et al., 2012) (other than the ‘blind test’ discussed above). This is the main conclusion of this review. Probably, with the YD impact event essentially confirmed, the YD impact hypothesis should now be called a ‘theory’.

However, an important observation concerns the manner in which this important research debate has been carried out. The original claims made by Firestone et al. (2007) were rightly scrutinised and tested by other research groups. Given the extraordinary nature of these claims, demands for an extraordinary level of supporting evidence are reasonable. These demands appear to have now been met, at least as far as the impact evidence is concerned. However, it is incumbent on opponents of the hypothesis to reach similarly high standards of evidence in their refutations, but this has rarely occurred.

Perhaps the most basic and frequent error of YD impact theory opponents concerns their treatment of uncertainty in scientific data. For example, at least two reports that claim to refute the hypothesis fail to report the uncertainty in their own age-depth models of YDB sediments (Gill et al., 2009; Meltzer et al., 2014). Others make strong conclusions against the hypothesis on the basis of single radiocarbon measurements from YDB sediments (Kaiser et al., 2009; van Hoesel et al., 2012), while another report even uses unpublished data and field notes to make its case (Meltzer et al., 2014).

Another common strategy used by opponents has been to make misleading spurious and fallacious arguments, leading, in one case, to the claim that the proposed impact scenario is unlikely to have ever occurred over the whole lifetime of the universe (Boslough et al., 2013). Of course, these statistics do not actually apply to the proposed impact scenario, but rather to a scenario invented by the opposing authors (Napier et al., 2013). Likewise, it is frequently argued that wildfires might produce nanodiamonds (van Hoesel et al., 2014; van Hoesel et al., 2013). However, there is no single case documented where this is known to have occurred, and, of course the counter-argument is obvious; if wildfires could produce nanodiamonds, they would be ubiquitous and abundant in sediments, as for charcoal. But they are not. Nor can wildfires explain the abundance of nanodiamonds in Greenland's ice. Strangely, it has even been argued that cosmic impacts do not produce extensive wildfires (Holliday et al., 2020b), an obviously incorrect argument on physical grounds. Other fallacious arguments against the impact hypothesis include the occurrence of multiple black mats with a few similar geochemical signals (Pigati et al., 2012). But it is clear the YDB evidence must be considered on its own terms, and, in any case, multiple cosmic impacts, or unrelated volcanic eruptions, over a 40,000-year timespan should not be so hastily ruled out. Moreover, when attempting to reproduce purported evidence for a cosmic impact, it is important that similar samples from exactly the same stratum at the same site are taken. Daulton et al.'s (2010) search for nanodiamonds appears to be hamstrung by this issue, an error these researchers seem determined not to admit (Scott et al., 2017).

And regarding what is probably the most significant evidence so far, the platinum anomaly first discovered in Greenland ice by Petaev et al. (2013a), it is largely ignored or significantly downplayed by opponents of the impact hypothesis. Indeed, Holliday et al. (2014) even misrepresented Petaev et al.'s (2013a) conclusions in their highly critical review. Mistakes like these, and those above, ultimately lead to a loss of confidence in the objectivity of impact hypothesis opponents. This is shame, because while the impact hypothesis evidence should be challenged, it must be on a fair and competent basis.

Finally, given the strength of the impact evidence, reviewed here, it is now imperative that future research into the Younger Dryas climate change and associated human population and cultural changes and end-Pleistocene megafaunal extinctions should take this cosmic impact event into account. It remains the case that research continues to be published that effectively ignores it. For example, recent work by Stewart et al. (2021) investigating the end-Pleistocene megafaunal extinctions concludes that the onset of Younger Dryas cooling is pivotal, but fails to consider the impact event as a mechanism for both. Related to this issue is the use of the YDB as a datum. Future research into YD-related phenomena should, where possible, relate archaeological finds (such as megafaunal remains and stone tools) and other evidence (such as volcanic tephra) to their position relative to the YDB in the same time-series. Failure to do this can lead to confusion, given the uncertainty inherent in radiocarbon dating and in converting dates between ice cores, for example.

Acknowledgements

I am grateful for the insightful comments of two anonymous referees that significantly improved the original manuscript, and to Marc Young and George Howard for their assistance with the literature search.

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