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Review Article

Geochemical re-evaluation supports cosmic impact rather than volcanism at Younger Dryas onset, Hall's Cave, Texas: Reply to Sun et al. 2020

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ABSTRACT

Hall's Cave, situated on the Edwards Plateau of central Texas, contains a well-dated latest Quaternary sedimentary sequence containing a high-resolution record of faunal, climatic, and geochemical changes. In a recent study, Sun et al. (2020) examined trace element concentrations and osmium isotope compositions from this sequence and concluded that a peak in platinum group elements (PGEs) and a negative excursion in $^{187}Os/^{188}Os$ values near 151 cm depth were best interpreted as being more consistent with volcanic emissions from the Laacher See eruption in Germany (~12.9 ka) than with an extraterrestrial impact. Here, we re-examine their geochemical dataset from Hall's Cave, including previously unreported data from a sample at 153 cm depth that exhibits the highest measured platinum concentration (1807 ppb) in the sequence. This critical sample aligns stratigraphically with the onset of the Younger Dryas cooling event, dated to approximately 12,800 cal yr BP and not with the timing of the Laacher See volcanic eruption in Germany. We assess the implications of these results in the context of both cosmic impact and volcanic hypotheses and highlight the importance of comprehensive data inclusion, high-resolution sampling, and stratigraphic consistency in evaluating proposed causal mechanisms for abrupt climate events and associated geochemical anomalies.

KEYWORDS

Younger Dryas, airburst, volcanic geochemistry, extraterrestrial geochemistry, impact hypothesis, climate change, impact events, megafauna extinction

Introduction

The Younger Dryas Impact Hypothesis (YDIH), first proposed by Firestone et al. (2007), posits that the onset of Younger Dryas (YD) cooling ~12,800 years ago coincides with a major cosmic impact event that affected much of the Earth. The most likely scenario based on published evidence involves an encounter with a particularly dense and violent meteor shower, likely resulting from the recent disintegration of a large-diameter (>100 km) comet, producing many small, widely distributed impacts and touch-down airbursts [1]. The YDIH is thought to have contributed to multiple significant environmental, biotic, human, and climatic changes. These include the destabilisation of the northern ice sheets [2], glacial outburst flooding [3, 4], ocean circulation change [4–6], abrupt cooling [6], and abrupt extinctions of the North American (Rancholabrean) megafauna [7–9]. It further coincided with an extraordinary biomass burning event [10, 11] and widespread human cultural change and/or population decline [12, 13]. Several early attempts to replicate various evidence were unsuccessful, leading to a 'premature rejection' of the YDIH by the scientific community [14].

Evidence supporting the YDIH comes in the form of peaks in impact-related spherules, meltglass, and multiple geochemical proxies in a broadly distributed, thin layer, the Younger Dryas Boundary (YDB), which has been replicated at more than 60 sites spanning 6 continents (Figure 1). Each site exhibits peak abundances in various combinations of high-temperature magnetic and non-magnetic microspherules [16–20], meltglass [21, 22, 23–25], nanodiamonds [26–28], carbon spherules and glass-like carbon [2, 20, 29], elevated concentrations of platinum group elements [19, 20, 30–34], shock-fractured quartz [20, 21], and combustion aerosols and soot [10, 11]. For more than a decade, one of the strongest lines of evidence supporting the YDIH is a global peak in Pt, directly coinciding with the onset of YD cooling in the GISP2 ice core [30], and with the YD onset in many other sites [19, 20, 31–34, 35].

Arguments against the YDB impact hypothesis often stem from historically insufficient knowledge and understanding about proxies resulting from cosmic airbursts. Many of the proxies used to identify the YDB layer are not well-established in the literature (see Holliday et al. 2023 [36]; Powell

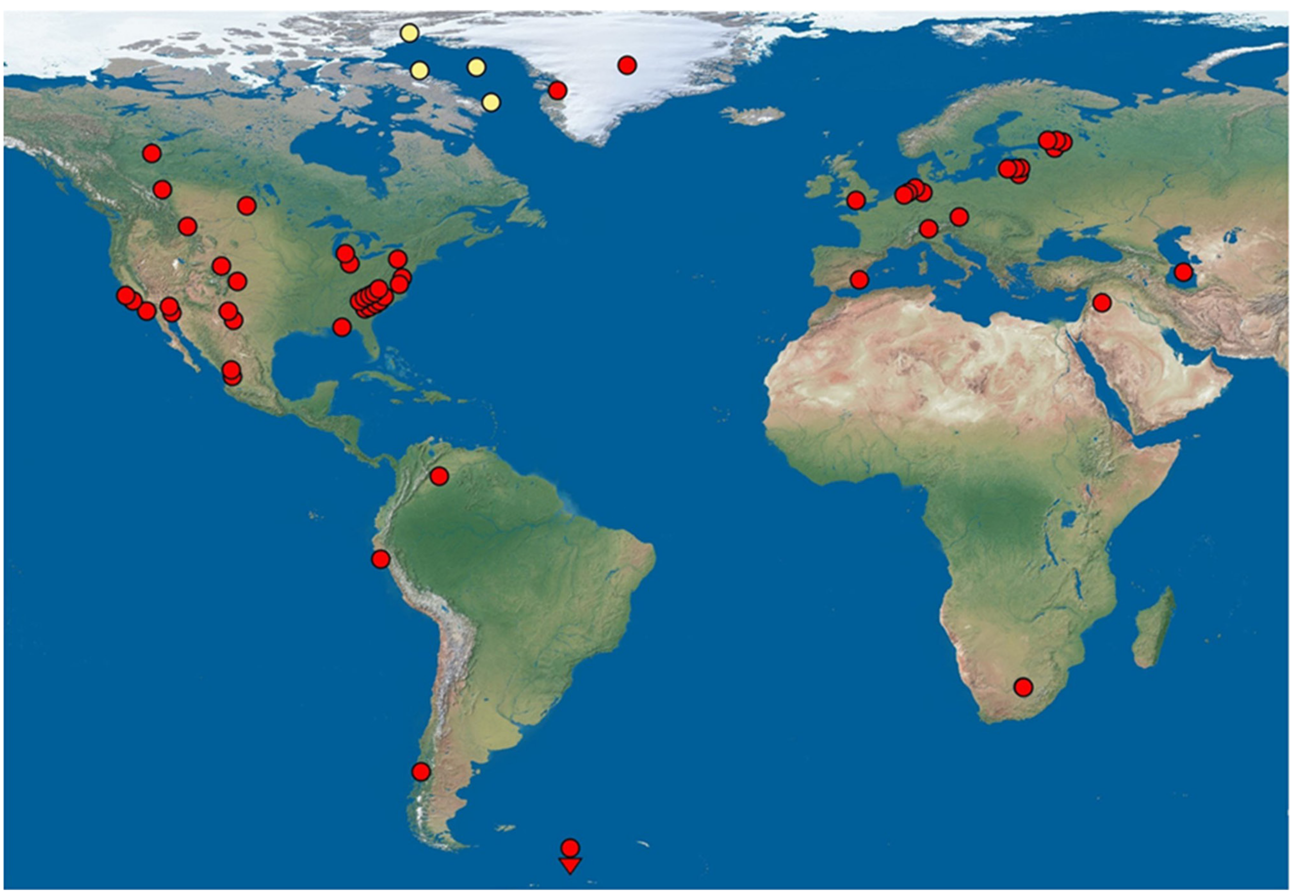

Figure 1: World map showing the distribution of the YDB layer. The YDB layer at each of the 60 sites spanning 6 continents have exhibited some combination of geochemical impact proxies. The yellow points near Greenland indicate YDB proxies from a recently published study on Baffin Bay marine sediment cores [15]. The base map was provided by Tom Patterson (www.shadedrelief.com). Reproduced from Moore et al. (2025) [15]: Creative Commons 4.0 CC BY-NY.

[14, 37, 38]). Largely because of this, several attempts to declare the YDIH dead (e.g., Pinter 2011 [39]; Holliday et al. 2014 [40]) have been traced to methodological failures by the critics [14, 16]. However, the impact hypothesis is far from dead with mounting evidence, including the discovery of new impact proxies [14, 21, 23], new geochemical and nanoparticle tracers [15], and additional sites including Greenland ice [30] and the deep-sea sedimentary records [15]. Also, there are new modelling experiments that are consistent with airburst impacts scenarios [41–44]. Collectively, the results of this work has been described in about 20 journal articles published since the most recently announced death of the hypothesis in 2023 [36].

Limitations of osmium isotopic record

Sun et al. (2020) [45] measured highly siderophile elements (HSEs) and $^{187}Os/^{188}Os$ across the well-dated Hall's Cave sequence with the aim of distinguishing ordinary crustal inputs from any anomalous signals. They defined two groups: a "radiogenic" set marked by $^{187}Os/^{188}Os = 1.11–2.35$ and low Os (≈23–57 ppt) typical of upper continental crust, and an "unradiogenic" set with $^{187}Os/^{188}Os = 0.12–0.42$ and elevated Os (≈105–4478 ppt), implying an influence of mantle-like material. Although unradiogenic layers might superficially suggest extraterrestrial or mantle sources, Sun et al. (2020) compared concentrations against CI-chondrites (≈486,000 ppt Os) and continental crust (≈30 ppt Os) and suggested that CI-normalized HSE patterns and mass-balance mixing fail to match any chondritic projectile. Instead, they interpreted the unradiogenic intervals, including a single YD-basal sample (151 cm) as representing episodic deposition of volcanic aerosols adhering to cryptotephra from a distant Plinian eruption, rather than impact ejecta.

Younger Dryas onset platinum peak

Several previous investigations have discovered and replicated a major Pt abundance peak at the Younger Dryas Boundary (YDB) at ~25 sites spanning 5 continents. The initial study by Petaev et al. [30] was undertaken to test the YDIH; in search of a major iridium (Ir) spike at the YD onset in the Greenland GISP2 ice core, which if absent would invalidate the impact hypothesis [46]. However, instead of Ir, this investigation discovered a 100-fold increase of Pt over a ~14-year interval followed by a decline over the subsequent ~7 years, consistent with the expected ~5-year lifetime of stratospheric dust injection from such an event. The study concluded that while the geochemistry of the proposed impactor is novel, *"an extraterrestrial source of Pt appears likely"* [30].

Later, a study by Moore et al. [33] replicated the Pt event at the YDB in sediments from 11 archaeological sites across North America, proposing its potential utility as a global geochronological datum for the onset of the YD. Such an approach could, according to Moore et al. [33], overcome concerns related to synchroneity of radiocarbon dates at the YD onset and allow researchers to readily identify the stratigraphic level of the YDB, and thus the onset of the Younger Dryas in any stratigraphic section globally. Assuming the approximate stratigraphic level of the YDB onset is known, measuring Pt concentrations across a section should act as a datum, allowing precise determination of the YDB, and hence the YD onset itself. In 2019, a further three studies replicated the YDB Pt event in sediment cores from Wonderkrater, South Africa [34], Pilauco, Chile [19], and White Pond, South Carolina [35]. These studies established the global distribution of the Pt peak and validated its use as a geochronological datum. Moore et al. [20, 31] replicated the Pt event at 4 additional sites across the southeastern USA, and Mahaney [47] replicated it in the Viso Massif between Italy and France.

Today, the Pt geochemical datum event that marks the YD onset has been replicated in ice and/or sediment cores from Greenland, North America, South America, Africa, Europe, Asia and most recently in ocean cores from Baffin Bay [15]. While many of these studies were published after 2020, the Pt event had already been replicated at 15 sites spanning both hemispheres when Sun et al. (2020) was submitted. Regarding the YDB Pt event, Sun et al. (2020) [45] stated the following:

> *"The cause of the elevated HSE concentrations and the Os isotopic ratios in YD layer sediments remains equivocal and has been used to both support and negate the YD impact hypothesis. For example, Petaev et al. found a Pt enrichment accompanied with an extremely high Pt/Ir but Al-poor signature in the Greenland Ice Sheet Project 2 ice core at the Bølling-Allerød/YD transition period, which they interpreted to be consistent with an ET impactor. Also, the elevated Pt abundance anomalies of 100 to 65,000 parts per trillion (ppt) at the onset of the YD in sites from North America is purportedly consistent with the Greenland ice core Pt data. Moore et al. found Pt and Pd/Pt anomalies in the YD basal layer in South Carolina."*

This statement demonstrates that the authors were aware that a major Pt anomaly marks the YD onset and that the Pt event likely represents a global geochronological datum marking the YDB. It also demonstrates their awareness that the proposed YDB impactor may have had distinctive, novel geochemistry.

The Laacher See eruption hypothesis

Based solely on changes in the concentrations of unradiogenic (UR) osmium ratio (Figure 2) and 'non-chondritic' REE concentrations for what they claimed to be the YDB layer, Sun et al. (2020) proposed that the YD was likely triggered by the Laacher See volcanic eruption in Germany as proposed by Baldini et al. [48]. However, there are significant difficulties with this claim that were addressed in detail by Sweatman [49, 50], Engels et al. [51], Svensson et al. [52] and Reinig et al. [53]. Chief among them is that the Laacher See volcanic eruption (LSE) is now well-established to have occurred at 13,006 ± 9 BP, some 120 to 200 years prior to the YD onset based on high-chronological resolution dendrochronological and radiocarbon measurements of subfossil trees [53].

The latest high-resolution multi-proxy record using tephrochronology, radiocarbon dating and lake varve counting, clearly demonstrates distinct separation between the LSE and the YDB in European lake cores [51]. Furthermore, additional studies have demonstrated the stratigraphic separation of the Laacher See tephra and the layers containing YDB impact proxies [54]. Also, the GISP2 ice core has been interpreted to record a cluster of volcanic episodes between ~13,025 and 12,975 BP in the Greenland Ice Core Chronology 2005 (GICC05) [55], thus closely matching the LSE, dated at 13,006 ± 9 BP. In the same core, the YD onset clearly begins 120 years later at 12,855 BP [55]. Sun et al. [45] also identified 4 other Os rich intervals in the 4000-year record of Hall's Cave, for a total of 5 (Figure 2) all interpreted to represent volcanic episodes.

The following are relevant quotes used by Sun et al. [45] in attempt to refute the YDIH followed by our rebuttals:

"The five unradiogenic Os peaks, including the YD layer, fall within a ~4000-year time interval. The unradiogenic 187Os/188Os ratio and HSE abundance data from Hall's Cave sediments are inconsistent with the YD impact hypothesis. Alternatively, these levels contain cryptotephra and associated aerosols derived from large Plinian volcanic eruptions."

The claims by Sun et al. [45] regarding the presence of cryptotephra are based solely on bulk sediment geochemistry and completely lack any physical characterisation or identification of volcanic ash or volcanic glass shards in the section. Normally, to determine the presence of cryptotephra, volcanic glass shards and ash content when present are separated from bulk sediments for targeted geochemical analysis [56]. An abundance of highly siderophile elements (HSE) including Os in bulk sediments is not sufficient to identify cryptotephra, because peaks in HSEs can result from other processes. Instead of adhering to established methodologies for the recognition of cryptotephra, Sun et al. [45] simply digested their bulk sediments with aqua regia, to chemically separate the HSEs and then measured Os isotopes using ICP-MS.

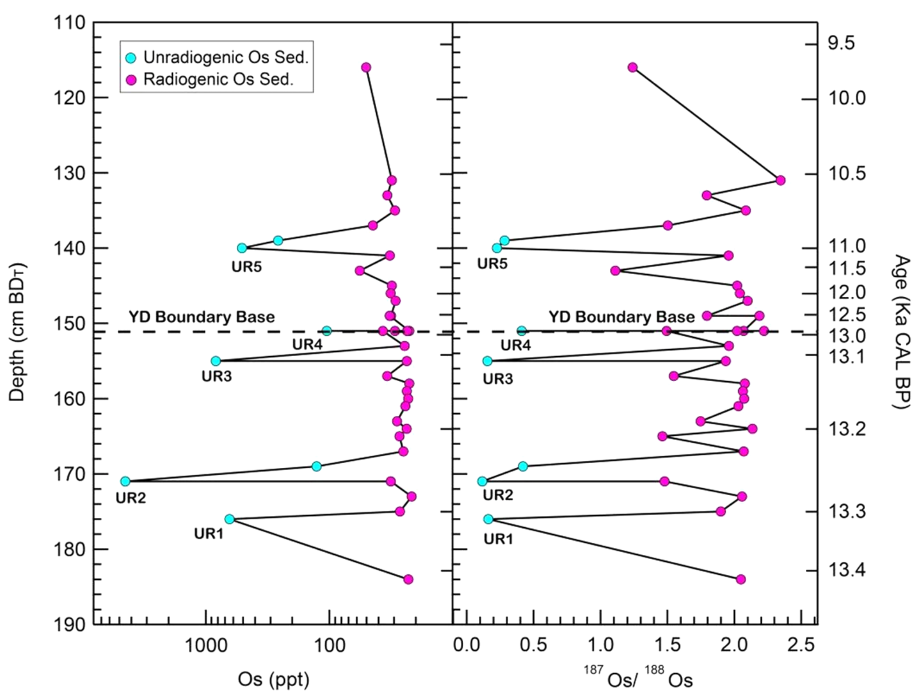

Figure 2: Profiles of depth below stratigraphic reference datum (BD_T) and ages. A: total Os abundances (ppt) and B: $^{187}Os/^{188}Os$ ratios of Hall's Cave sample section. Local YD onset datum used in this study was placed by Toomey, 1986. UR = unradiogenic. UR1 to UR5 represent five unradiogenic Os peaks. Sample depths are the basal depth of 1-cm-thick intervals relative to the reference datum. Six ages were calibrated using direct AMS ^{14}C measurements with 95.4% confidence intervals and then used to calculate the other dates using linear interpolation between the dated levels. Reproduced from Sun et al. (2020) [45]: Creative Commons 4.0 CC BY-NC.

"The YD horizon correlates in time with the Laacher See eruption with a VEI of 6 and a 6.2 km3 eruptive volume that was dispersed throughout the Northern Hemisphere. Previously found YD markers, such as nanodiamonds and other wildfire products, are not necessarily solely impact-induced. Instead, these could originate from high-temperature, large-scale volcanic eruptions whose explosive conditions are capable of producing molten silica and carbon spherules and possibly nanodiamonds (Lonsdaleite)."

As above, their notion that the YD onset correlates with the LSE has been rejected by the latest studies and had already been questioned when Sun et al. [45] was published. A further issue related to the above interpretation is that the authors cite van Hoesel et al. [57] in support of their claim that lonsdaleite, a specific hexagonal type of nanodiamond, can be produced by volcanism. Yet, that claim was speculative with no evidence or conceptual framework for how volcanic nanodiamonds may form. Importantly, no study has yet confirmed that nanodiamonds can be formed during subaerial volcanic processes, particularly lonsdaleite; although other types of nanodiamond have been considered to form through submarine volcanic processes, based on their presence in the oceanic lithosphere [58, 59].

Methodological deficiencies

Close inspection of Sun et al. (2020)'s data (supplemental information) reveals that their samples were collected during three distinct field seasons over three years: samples with the HC15 prefix were sampled in 2015; HC16 in 2016; and HC17 in 2017 (Figure 3). Furthermore, sample resolution sizes sometimes differ between these sampling episodes and location in vertical profiles. Yet, all the data was combined as one single vertical sediment column. This meant that the stratigraphic levels of samples taken during the three episodes are not necessarily in the correct stratigraphic order, nor comparable when taken from the supposed same stratigraphic level. This is especially the case in the interval at or close to the YD onset.

As shown in their data (Figure 3), several depth intervals were sampled more than once between the different and even

Sample[§] (Hall's Cave)	Depth, BDT cm	Age CAL ka BP	Sample Weight gram	$^{187}Os/^{188}Os$*	± 2 σ	Os ppt	Ir ppt	Ru ppt	Pt ppt	Pd ppt	Re ppt
HC15_18	116	9.865^	0.51	1.24	0.06	50.5		23.9	434.4	51.5	441.8
HC15_16	131	10.524	0.53	2.35	0.20	31.3	27.0	26.8	282.0	58.7	414.6
HC16_22	133	10.612	1.08	1.79	0.06	34.0	23.4	12.9	113.3	101.1	421.1
HC16_21	135	10.699	1.11	2.09	0.09	29.5	9.0	4.2	136.3	140.1	302.7
HC16_20	137	10.787	1.04	1.50	0.04	44.6	11.1	25.0	180.0	46.1	314.4
HC16_19	139	10.897^	1.10	0.28	0.00	259.9	2.2	14.6	275.5	41.1	301.7
HC15_13	140	10.990	0.52	0.23	0.00	509.7	71.5	26.6	102.9	188.2	355.6
HC16_18	141	11.173	1.02	1.96	0.08	32.5	10.7	12.0	185.7	158.9	323.7
HC16_17	143	11.541	1.06	1.11	0.02	56.9	13.1	17.9	965.6	33.2	331.4
HC16_16	145	11.908	1.07	2.02	0.08	31.3	8.2	16.5	237.2	112.0	353.6
HC15_12	146	12.091	0.53	2.04	0.16	32.0	13.9	14.1	171.7	593.8	356.6
HC16_15	147	12.274	1.12	2.10	0.09	29.1	3.9	7.7	128.1	140.9	282.5
HC15_42	149	12.642	0.51	2.19	0.18	32.5		14.9	157.7	304.1	268.4
HC16_14	149	12.642	1.13	1.80	0.07	31.8	8.2	21.1	78.1	72.5	320.2
HC15_11	151	13.008^	0.51	1.49	0.10	37.0	29.4	25.8	64.3		262.1
HC16_01	151	13.008^	1.06	2.07	0.12	22.6	16.0	8.6	136.4	26.7	303.2
HC17_01	151	13.008^	1.01	2.02	0.11	23.6	7.8	12.2	435.1	38.7	292.3
HC17_39	151	13.008^	1.18	2.22	0.09	29.5	6.0	5.2	120.0	104.3	260.6
HC17_44	151	13.008^	1.03	0.41	0.01	105.3	32.1	11.7	86.6	154.9	328.4
HC15_10	155	13.008^	0.52	1.94	0.21	23.7	26.1	20.2	102.4	33.4	236.8
HC16_03	155	13.008^	1.00	0.15	0.00	829.7	22.7	5.1	124.7	44.8	328.8
HC16_04	157	13.153	1.06	1.55	0.06	34.1	13.1	31.9	176.9	53.3	351.9
HC15_15	158	13.160	0.51	2.08	0.25	22.6		28.7	312.1	58.4	290.4
HC16_05	159	13.167	1.02	2.06	0.12	23.7	11.4	16.4	151.7	268.4	297.2
HC15_09	160	13.173	0.52	2.07	0.24	23.1	20.6	32.8	132.4		259.1
HC16_06	161	13.180	1.01	2.03	0.11	24.3	8.6	14.0	120.4	117.2	281.6
HC16_07	163	13.194	1.03	1.75	0.08	28.4	8.5	15.1	132.5	19.3	364.8
HC15_08	164	13.200	0.52	2.13	0.24	23.7	30.8	24.8	53.8	257.8	226.9
HC16_08	165	13.207	1.01	1.46	0.09	27.1	7.9	15.2	168.5	72.8	370.3
HC16_09	167	13.220	1.10	2.07	0.10	25.2	15.5	31.6	136.6		298.3
HC16_10	169	13.241^	1.13	0.42	0.00	127.1	18.9	7.8	171.6	175.0	290.5
HC15_07	171	13.241^	0.52	0.12	0.00	4,477.8	17.7	65.8	67.0		348.2
HC16_11	171	13.241^	1.09	1.48	0.05	32.0	12.0	9.3	321.8	90.4	270.6
HC16_12	173	13.277	1.10	2.06	0.11	21.7	17.3	18.8	127.3	50.0	226.9
HC16_13	175	13.302	1.08	1.90	0.09	26.9	12.1	20.3	134.8	234.7	264.8
HC15_06	176	13.314^	0.52	0.16	0.00	643.3	93.7	12.2	139.2	541.6	379.0
HC15_05	184	13.412	0.51	2.05	0.24	23.0	37.6	21.6	243.5		707.7

Figure 3: Data table showing sample names, depths, radiocarbon ages, sample weights, osmium ratios, and rare earth element concentrations. Red Box = distinct sampling episodes: HC15 sampled in 2015, HC16 sampled in 2016, and HC17 sampled in 2017. Yellow Box = sampling depths from a site-wide datum level. Blue Box = anomalous gap between samples at the YD onset boundary (YDB interpreted by Sun et al. (2020) as 151 cm below datum). Adapted from Table S1 from Sun et al. [45] Creative Commons 4.0 CC BY-NC.

the same sampling episodes. For example, the 151 cm depth layer was sampled at least five times during the three sampling episodes, three of them in 2017. Yet, the PGE abundances and osmium ratios of samples purportedly taken from the same stratigraphic level differ significantly; Osmium ratios and Pt concentrations differ significantly from the five samples they collected from 151 cm, their supposed YDB level, with Os ratios ranging from 0.41 to 2.22, and Pt concentrations ranging from 64.3 ppt to 435.1 ppt (Figure 3). This implies, according to their methodology, that the osmium ratio and concentration at the 151 cm YDB are simultaneously crustal and non-crustal, which clearly cannot be the case unless there was mixing of two populations. Similar discrepancies occur at other depths where multiple samples were taken, such as at 171 cm, where the osmium ratio is simultaneously crustal (1.48) and non-crustal (0.12), with a 13,990% disparity between the osmium concentration in each supposedly identical sample level (Figure 3). Clearly their sequence of data is problematic, and a closer look at their sampling methods reveals the source of these disparities exist.

The authors demonstrated their understanding of how the central reference level, from which all depths at Hall's Cave were derived, relates to the cave stratigraphy. This is represented by the stadia rods in each panel of Figure 4. However, the left-hand image in Figure 4, reproduced from supplemental information of Sun et al. [45], clearly shows that the stratigraphic profile throughout the exposed section is not level but is undulatory. The undulatory nature of the strata means that the collected samples taken relative to the same stratigraphic reference point are from different stratigraphic levels and ages (Figure 4a, b). This is illustrated example in Figure 4b. Each black rectangle in Figure 4b represents a sample taken from the same depth relative to the same (central) reference point for each of the three sampling years.

In this example (B), the true YDB (black undulating line) is only partially captured during one sampling episode. This demonstrates that for samples collected at the same central depth, but different horizontal position, to be comparable, they would need to have sampled by reference to the stratigraphic layers rather than relying on central datum depth; following the first sampling episode, the datum would need to be anchored to the strata and traced horizontally for subsequent sampling episodes. Alternatively, the central datum could have been abandoned in favor of the

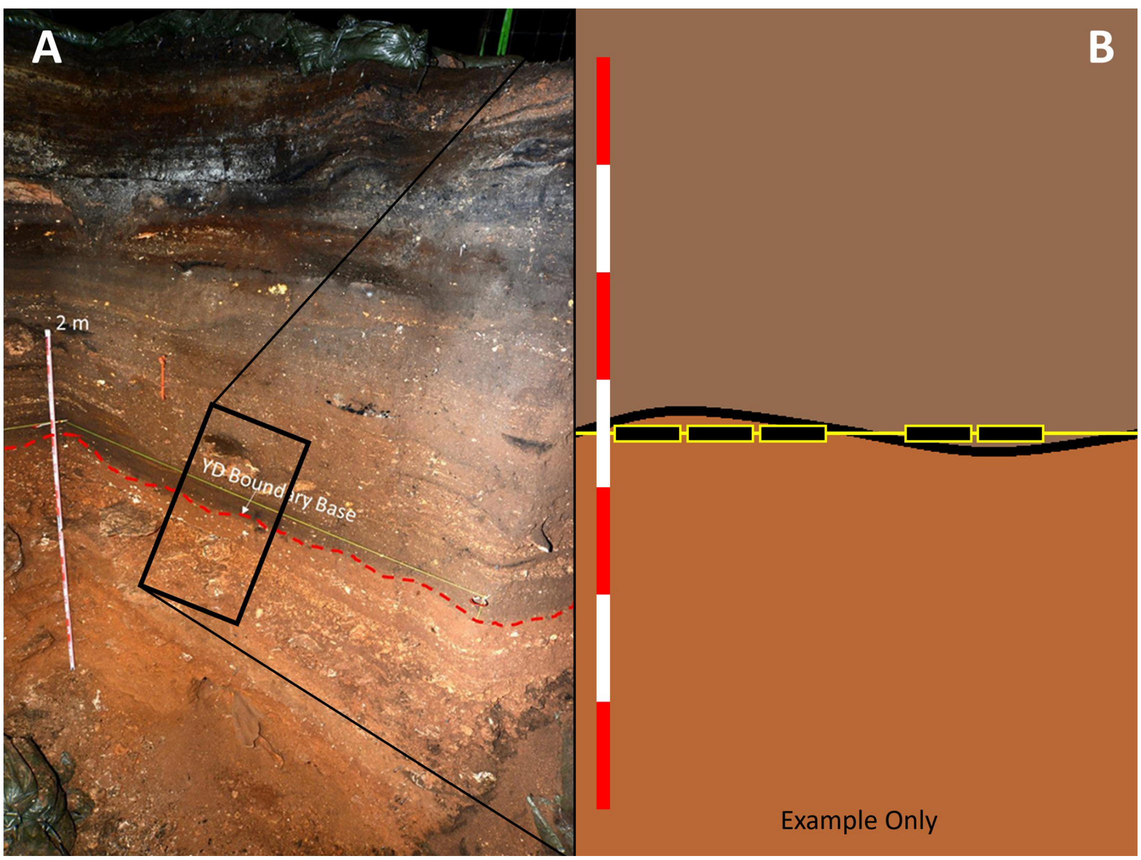

Figure 4: Hall's Cave stratigraphy. A: photo from Sun et al. 2020 showing stratigraphy in Hall's Cave. Red Dotted Line = Purported onset YD boundary layer. B: Diagrammatic representation of stratigraphic age differences resulting from the same horizontal level sampling in different areas of the cave. Yellow Line = Height based on datum (Red & White Pole). Black Boxes = Hypothetical sample locations at 151 cmbd. Adapted from Sun et al. [45]: Creative Commons 4.0 CC BY-NC.

YDB layer as point 0. This method has often been used by YDIH workers beginning with the original Firestone et al. [2] paper. The stratigraphy and sample locations shown in Figure 4b illustrate why one of the 151 cm samples from 2017 exhibits an elevated Pt concentration (435.1 ppt) compared with the other 4 from the same depth; suggesting that this was the only sample to partially intersect the thin YDB layer.

These errors call into question the reliability of the data presented by Sun et al. (2020). Specifically, separate plots for each sampling episode suggest a maximum of three, rather than 5 Osmium peak events, because this is the maximum number that were identified during the same sampling episode. At least two events were almost certainly duplicated between sampling episodes. Most importantly, for the collecting episode that revealed 3 Os events, none co-occur with the likely YDB layer.

Omission of data

Examination of the dataset of Sun et al. (Figure 3) shows a consistent sampling resolution of 1-2 cm throughout the middle part of the section. However, there appears to be a sample missing from the dataset. Directly below their claimed YDB layer at 151 cm depth, there is a conspicuous 4 cm gap into which a sample from 153 cm depth would have completed the section at the same sampling interval. As Sun et al.'s [45] conclusions rely on the authors having correctly interpreted the sample they claim to be the YDB layer, directly above this conspicuous gap in the section, this sampling gap thus raises a significant issue that requires explanation. This is especially so because a separate and independent Hall's Cave stratigraphic study by Stafford et al. [60], shown below in Figure 5, reported the presence in a thin layer between 151 and 153 cm of peak abundances in impact-related proxies: magnetic microspherules, nanodiamonds, carbon spherules; as well as elevated biomass burning proxies (Figure 5). This proxy assemblage has now been reported in multiple stratigraphic sequences in support of the YDIH [24, 26, 28, 29, 61, 62].

The results of Stafford et al. [60] demonstrate a precedent that the thin YDB layer was recognised at this depth (151 – 153 cm) in Hall's Cave. However, because the depth of the thin layer varies by up to several centimetres throughout the cave, this alone is not sufficient to conclusively claim that the YDB layer is present in the missing sample from 153 cm depth in Sun et al. (2020)'s stratigraphic dataset. As demonstrated earlier, Sun et al. (2020) clearly understood the significance of elevated Pt associated with the YD onset and its potential use as a geochronological datum for the YDB. Yet only one of Sun et al.'s several samples from 151 cm was shown to exhibit a slightly elevated Pt concentration. We were provided with the complete original geochemical dataset related to the Sun et al. [45] investigation by a former coauthor originally involved in that work. The dataset contains the original geochemical sample at 153 cm depth that Sun et al. omitted, creating the anomalous gap in the sequence (Table S1). It is important to note that this sample contains by far the highest Pt concentration in the record

Testing Younger Dryas ET Impact (YDB) Evidence at Hall's Cave, Texas

HC17_01	151
HC17_39	151
HC17_44	151
HC15_10	155
HC16_03	155

Show affiliations

Stafford, T. W. ; Lundelius, E. ; Kennett, J. ; Kennett, D. J. ; West, A. ; Wolbach, W. S.

We collected and analyzed sediments at high resolution above and below the distinct lithologic contact at 151 cm. The red clays from 151 to 153 cm and immediately preceding the lithologic contact contain an abundance of nanodiamonds (5 different allotropes), aciniform soot at 2400 ppm, magnetic spherules, and carbon spherules, all of which we interpret as evidence for a unique chronostratigraphic marker (YDB) in the Western Hemisphere. Because the age of this horizon is ~ 13,000 CAL BP, we interpret the age of the event as the beginning of the Younger Dryas cooling.

Publication: American Geophysical Union, Fall Meeting 2009, abstract id. PP33B-08

Pub Date: December 2009

Figure 5: Relevant section of a published abstract from a poster presentation at the American Geophysical Union Fall Meeting 2009 by Stafford et al. [60]. Red Box = highlighting the depth of the YDB. Red Underline = Important information about the YDB at Hall's Cave. Yellow Box = Samples from the same depth in Sun et al. (2020), with the missing 153 cm sample highlighted by the red line.

(1807 ppb), more than four times higher than the highest concentration found at 151 cm (Figure 6). These results are consistent with the presence of peaks in other cosmic impact proxies reported by Stafford et al. [60], indicating the YDB interval occurs between 151 and 153 cmbd.

Re-plotting of the sampling sequence only for the HC16 sampling episode produces a totally coherent sediment column with a consistent 2 cm sampling resolution (Figure 7). This also reduces the number of Os events to three, with one of them immediately below the YDB Pt peak event, in a stratigraphic position consistent with the LSE tephra event. Furthermore, some consistency remains even when combining HC16 with HC15. Only when adding the extra three replicates from 151 cm from HC17 does the dataset become completely incoherent.

Conclusions

Using geochemical time series data, Sun et al. [45] examined the well-studied, high-resolution, Hall's Cave stratigraphic sequence in central Texas in search of signatures of the YDB

Sample (Hall's Cave)	Depth, BDT cm	Sample Weight gram	187Os/188Os	±2σ	Os ppt	Ir ppt	Ru ppt	Pt ppt	Pd ppt	Re ppt		RC yr. ± 1 SD CAL BP (2 Sigma)
HC15-18	116	0.51	1.24	0.06	50.55		50.55		23.91	434.4		8800 ± 60 RC yr. 10,175-9555 CAL BP
HC15-16	131	0.53	2.35	0.2	31.32	27.02	26.77	282	58.71	1543		
HC16_22	133	1.08	1.79	0.06	33.98	23.39	12.86	113.3	101.1	1475		
HC16_21	135	1.11	2.09	0.09	29.54	8.98	4.18	136.3	140.1	1069		
HC15_14	136	0.51	2.45	0.24	28.65	21.44	31.45	190.2	4.392	272.1		
HC16_20	137	1.04	1.5	0.04	44.6	11.1	24.98	180	46.14	1090		
HC16_19	139	1.1	0.28	0	259.9	2.24	14.6	275.5	41.09	1038	I	9580 ± 70 RC yr. 11,205-10,589 CAL BP
HC15-13	140	0.52	0.23	0	509.7	71.47	26.61	102.9	188.2	1233		
HC16_18	141	1.02	1.96	0.08	32.49	10.7	12.01	185.7	158.9	1154		
HC16_17	143	1.06	1.11	0.02	56.91	13.06	17.87	965.6	33.19	1174		
HC16_16	145	1.07	2.02	0.08	31.29	8.21	16.47	237.2	112	1205		
HC15_12	146	0.53	2.04	0.16	32.05	13.88	14.07	171.7	593.8	356.6		
HC16_15	147	1.12	2.1	0.09	29.14	3.93	7.66	128.1	140.9	1013		
HC15_42	149	0.51	2.19	0.18	32.53		32.53		14.87	157.7		
HC16_14	149	1.13	1.8	0.07	31.77	8.15	21.08	78.12	72.52	1121		
HC15_11	**151**	0.51	1.49	0.1	36.97	29.43	25.77	64.27	?	262.1		
HC16_01	**151**	1.06	2.07	0.12	22.63	15.96	8.58	136.4	26.674	1057		
HC17_01	**151**	1.01	2.02	0.11	23.56	7.76	12.17	435.1	38.7	1062		
HC17_39	**151**	1.18	2.22	0.09	29.53	6.01	5.24	120	104.3	937		
HC17_44	**151**	1.03	0.41	0.01	105.3	32.06	11.68	86.59	154.9	1136	II	11,155 ± 25 RC yr. 13,115-12,901 CAL BP
HC16_02	153	1.09	1.96	0.1	24.64	22.86	14.05	1807	31.312	1099		
HC15_10	155	0.52	1.94	0.21	23.7	26.1	20.18	102.4	33.36	236.8		
HC16_03	155	1	0.15	0	829.7	22.7	5.09	124.7	44.84	1151	III	11,275 ± 25 RC yr. 13,227-13,052 CAL BP
HC16_04	157	1.06	1.55	0.06	34.13	13.11	31.9	176.9	53.25	1276		
HC15-15	158	0.51	2.08	0.25	22.62		28.66	312.1	58.44	1129		
HC16_05	159	1.02	2.06	0.12	23.67	11.43	16.39	151.7	268.4	954		
HC15-09	160	0.52	2.07	0.24	23.06	20.59	32.81	132.4		259.1		
HC16_06	161	1.01	2.03	0.11	24.33	8.6	14	120.4	117.2	970.2		
HC16_07	163	1.03	1.75	0.08	28.4	8.51	15.06	132.5	19.3	1191		
HC15-08	164	0.52	2.13	0.24	23.71	30.83	24.84	53.8	257.8	226.9		
HC16_08	165	1.01	1.46	0.09	27.12	7.89	15.18	168.5	72.82	1331		
HC16_09	167	1.1	2.07	0.1	25.22	15.53	31.63	136.6		1040		
HC16_10	169	1.13	0.42	0	127.1	18.87	7.78	171.6	175	1025	IV	11,360 ± 70 RC yr. 13,431-13,050 CAL BP
HC15_07	171	0.52	0.12	0	4478	17.67	65.78	66.95		348.2		
HC16_11	171	1.09	1.48	0.05	31.96	11.99	9.26	321.8	90.38	956.6		
HC16_12	173	1.1	2.06	0.11	21.66	17.27	18.77	127.3	49.96	846.5		
HC16_13	175	1.08	1.9	0.09	26.88	12.11	20.34	134.8	234.7	979.8		
HC15_06	176	0.52	0.16	0	643.3	93.69	12.15	139.2	541.6	379	V	11,460 ± 90 RC yr. 13,558-13,070 CAL BP
HC15_05	184	0.51	2.05	0.24	22.97	37.59	21.64	243.5		707.7		

Very high values
Replicate samples at 151 cm BD
Analyses questioned
IV Volcanic Event?
14C AGE of EVENT

Figure 6: Dataset prior to the omission of the HC16_02 153 cm sample containing the largest Pt spike (1807 ppt) in the entire record at the YDB (see data availability section for data source).

Sample (Hall's Cave)	Depth, BDT cm	Sample Weight gram	187Os/188Os	±2σ	Os ppt	Ir ppt	Ru ppt	Pt ppt	Pd ppt	Re ppt		RC yr. ± 1SD CAL BP (2 Sigma)	
HC16_22	133	1.08	1.79	0.06	33.98	23.39	12.86	113.3	101.1	1475			
HC16_21	135	1.11	2.09	0.09	29.54	8.98	4.18	136.3	140.1	1069			
HC16_20	137	1.04	1.5	0.04	44.6	11.1	24.98	180	46.14	1090			
HC16_19	139	1.1	0.28	0	259.9	2.24	14.6	275.5	41.09	1038	I	9580 ± 70 RC yr. 11,205-10,589 CAL BP	
HC16_18	141	1.02	1.96	0.08	32.49	10.7	12.01	185.7	158.9	1154			
HC16_17	143	1.06	1.11	0.02	56.91	13.06	17.87	965.6	33.19	1174			
HC16_16	145	1.07	2.02	0.08	31.29	8.21	16.47	237.2	112	1205			
HC16_15	147	1.12	2.1	0.09	29.14	3.93	7.66	128.1	140.9	1013			
HC16_14	149	1.13	1.8	0.07	31.77	8.15	21.08	78.12	72.52	1121			
HC16_01	**151**	1.06	2.07	0.12	22.63	15.96	8.58	136.4	26.674	1057			
HC16_02	153	1.09	1.96	0.1	24.64	22.86	14.05	1807	31.312	1099		12,855 yr BP (GISP2 Pt)	YDB
HC16_03	155	1	0.15	0	829.7	22.7	5.09	124.7	44.84	1151	II	11,275 ± 25 RC yr. 13,227-13,052 CAL BP	LSE
HC16_04	157	1.06	1.55	0.06	34.13	13.11	31.9	176.9	53.25	1276			
HC16_05	159	1.02	2.06	0.12	23.67	11.43	16.39	151.7	268.4	954			
HC16_06	161	1.01	2.03	0.11	24.33	8.6	14	120.4	117.2	970.2			
HC16_07	163	1.03	1.75	0.08	28.4	8.51	15.06	132.5	19.3	1191			
HC16_08	165	1.01	1.46	0.09	27.12	7.89	15.18	168.5	72.82	1331			
HC16_09	167	1.1	2.07	0.1	25.22	15.53	31.63	136.6		1040			
HC16_10	169	1.13	0.42	0	127.1	18.87	7.78	171.6	175	1025	III	11,360 ± 70 RC yr. 13,431-13,050 CAL BP	
HC16_11	171	1.09	1.48	0.05	31.96	11.99	9.26	321.8	90.38	956.6			
HC16_12	173	1.1	2.06	0.11	21.66	17.27	18.77	127.3	49.96	846.5			
HC16_13	175	1.08	1.9	0.09	26.88	12.11	20.34	134.8	234.7	979.8			

Figure 7: We replotted Sun et al.'s original data set using only the HC16 sampling episode, including the 153 cm sample omitted from their paper. A very large Pt anomaly (yellow) appears to mark the onset YD, and an unradiogenic Os ratio (red) accompanying peak (white box) below the 153 cm YDB that is consistent in age with the LSE (see data availability section for data source).

cosmic impact event and the Laacher See volcanic eruption in Germany for the interval between about 12,800 to 13,000 kyr BP. To assess the voracity of Sun et al. [45]. conclusions of an absence of evidence for a YDB cosmic impact event, we conducted a detailed analysis of their sampling approaches and of the original geochemical dataset made available to us. This has shown that Sun's main conclusions were flawed because of critical sampling and stratigraphic errors, and the omission of critical data from the original data set at the interval marking the onset of the YD. The original data clearly indicates the presence of a major Pt peak, well established as marking the YD onset, and consistent with a YDB cosmic impact event. Our re-evaluation of Sun et al.'s data, where we examine a single continuous sediment column (HC16), also reveals an absence of evidence of increased volcanism (based on Os proxy) in the same YDB layer matched by a major Pt peak and several other proxies as reported by Stafford et al. [60] consistent with a cosmic impact. Sun's complete, original data strongly supports the YDB cosmic impact and not a volcanic episode at the YD onset (Laacher See eruption).

The omitted sample exhibits the highest Pt concentration in the entire record and occurs in stratigraphic context with other known YDB impact proxies, thereby undermining the conclusion that the observed geochemical anomalies can be attributed solely to volcanic activity. Additionally, the restricted sampling resolution and absence of key data in the original study limited the ability to accurately determine the placement of the YDB layer at Hall's Cave. When the complete dataset is considered, the geochemical profile at this site, including elevated PGEs, magnetic spherules, and abrupt isotopic excursions, demonstrates strong correspondence with the known characteristics of the YDB layer at other globally distributed sites.

Thus, rather than contradicting the YDIH, the full geochemical sequence at Hall's Cave offers strong support for the hypothesis. These findings emphasize the critical importance of comprehensive data reporting, adequate sample resolution, careful high-resolution stratigraphy, and methodological transparency in assessments of stratigraphic events of global significance. Continued high-resolution analysis of key paleoenvironmental sites like Hall's Cave is essential for resolving outstanding questions regarding the origin and consequences of the Younger Dryas onset.

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Data availability

An extensive document cache related to the publication of Sun et al. 2020, including the original data, was provided by the former 6th coauthor of the publication and is hosted on Zenodo at the following URL: https://zenodo.org/records/16956140

Sample availability

No samples from this study are available.

Author contributions

All authors reviewed and approved the manuscript. M.D.Y. conceived and directed the project, wrote the manuscript, and contributed data and technical analysis for the paper.

Potential conflicts of interest

The author declares no competing interests.

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