



Research Article

Impact-Related Proxies, Environmental Change, and Faunal Extinctions across the Younger Dryas Boundary in Hall's Cave, Texas

Christopher R. Moore^{1,2,*}, Allen West³, James P. Kennett^{4,*}, Mohammed Baalousha⁵, Wendy S. Wolbach⁶, Mahbub Alam⁵, Malcolm A. LeCompte⁷, Chad S. Lane⁸, Theodore R. Them II⁹, Terry A. Ferguson¹⁰, Victor Adedeji¹¹, Marc D. Young³, Joshua J. Razink¹², Brian van Devener¹³, Jesus Paulo Perez¹³, Randy Polson¹³ and Timothy Witwer³

¹South Carolina Institute for Archaeology and Anthropology, University of South Carolina, Columbia, SC, USA; ²South Carolina Department of Natural Resources, Heritage Trust Program, Land, Water, and Conservation Division, Columbia, SC, USA; ³Comet Research Group, Prescott, AZ, USA; ⁴Department of Earth Science and Marine Science Institute, University of California, Santa Barbara, CA, USA; ⁵Center for Environmental Nanoscience and Risk (CENR), Department of Environmental Health Sciences, Arnold School of Public Health, University of South Carolina, Columbia, USA; ⁶DePaul University, Chicago, IL 60614, USA; ⁷Center of Excellence in Remote Sensing Education and Research, Elizabeth City State University, Elizabeth City, NC, USA; ⁸Department of Earth and Ocean Sciences, University of North Carolina Wilmington, Wilmington, NC, USA; ⁹Department of Geology and Environmental Geosciences, College of Charleston, Charleston, SC 29424, USA; ¹⁰Department of Environmental Studies, Wofford College, 429 N Church Street, Spartanburg, SC 29303-3663, USA; ¹¹Department of Natural Sciences, Elizabeth City State University, Elizabeth City, NC, USA; ¹²CAMCOR, University of Oregon, Eugene, OR, USA; ¹³Electron Microscopy and Surface Analysis Lab, Nanofab, University of Utah, Salt Lake City, UT, USA

*Correspondence to: Christopher R. Moore, E-mail: MOORECR@mailbox.sc.edu; James P. Kennett, E-mail: isotope@ucsb.edu

Received: 10 April 2026; Revised: 10 April 2026; Accepted: 20 April 2026; Published online: 8 May 2026

How to cite: Moore C.R., et al. Impact-Related Proxies, Environmental Change, and Faunal Extinctions across the Younger Dryas Boundary in Hall's Cave, Texas. *Airbursts and Cratering Impacts*. 2026 | Volume 4 | Issue 1 | Pages: 1–33 | DOI: 10.14293/ACI.2026.0006

ABSTRACT

To test two competing hypotheses for the Younger Dryas trigger (extraterrestrial impact versus volcanism), we analyzed a high-resolution multiproxy record from Hall's Cave, Texas, which preserves a continuous sedimentary archive from the Last Glacial Maximum through the Holocene. A Bayesian age–depth model based on 61 radiocarbon dates places the Younger Dryas Boundary (YDB) at $12,780 \pm 170$ cal BP, coincident with abrupt cooling, aridification, and sharply reduced sedimentation. At this boundary, biotic indicators record major ecological disruption, including a collapse of megafaunal dung-fungus spores and declining species richness. Geochemical profiles (magnetic susceptibility, $\delta^{15}\text{N}$, C/N, Hg/TOC) document hydroclimatic change and show no pronounced Hg/TOC enrichment at the YDB, indicating no evidence for a significant Hg-rich volcanic input at Hall's Cave. In contrast, the YDB layer contains multiple high-temperature and shock proxies, including melted microspherules, carbon spherules, soot, nanodiamonds, and shocked quartz, identified using SEM-EDS and TEM analyses. Single-particle ICP-TOF-MS detects enrichments in Ni–Fe, Co–Fe, Fe–Si, Al–Ir, and Ti–Ir nanoparticle associations, including element combinations characteristic of meteoritic material and high-temperature condensation. These

proxies define a two-step sequence consisting of a condensed boundary layer containing high-temperature and high-pressure (shock metamorphism) materials, followed by an early Younger Dryas interval characterized by increased dust input consistent with regional aridification. Collectively, the chronological, geochemical, mineralogical, and faunal evidence indicates a high-temperature and high-pressure event at ~12.8 ka and supports an extraterrestrial airburst or impact as the most consistent explanation for the Younger Dryas Boundary, in agreement with the Younger Dryas Impact Hypothesis (YDIH).

KEYWORDS

Younger Dryas Boundary (YDB), Hall's Cave (Texas), multiproxy analysis, Bayesian age–depth modeling, paleoclimate change, Late Quaternary, nanoparticle geochemistry, high-temperature proxies, single-particle ICP-TOF-MS, platinum group elements (PGEs)

Introduction and background

Hall's Cave, situated on the Edwards Plateau of central Texas (30°08'N, 99°32'W), contains a continuous sedimentary sequence spanning from the Last Glacial Maximum to the Holocene. Extensively excavated and described by Toomey et al. [1] and Waters et al. [2], the site preserves ~3.7 m of finely stratified clays and silts, derived from colluvial and aeolian inputs eroded from the surrounding Edwards Limestone (Figure 1). Sediments were deposited primarily by sheetwash from a small (~0.8 ha) catchment area. The stratigraphy is well-preserved and suitable for high-resolution paleoenvironmental reconstruction, although some degree of post-depositional mixing cannot be entirely excluded [2]. Radiocarbon dating of more than 160 samples from multiple studies, including bone, charcoal, snails, humic acids, and sediment fractions, has established a robust and continuous chronology from ~18,240 ¹⁴C yr BP to the present, with no evidence of significant depositional hiatuses across the Younger Dryas interval [1, 4–7].

This unusually large number of radiocarbon determinations provides a well-constrained chronological framework relative to many YDB sites.

Hall's Cave preserves a high-resolution faunal record spanning the terminal Pleistocene extinction interval. Analyses document the local disappearance of numerous species, including small mammals such as prairie dogs (*Cynomys*), moles, and cold-adapted rodents. These losses broadly coincide with the Younger Dryas interval (YDB; ~12.8 ka), although the precise temporal relationships are subject to chronological and taphonomic uncertainties [1, 8]. However, resolving the relative contributions of climate change, ecological stress, and potential extraterrestrial forcing requires integration of faunal evidence with geochemical and sedimentological proxies.

Toomey et al. [1] and Waters et al. [2] documented stratigraphic transitions in the sediment sequence, shifts in grain size, color, and organic content, including those associated with the onset of the Younger Dryas (the YDB). They interpreted associated faunal and sedimentary changes as

resulting primarily from climatic rather than any catastrophic cause. In addition, stable-isotope analyses of faunal collagen from Hall's Cave further indicate climate-driven environmental change during this interval [9]. Similarly, Ellwood and Gose [10] performed high-resolution magnetic susceptibility measurements on Hall's Cave sediments and identified anomalies corresponding to Heinrich event 1 (~17.5 ka), the Younger Dryas onset (~12.8 ka), and the 8.2 ka event, widely linked to a large freshwater pulse into the North Atlantic that weakened ocean circulation and triggered climatic instability. Furthermore, in a broader ecological context, regional syntheses of community-level restructuring across the terminal Pleistocene, including that at Hall's Cave demonstrate isotopic/dietary niche space, survivor reassembly, and meso-carnivore release [11, 12].

Palynological and charcoal analyses by Cordova et al. [13] further support evidence for ecological change and fire activity near the YDB at Hall's Cave. They observed an increase in charcoal and a decline in conifer pollen consistent with vegetation shifts and increased biomass burning but made no inference regarding the cause of these changes.

Sun et al. [5] argued that proxies attributed to the Younger Dryas impact may instead result from terrestrial rather than extraterrestrial processes. Instead, they proposed that several proxies attributed to impact processes could be produced by terrestrial mechanisms, including volcanic or wildfire-related processes [5]. This debate about causation underscores the need for comprehensive multiproxy evaluations on this well-documented, high-resolution site. Competing hypotheses involving cosmic impact, volcanism, and climate-driven processes can be evaluated using high-resolution datasets.

In summary, Hall's Cave offers a uniquely well-dated, stratigraphically intact, and minimally disturbed high-resolution archive of Late Quaternary environmental change in the southern United States. Its finely stratified sediments, stable depositional regime, and multiproxy records, including faunal, isotopic, magnetic, palynological, and geochemical data, make it a valuable site for evaluating the origin, timing, and environmental interpretations. We specifically test whether stratigraphically restricted geologic

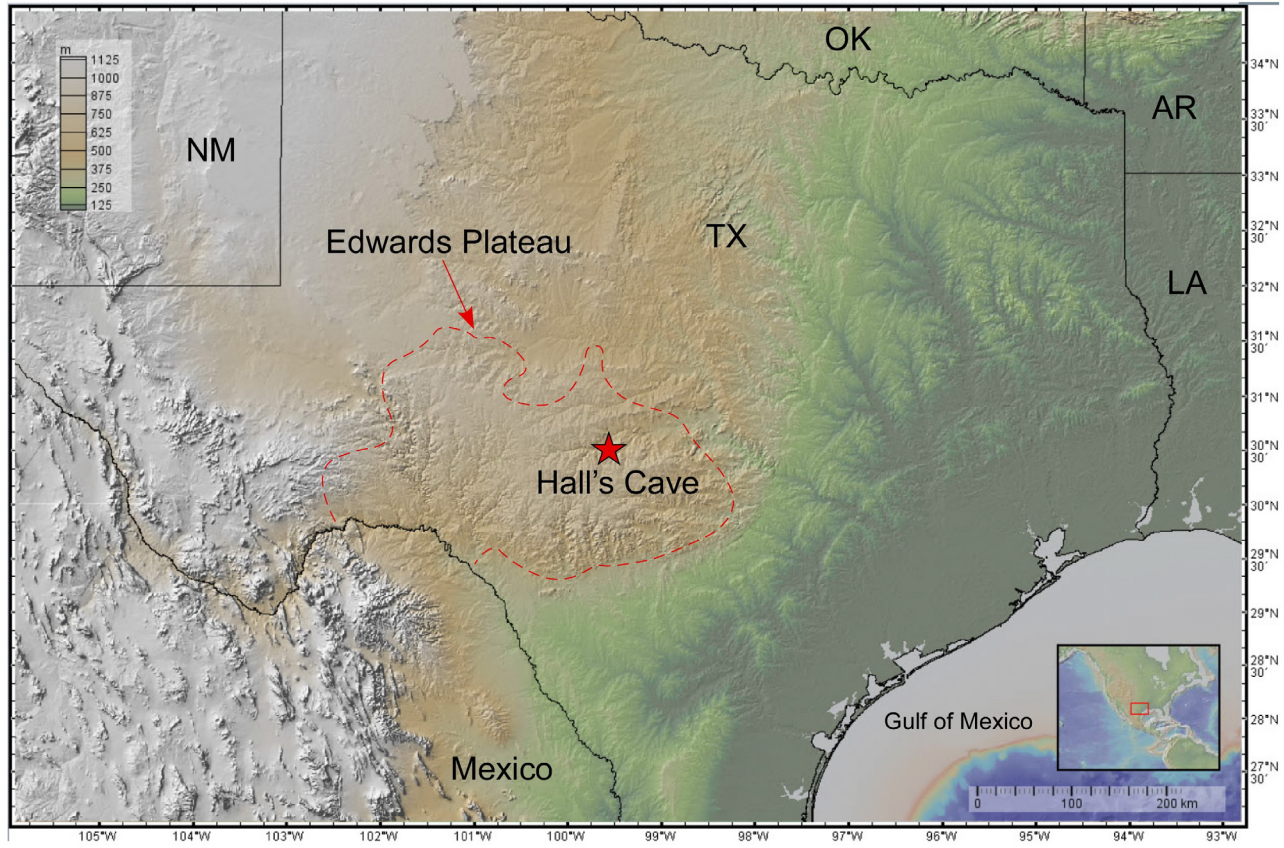


Figure 1: Site location map of Hall's Cave, Texas. Base map generated using GeoMapApp (www.geomapp.org) [3], using public topography/bathymetry grids (e.g., GMRT).

features and associated geochemical signals at Hall's Cave are more consistent with an extraterrestrial airburst or with volcanic deposition. To address this, we present new sedimentological, geochemical, magnetic, nanoparticle, and paleoecological data, and apply an integrated strategy that includes high-resolution Bayesian-modeled radiocarbon chronology using 54 previously published radiocarbon dates and 7 dates new to this study (Table S1), together with single-particle elemental analyses. A previous AGU conference abstract by Stafford et al. [6] briefly reported several of the proxies discussed here, including nanodiamonds, magnetic and carbon spherules, and aciniform carbon, and established the approximate age and stratigraphic position of the YDB layer at Hall's Cave. Those findings were not subsequently developed into a full-length peer-reviewed publication. The present paper documents these results in detail and expands the proxy inventory to include shocked quartz. We also provide a full Bayesian chronological framework for the YD onset, present new high-resolution nanoparticle abundance and compositional data across the boundary and integrate these records into a multiproxy stratigraphic interpretation that evaluates alternative explanations and links the YDB bed to a short-lived post-boundary dust pulse. This framework allows us to evaluate whether the record at Hall's Cave

is more consistent with a cosmic impact, volcanic forcing, or climate-driven change, while providing higher-resolution data relative to earlier composite or lower-resolution records.

Methods

Site, stratigraphy, and sample collection

Sediment sampling at Hall's Cave, Texas for this study, was conducted in February 2008 by Thomas Stafford Jr., Ernest Lundelius, James Kennett, and Allen West. Samples were collected from a single vertical profile in the excavation wall spanning the stratigraphic interval across the Younger Dryas Boundary (YDB; ~12.8 ka) at ~151 cm depth represented by a color change and lithologic break described in earlier work as Unit 1c [2]. The same general area of Hall's Cave was later sampled by Sun et al. [5] and Waters et al. [2]. Sediment was removed in contiguous 2 cm increments across the boundary layer and discontinuously in adjacent deposits. The exposed section was cleaned to minimize contamination; each increment was isolated, documented, and bagged individually. While care was taken to preserve stratigraphic integrity, some degree of micro-scale vertical mixing cannot be entirely excluded.

Radiocarbon dating and Bayesian age–depth modeling

We used a Bayesian age–depth model implemented in OxCal with the IntCal20 calibration curve [14, 15]. Within OxCal, the P_Sequence model was applied to dates with known depth relationships. The program calibrates all dates to calendar years, selects the most probable age at each depth, and combines ages into a depth profile. Each date and the overall model are evaluated using OxCal's Agreement Index, where values >60% indicate acceptable agreement between the data and the model structure. All dates were evaluated within the Bayesian framework using OxCal's Agreement Index and outlier model; dates were down-weighted where appropriate rather than excluded. Full date lists and OxCal code are provided in the Supporting Information, Table S1 and “Bayesian Code”. This age model, based on 61 AMS dates, provides higher sampling density and allows refined age–depth modeling relative to many previous YDB studies.

Bulk sediment properties and geochemistry Magnetic susceptibility

Magnetic susceptibility was analyzed at Wofford College on 13 of 15 Hall's Cave profile sediment samples collected between 130 cm and 173 cm below datum in 2008. MS primarily reflects the concentration of ferrimagnetic minerals, but it can also be influenced by magnetic grain size and mineralogy and therefore may reflect changes in sediment source and diagenetic or pedogenic processes. Samples were prepared and analyzed following procedures outlined by Dearing [16]. Throughout the analysis sediments were handled so as to minimize contamination. The samples contained fine sediment particles <2 mm and required no additional preparation, before filling to capacity $2 \times 2 \times 2$ cm (8 cm^3) plastic cubes. These cubes were weighed to thousandths of a gram with an Ohaus Discovery DV215CD balance and sample weights calculated by subtracting empty box weights. A Bartington MS2 meter with a MS2BB dual frequency magnetic susceptibility sensor was used to measure K (*Volume Susceptibility*), from which X (*Mass-Specific Susceptibility*), and $K_{fd}\%$ (*Frequency-Dependent Susceptibility*), were calculated following methods specified by Dearing [16]. Readings and calculations were repeated three times and the median values used in the analysis (See SI Table S7).

Total organic carbon, nitrogen, and stable isotopes ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$)

Dried, ground sediments were acidified (2 N HCl) to remove carbonates, redried at 60 °C, encapsulated, and analyzed using a Costech 4010 elemental analyzer coupled to a Thermo Delta V Plus IRMS at the University of North Carolina, Wilmington (UNCW). $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ are reported in ‰ relative to standards as $\delta = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 1000$. USGS-40/41 replicates indicate precision better than 0.5‰. $\delta^{13}\text{C}$ values are reported relative to VPDB and $\delta^{15}\text{N}$ values relative to AIR.

Aciniform carbon (AC; soot)

AC was isolated at DePaul University by W.S.W, following the methodology of Wolbach et al. [17, 18]: (1) HF/HCl demineralization; (2) $\text{Na}_2\text{Cr}_2\text{O}_7/\text{H}_2\text{SO}_4$ oxidation to remove non-soot organics; (3) SEM identification of aciniform (“grape-like”) aggregates of ~10–150 nm primary spherules; and (4) image-based quantification (ppm of bulk sediment). Procedural blanks were processed alongside samples to monitor background carbon contamination. A subset of samples were processed in duplicate to evaluate reproducibility of AC yields and image-based counts. SEM identification followed published morphological criteria (aciniform “grape-like” aggregates), and quantification was performed using consistent imaging/thresholding settings across runs.

Mercury (Hg)

Hg analyses were performed at the GAMES Laboratory (College of Charleston) using a DMA-80 evo Tricell analyzer (Milestone). ~50–100 mg of dried, homogenized powder was combusted to 750 °C; volatilized (Hg) was trapped by gold amalgamation and quantified spectrally. Certified Reference Materials (CRMs) TORT-3 ($296.3 \pm 8.0 \text{ ng g}^{-1}$; $N = 5$) and DORM-4 ($413.7 \pm 11.4 \text{ ng g}^{-1}$; $N = 4$) constrained accuracy. Twenty-five percent of samples were replicated ($2\sigma \text{ SD} \pm 0.8 \text{ ng g}^{-1}$, ~5%; range 0.4–1.4 ng g^{-1}).

Microspherule extraction, counting, and confirmation

Prior to looking for microspherules, bulk sediment samples were first ultrasonicated (30 min) in deionized water mixed with sodium hexametaphosphate, wet-sieved at 20 μm , dried, and size-fractionated (≥ 63 –<125 μm ; ≥ 20 –<63 μm). A grade-52 neodymium-boron (NdFeB) magnet (bagged) was passed over thinly spread fractions three times to extract magnetic grains. Extracts were screened using a stereomicroscope; candidate magnetic microspherules were placed on carbon tape for scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) confirmation [19]. A portion of the non-magnetic sediment fraction was also examined optically to identify candidate glassy spherules. Counts were normalized to microspherules kg^{-1} .

Electron microscopy and microanalysis (SEM/EDS)

At Elizabeth City State University (NC), images were acquired in low-vacuum mode on a JEOL-6000 SEM; major elements were measured with $\sim \pm 10\%$ uncertainty. Additional work was done at the Electron Microscopy and Surface Analysis Lab (EMSAL) at the University of Utah. Samples were examined by SEM at 20 kV, with magnifications reported on each micrograph at the bottom of the corresponding frame. Specimens were analyzed uncoated in environmental mode (~50 Pa) to minimize charging. Samples were mounted either (i) on glass slides using double-sided adhesive tape, or (ii) on $0.32 \times 10 \text{ mm}$ aluminum SEM stubs (hockey-puck style; Ted Pella Inc., Item

No. 16217). A strip of double-sided adhesive photographic tape was applied to each mount, and particles were placed directly onto the adhesive surface for analysis in the evacuated chamber. Magnification was adjusted to maximize screen fill and image detail. Elemental compositions were determined using an energy-dispersive X-ray spectroscopy (EDS/EDX) detector.

Nanodiamond extraction and identification

Nanodiamonds (NDs) were extracted following the methodology of Kinzie et al. [20]. Sediment samples were first sieved to isolate the $<38\ \mu\text{m}$ fraction and then suspended in sodium hydroxide (NaOH). The suspension was acidified using 9 M hydrochloric acid (HCl), followed by oxidation with sodium dichromate to remove organic matter. Silicate minerals were removed using sequential hydrofluoric acid (HF) and HCl treatments, and residues were subsequently defluorinated using 9 M HCl. In selected samples, perchloric acid (HClO_4) was applied as an optional step to further target cubic nanodiamond phases. Final residues were suspended in ammonium hydroxide (NH_4OH) and ethanol and mounted onto gold (Au) or molybdenum (Mo) transmission electron microscopy (TEM) grids coated with ultrathin carbon support films.

Nanodiamond identification was performed using TEM, including high-resolution TEM (HRTEM) and scanning TEM (STEM). Crystallinity and diagnostic lattice spacings were evaluated using selected-area electron diffraction (SAD) and fast Fourier transform (FFT) analysis of high-resolution images. Elemental composition was assessed using energy-dispersive X-ray spectroscopy (EDS) to confirm carbon-only chemistry, and bonding characteristics were evaluated using electron energy-loss spectroscopy (EELS) and energy-filtered TEM (EFTEM) to assess relative sp^2 and sp^3 bonding. Particles were classified as candidate nanodiamonds if they were carbon-dominated, crystalline, and exhibited d-spacings consistent with reported nanodiamond allotropes; however, we recognize that distinguishing nanodiamonds from structurally similar carbon phases remains an area of ongoing debate. All extraction steps were conducted using low-temperature processing and contamination controls to minimize phase alteration and reduce the potential for laboratory-introduced artifacts.

Shocked quartz identification

We applied nine complementary analyses to identify glass-filled lamellae/fractures: optical transmission microscopy (crossed polars), epi-illumination to distinguish open versus filled fractures, scanning electron microscopy (SEM) using secondary-electron (SE) imaging for surface topography and backscattered-electron (BSE) imaging for compositional (atomic-number) contrast, SEM–EDS and TEM–EDS of fracture fills, focused ion beam (FIB) foil preparation, high-resolution transmission electron microscopy (HRTEM) to distinguish amorphous versus crystalline domains and

to perform (hkil) indexing, scanning transmission electron microscopy (STEM) imaging, selected-area electron diffraction (SAED) with fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT) analyses to verify amorphous silica and map glass versus crystalline regions, and electron backscatter diffraction (EBSD) to document lattice damage. Fractures were indexed on a universal stage where possible. Full criteria follow West et al. [21] and Hermes et al. [22].

Single-particle inductively coupled plasma time-of-flight mass spectrometry

We applied single-particle inductively coupled plasma time-of-flight mass spectrometry (SP-ICP-TOF-MS) because it enables high-throughput, single-particle analysis of nanoparticles, including identification of elements that may be consistent with extraterrestrial material.

Particle extraction

For SP-ICP-TOF-MS, 100 mg sediment aliquots were suspended in 10 mL ultrapure water (Millipore Advantage System) in acid-washed 15 mL tubes, vortexed, and ultrasonicated (Branson 2800, 40 kHz, 15 min). After 24 h settling, the upper 5 mL was decanted to clean tubes and stored at 4 °C. Prior to analysis, suspensions were diluted 5000-fold with ultrapure water and sonicated before and after dilution.

Instrument setup, calibration, and data reduction

Analyses used a TOFWERK SP-ICP-TOF-MS with a 2DX autosampler (Element Scientific), MicroMist U-series nebulizer, and quartz cyclonic spray chamber [23–25]. Monitored isotopes and settings are in Supporting Information, Tables S2 and S3. Calibration employed multi-element ICP standards ($0\text{--}10\ \mu\text{g L}^{-1}$ in 1% HNO_3) and NIST RM 8013 Au nanoparticles to determine transport efficiency via the known-size method [26]. A 4.5% H_2/He collision gas optimized $^{56}\text{Fe}^+$ and $^{28}\text{Si}^+$. Data processing (Poisson thresholding [27], event correction) used TOFpilot v2.11.3 (TOFWERK). Samples and blanks were run in triplicate (200 s per replicate); replicates were combined for interpretation.

Data and code availability

All raw and processed data, SEM/TEM images, and OxCal code are available in the Supporting Information and associated data repository). <https://zenodo.org/uploads/19501481>.

Results

Bayesian age-depth model for Hall's Cave

We applied OxCal's General Outlier model (prior $p = 0.05$) and a Poisson-process deposition model with a contiguous Sequence and bounded Phases. Dates flagged as outliers were down-weighted but retained unless stratigraphically inconsistent. The OxCal code and a list of 54 previously

published and 7 new radiocarbon ages used in this study is provided in the Supporting Information (see Tables S1 and S4 and Supporting section “Bayesian Code”). This approach integrates radiocarbon dates with stratigraphic ordering to produce probability-modeled calendar ages, while also identifying potential outliers (Figure 2). The model refines the age–depth relationship of the Hall’s Cave sediment sequence, enabling robust placement of the YDB stratigraphic horizon within the profile and facilitating direct comparison with global records of abrupt climate change.

Interpretation

The Bayesian age–depth model provides a probabilistic chronological framework for evaluating the sedimentary and nanoparticle records from Hall’s Cave (Figure 2). Here, we define the Younger Dryas Boundary (YDB) operationally as the stratigraphic interval corresponding to the modeled onset of Younger Dryas cooling (Greenland Stadial 1; GS-1) at ~12.9 ka, operationally expressed as the modeled interval spanning 12,875–12,775 cal BP (95% confidence interval) based on independent North American and European chronologies [28] overlapping with uncertainty with the Greenland ice-core age for the GS-1 onset (~12,870 yr BP [30]). The modeled onset of the Younger Dryas at Hall’s Cave ($12,780 \pm 170$ cal BP) overlaps with independent estimates within stated uncertainties. Of 61 radiocarbon dates available, including 7 from this study, all were Bayesian-modeled (criteria detailed in Methods), providing one of the most complete chronological frameworks assembled for this site.

Sedimentation rate changes across the YDB

To investigate changes in depositional dynamics at Hall’s Cave, we calculated sedimentation rates from radiocarbon-dated horizons using Bayesian modeling (Figure 3 and Supporting Table S5). This approach allows estimation of the relative rate of accumulation before, during, and after the Younger Dryas Boundary (YDB).

Interpretation

The modeled sedimentation rates show four distinct phases that align with well-established regional climate changes:

Last glacial maximum and late glacial (~21–14.7 ka)

Sedimentation rates in Hall’s Cave were moderate, probably reflecting cooler conditions and relatively sparse vegetation. Paleoclimate records from the central Texas region indicate a mosaic of open grassland and oak–juniper woodland under semi-arid conditions [1].

Bølling–Allerød (~14.7–12.8 ka)

Sedimentation rates increased sharply, coinciding with a period of enhanced precipitation and warmer temperatures across North America. Pollen and isotopic records from the Edwards Plateau indicate expansion of mesic woodlands

and increased soil development [8]. This wetter interval promoted higher runoff, consistent with greater sediment flux into Hall’s Cave.

Younger Dryas (~12.8–11.6 ka)

At the onset of the YDB, sedimentation rates decreased sharply to the lowest values in the record. This decline is consistent with a shift to colder, drier conditions, with regional evidence for reduced precipitation, increased aridity, and expansion of xerophytic grasslands [1, 31]. Proxy data from the Santa Barbara Basin and Greenland ice cores show synchronous abrupt cooling and dust increases [32, 33].

Early Holocene (~11.6–10 ka)

Sedimentation rates again slightly increased, consistent with the gradual warming of temperatures and increased moisture availability. Vegetation records indicate the establishment of oak–juniper–grassland savanna mosaics, which supports a more stable soil and hydrologic regime [34]. However, sedimentation rates never fully returned to Bølling–Allerød levels, suggesting that aridification remained a feature of the early Holocene landscape.

Taken together, the sedimentation rate record from Hall’s Cave mirrors regional and global evidence of abrupt climate reorganization across the late Pleistocene to Holocene transition. The sharp decline in sediment accumulation beginning at the YDB coincides with evidence of widespread environmental stress, megafaunal extinctions, and biomass burning [35, 36].

Biotic turnover across the YDB at Hall’s Cave

To assist with the evaluation of biotic turnover at or close to the Younger Dryas Boundary (YDB) at Hall’s Cave, we juxtapose a proxy indicator of local megaherbivore biomass, *Sporormiella* dung-fungus spore counts, with vertebrate species richness and the stratigraphic range of documented megafaunal taxa recorded in the cave sequence (Figure 4). *Sporormiella* is widely used as a proxy for large-herbivore abundance, with declines interpreted as loss of megafaunal biomass [37, 38]. The broader Hall’s Cave dataset allows us to assess whether faunal and floral restructuring at Hall’s Cave occurred at or close to the YDB-interval and subsequent Younger Dryas (YD) cool episode [1, 13].

Interpretation

Panel A (*Sporormiella*); Figure 4A: The sharp rise in *Sporormiella* just prior to the YDB followed by a severe decline is consistent with a rapid contraction in local megaherbivore populations. *Sporormiella* spores are a well-established proxy for the presence/abundance of large herbivores; high counts indicate substantial dung input (i.e., sizable, frequently present herds), whereas large decreases in spores indicate the loss of those herds from the catchment [37, 38]. The observed pre-YDB peak implies highly favorable environmental conditions and robust megafaunal use

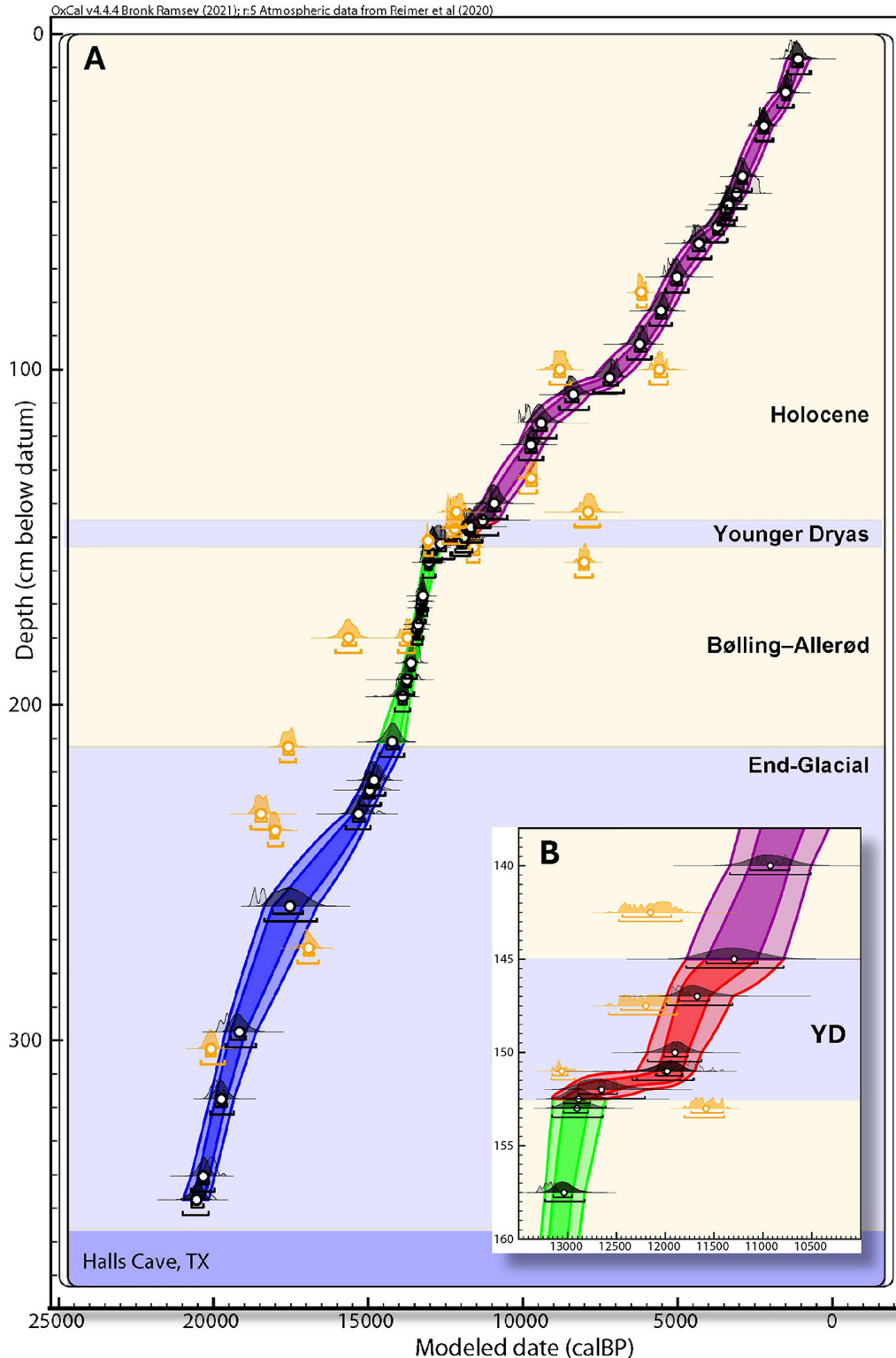


Figure 2: Bayesian-modeled age-depth profile for Hall's Cave. A) Model generated with OxCal v4.4. Blue Bayesian-modeled lines and fill mark the end-Glacial interval, green lines and fill the Bølling-Allerød, red lines and fill the Younger Dryas, and purple lines and fill the Holocene. Bayesian posterior probability distributions are shown in black ($n = 44$); determinations flagged by OxCal's outlier model are highlighted in orange ($n = 17$). Stratigraphic/climatic intervals are highlighted with shaded backgrounds: late Glacial and Younger Dryas horizons in light blue, and the Bølling-Allerød and Holocene intervals in beige. **B)** Closeup inset of the YD onset region of the model. The modeled onset of the Younger Dryas at Hall's Cave is $12,780 \pm 170$ cal BP, consistent with published multi-site estimates [28, 29]. See Supporting Information, Tables S1 and S4 and "Bayesian code" (<https://zenodo.org/uploads/19501481>).

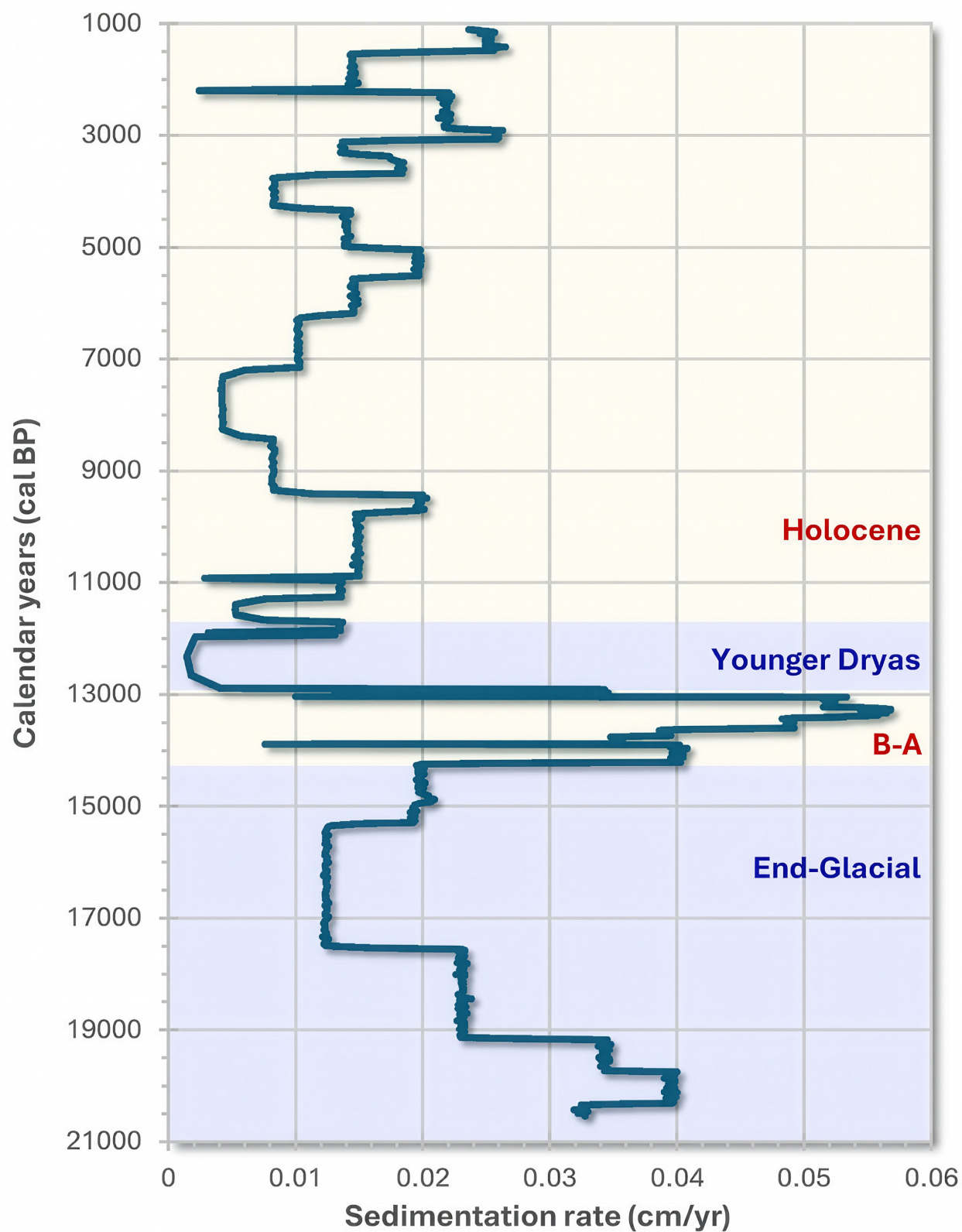


Figure 3: Bayesian-modeled sedimentation rates at Hall's Cave. Sediment accumulation rates (cm/yr) determined for the last 21 ka. The onset of the Younger Dryas ($\sim 12,780 \pm 170$ cal BP) associated with a sharp decline in sedimentation rate, contrasting with higher accumulation during the Bølling–Allerød. Rates remain low throughout the Younger Dryas, with a slight but variable increase during the Holocene. See Supporting Information, Table S5 (<https://zenodo.org/uploads/19501481>).

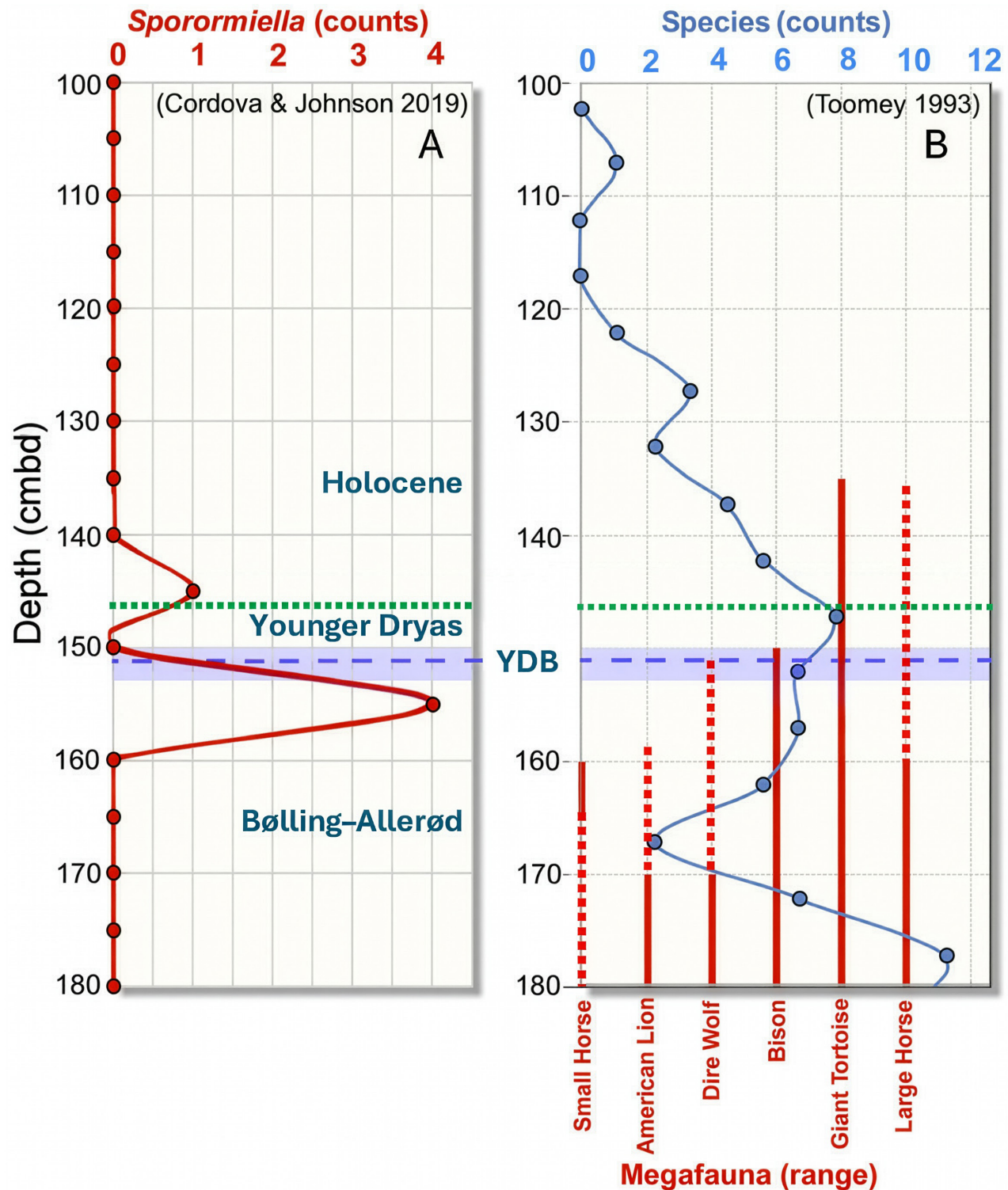


Figure 4: Hall's Cave biotic turnover across the YDB. (A) *Sporormiella* counts [13] (megafaunal proxy; red line/points). These counts rise steeply in the Bølling-Allerød immediately before the YDB, suggesting that environmental conditions may have supported larger megaherbivore populations, which then declined at or close to the boundary, consistent with a rapid reduction in large-herbivore presence in the catchment [37, 38]. (B) Species richness and megafaunal presence by depth based on data from Toomey [1]. The blue line/points shows vertebrate species richness by depth: species richness peaks in the late glacial, remains comparatively high through the YD, and declines gradually during the Holocene, a trajectory consistent with increasing warmth/seasonality and regional aridification on the Edwards Plateau [1, 13]. Solid red lines denote megafaunal taxa recorded in Hall's Cave; most disappear at or a few centuries before the YDB, with the exception of the giant tortoise, which persisted into the Holocene. Interpreting these ranges requires the Signor-Lipps effect: last observed occurrences almost always predate

← true extinction due to an incomplete record and/or sampling, so survivorship plausibly extended to the boundary even if not directly observed [39, 40]. The horizontal dashed blue line indicates a major lithologic transition at 151 cm below datum (cmbd), the light blue bar represents the modeled YDB interval, and the green dashed line indicates the ~Holocene boundary.

of the Hall's Cave landscape in the latest Bølling–Allerød, while the downturn at, or immediately bracketing, the YDB horizon marks an abrupt ecological change consistent with regional megafaunal decline. Although methodological uncertainties exist (e.g., spatial sensitivity of spore delivery and contributions from non-megaherbivores), the overall pattern is consistent with independent faunal and geochemical evidence, although uncertainties in proxy sensitivity and transport remain. In North American records, similar *Sporormiella* downturns coincide with ecosystem reorganization and enhanced burning near the Pleistocene–Holocene transition [37, 41].

Panel B (blue solid line: species richness): Species richness at Hall's Cave peaks in the late glacial, remains comparatively high through the Younger Dryas, and then declines gradually through the Holocene. This trajectory is broadly consistent with central Texas hydroclimate and vegetation reconstructions: pollen–phytolith data indicate a late-glacial mixed grass–woodland, a YD reduction in arboreal pollen, and an Early Holocene shift toward warmer, seasonally drier conditions with greater C_4 -grass prominence, changes that would reduce habitat breadth for moisture-sensitive taxa and favor drought-tolerant communities [1, 13]. The gradual Holocene attrition in species richness is therefore consistent with increasing aridity/seasonality, soil mantle loss on the Edwards Plateau, and attendant ecological filtering, rather than a single “step” extinction across the entire fauna. Ancient-DNA results from Hall's Cave similarly show that animal diversity declined during the YD and failed to rebound in the Early Holocene even as plant diversity recovered, reinforcing a climate-linked but taxon-specific biotic response [42].

Panel B (red solid lines: megafauna): The disappearance of most megafaunal species at or a few centuries before the YDB, with giant tortoise as an exception, needs to be interpreted with context of the Signor–Lipps effect: last observed occurrences almost always predate true extinction because the fossil record is incomplete and sampling is finite [39, 40]. In practical terms, the Hall's Cave last appearances plausibly bracket survivorship up to the YDB even if the final individuals were not preserved. Extinctions are seldom instantaneous or perfectly synchronous across a continent, and small, isolated populations may have persisted in ecological refugia for decades to even millennia. Such remnants, however, would have been highly vulnerable to demographic stochasticity, environmental stress, and low-density dynamics, including Allee effects that reduce survival and reproduction at very small population sizes, which may contribute to extinction dynamics [43]. Comparative studies of late-Quaternary mammal

paleocommunities demonstrate that losses were staggered over time and space, and that surviving taxa underwent substantial ecological reorganization, leaving “missing pieces” in niche structure [11, 44].

The results have implications for the YDB impact event and YD climate change. At Hall's Cave, a *Sporormiella* collapse and the associated disappearance of several megafauna near the YD onset appear synchronous with numerous impact-related markers reported at ~12.8 ka. At the same time, regional hydroclimate change during the YD and early Holocene (cooling then warming with resulting increased seasonal dryness) provides a sustained mechanism for continued extinctions and the decreased diversity shown in Panel B [1, 13, 42]. In sum, the Hall's Cave record is compatible with scenarios in which an abrupt YDB disturbance, potentially including an impact-related event, occurred within a broader interval of climatic and ecological change; however, the data do not uniquely resolve the relative roles of these processes in megafaunal decline. Such mechanisms could contribute to disruption of ecological networks, while subsequent Holocene aridity and small-population dynamics governed the protracted, taxon-specific paths to extinction causing diversity decrease and community simplification.

Bulk magnetic and geochemical profiles across the YDB at Hall's Cave

Here we evaluate four depth-resolved proxies that bracket the Younger Dryas Boundary (YDB) in the Hall's Cave sequence: mass-corrected low-field magnetic susceptibility, χ ($10^{-6} \text{ m}^3 \text{ kg}^{-1}$); bulk organic-matter $\delta^{15}\text{N}$ (EA-IRMS; here “ $\delta^{15}\text{N}$ per mil”); elemental C/N (elemental analyzer); and mercury normalized to total organic carbon (Hg/TOC; direct-combustion Hg analyzer with TOC normalization) (Figure 5 and Supporting Tables S6 and S7; <https://zenodo.org/uploads/19501481>). Interpreting these collectively provides a test of potential relationships between sediment source and redox (χ), nitrogen cycling and hydroclimate ($\delta^{15}\text{N}$), organic-matter sources/diagenesis (C/N), and atmospheric Hg inputs potentially linked to biomass burning or volcanism (Hg/TOC). Here we use bulk $\delta^{15}\text{N}$ as a proxy for nitrogen-cycle openness, where higher $\delta^{15}\text{N}$ indicates greater fractionating N losses (e.g., denitrification, volatilization, leaching) and increased reliance on external inputs, whereas lower $\delta^{15}\text{N}$ reflects tighter internal N recycling. $\delta^{15}\text{N}$ commonly tracks aridity and nitrogen-cycle openness at regional scales; C/N helps distinguish terrestrial versus algal/microbial organic inputs; and Hg/TOC is widely used to screen for exceptional atmospheric Hg loading from wildfires or volcanism.

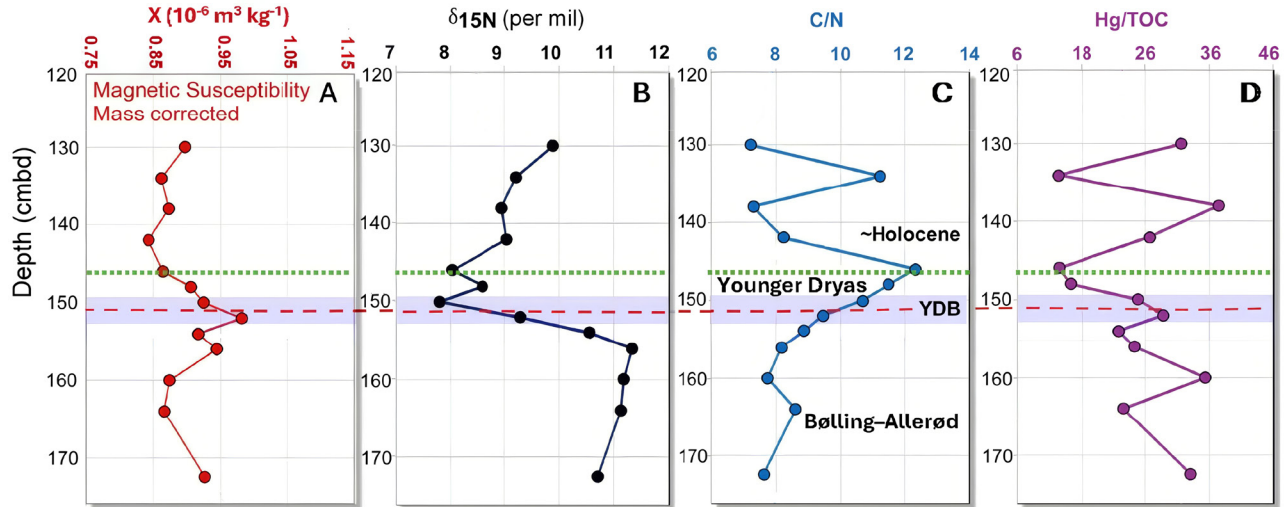


Figure 5: Magnetic susceptibility, $\delta^{15}\text{N}$, C/N, and Hg/TOC across the YDB at Hall's Cave. **(A)** Magnetic Susceptibility (mass-corrected X ($10^{-6} \text{ m}^3 \text{ kg}^{-1}$)): Red points/line; units as labeled. A sharp local maximum occurs precisely at the YDB onset (lavender band), standing out against lower values above and below. **(B)** $\delta^{15}\text{N}$: Black points/line; values decrease through the YDB ($\sim 8\text{‰}$) and rise into the overlying section. **(C)** C/N: Blue points/line; modest variation ($\approx 8\text{--}13$) with no sharp excursion at the boundary but rising to the highest peak across the YD. **(D)** Hg/TOC: Purple points/line; no distinct change coincident with the YDB; higher values occur well above the boundary during the early Holocene. Depth increases downward (cm below datum, cmbd). The dashed red line indicates a major lithologic transition at 151 cmbd, the light blue bar represents the modeled YDB interval, and the green dashed line indicates the $\sim$ Holocene boundary. Data tables are in Supporting Information, Tables S6 and S7 (<https://zenodo.org/uploads/19501481>).

Interpretation

The four proxies together indicate a hydroclimate–ecosystem inflection over the YDB interval with no evidence for an anomalous Hg deposition pulse during the YD onset:

Sediment magnetic properties

A distinct rise in magnetic susceptibility at the YDB, indicates a transient enrichment of ferrimagnetic grains or enhanced delivery of magnetic detritus coincident with boundary deposition (Figure 5A and Supporting Information, Table S7; <https://zenodo.org/uploads/19501481>). This single-point excursion suggests a short-lived depositional or process anomaly rather than a long-term shift in background magnetism and is stratigraphically consistent with other impact-related proxies concentrated at the boundary.

Nitrogen cycling and hydroclimate

The low $\delta^{15}\text{N}$ value at the YDB followed by a rise into the early Holocene is consistent with a shift in nitrogen cycling that may reflect changes in moisture balance, ecological inputs, or diagenetic processes, patterns widely observed where $\delta^{15}\text{N}$ covaried with moisture balance and nitrogen loss trends (Figure 5B and Supporting Information, Table S6; <https://zenodo.org/uploads/19501481>). In central Texas specifically, independent pollen-phytolith records from Hall's Cave and regional syntheses have documented reduced arboreal cover beginning at the YDB and continuing during the YD with increasing warmth/seasonal dryness into the Holocene, aligning with the isotopic trends [13].

The magnitude and direction of this $\delta^{15}\text{N}$ excursion are also consistent with changes in trophic contributions to the cave sediments. Nitrogen isotopes in cave deposits are often interpreted as reflecting inputs from animal-derived waste such as guano or other detritus from cave-dwelling organisms, which typically yield strongly positive $\delta^{15}\text{N}$ values. The sharp drop in $\delta^{15}\text{N}$ at the Younger Dryas Boundary may therefore indicate a reduction in high-trophic level inputs. Alternatively, the excursion could represent a turnover in which lower-trophic omnivores or herbivores became the dominant contributors of nitrogenous material. Either scenario is consistent with ecological disruption and faunal reorganization documented at the YDB. We note that $\delta^{15}\text{N}$ variation in cave settings can also result from diagenesis and local redox; thus, trophic-source and hydroclimatic interpretations should be viewed as complementary rather than exclusive.

Organic-matter source/diagenesis

C/N values remain in a moderate range ($\sim 8\text{--}13$) across the boundary, implying a mixed microbial/algal–terrestrial contribution without a sharp change in source at the YDB; modest increases in the layers above the YDB could reflect greater terrestrial input and/or preferential N loss during early diagenesis under drier conditions (Figure 5C and Supporting Table S6).

The $\delta^{13}\text{C}$ values remain remarkably steady throughout the Hall's Cave sequence, while moderate C/N values ($\sim 8\text{--}13$) indicate that the sedimentary organic matter (SOM)

is unlikely to derive solely from terrestrial vascular plants (Figure 5 and Supporting Table S6). Instead, SOM is more plausibly algal or microbial/animal in origin. If vascular plant material contributed substantially, the $\delta^{13}\text{C}$ values would fall intermediate between C_3 and C_4 plants, suggesting a mixture of both; however, the observed stability of $\delta^{13}\text{C}$ is equally consistent with algal or microbial sources. In either case, the $\delta^{13}\text{C}$ record by itself does not indicate major shifts in vegetation or climate, but it provides essential context for interpreting the nitrogen-isotope excursions.

Hg deposition

The Hg/TOC record reveals no YDB-coincident Hg/TOC enrichment at this site, although the absence of a Hg anomaly does not exclude volcanic or fire-related inputs at that depth. Higher Hg/TOC values occur well above the YDB layer (Figure 5D and Supporting Table S6). Because Hg enrichment anomalies are site- and host-phase-dependent and are most robust when normalized (e.g., to TOC) and tied to demonstrable volcanic or fire inputs, the absence of a boundary peak here does not preclude regionally heterogeneous perturbations.

Implications for the YDB event and YD climate

This proxy assemblage at Hall's Cave appears to primarily reflect climate change: $\delta^{15}\text{N}$ and C/N trends across and above the YDB layer are compatible with the well-known cooling and hydroclimatic reorganization during the YD and a shift toward warmer, seasonally drier Holocene conditions in central Texas.

These data alone neither require nor exclude a cosmic impact contribution; however, they are consistent with a scenario in which abrupt YDB climate forcing, as inferred elsewhere from independent markers such as Pt anomalies, impact microspherules, and extraordinary biomass burning, was followed by sustained YD–early Holocene hydroclimate stress that promoted ecological changes at Hall's Cave.

In short, the bulk geochemical changes suggest hydroclimate-driven restructuring across the YDB with no site-specific Hg/TOC peak. These data do not independently support a specific mechanism; interpretation relies on integration with additional proxies discussed below (e.g., spherules, shocked quartz, nanodiamonds, charcoal).

Multiple impact proxies across the YDB

We conducted analyses to determine if Hall's Cave sediments preserve an anomalous horizon at ~12.8 ka containing high-temperature or cosmic impact-related proxies (Figure 6 and Supporting Information, Table S8; <https://zenodo.org/uploads/19501481>). These include carbon spherules, quantified by microscopic inspection and mass-normalized counts; soot/aciniform carbon, measured as particulate black carbon concentrations; spherules, enumerated by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS); nanodiamonds, quantified using transmission

electron microscopy (TEM) and selected-area electron diffraction, and shocked quartz.

Interpretation

The coeval peak enrichment of carbon spherules, soot, spherules, nanodiamonds, and shocked quartz at ~150 cm depth documents a multiproxy anomaly coincident with the Younger Dryas onset (Figure 6 and Supporting Information, Table S8). The carbon spherules and aciniform soot reflect incomplete biomass combustion, consistent with extensive wildfires documented at numerous YDB sites [17, 18]. Many spherules display glassy or vesicular melt surfaces or morphologies consistent with rapid melting and quenching [36, 45], while the nanodiamonds and shocked quartz represent high-temperature (and in some cases high-pressure) formation processes that are commonly associated with impact events [20, 32]. Together, these proxies are consistent with earlier reports of a widespread YDB impact layer characterized by extreme thermal conditions and continental-scale wildfires [17, 18, 35].

The presence of this anomaly at Hall's Cave, in stratigraphic agreement with Bayesian-modeled age–depth results [29], indicates that central Texas records an anomalous interval that occurs within the broader timeframe of similar anomalies reported at other sites. This multiproxy evidence is consistent with hypotheses proposing an extraterrestrial event ~12,800 years ago, although the data do not independently establish synchronicity or causation.

Spherule morphologies at Hall's Cave

To investigate spherule formation and morphology in Hall's Cave sediments, we conducted high-resolution imaging and elemental analyses using scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS) (Figure 7 and Supporting Information, Table S8). These methods enable the assessment of particle morphology, surface textures, and composition at the micron scale, providing critical evidence for high-temperature processes and potential impact-related origins (see SEM/EDS data in Supporting Information, Figures S1–S15). The spherules were identified in stratigraphic horizons bracketing the Younger Dryas Boundary (YDB) and are representative of morphologies previously reported at other sites across North America and beyond [36, 45]. We also explore other potential formation mechanisms below.

Interpretation

The Hall's Cave spherules exhibit surface morphologies and compositional signatures consistent with high-temperature melting and quenching processes, including dendritic crystallization, vesiculation, micro-impact cratering, and melt-quenched surfaces (Figure 7 and Supporting Information, Figures S1–S15; <https://zenodo.org/uploads/19501481>). Such features closely parallel impact spherules described at multiple YDB sites across four continents [45], as well

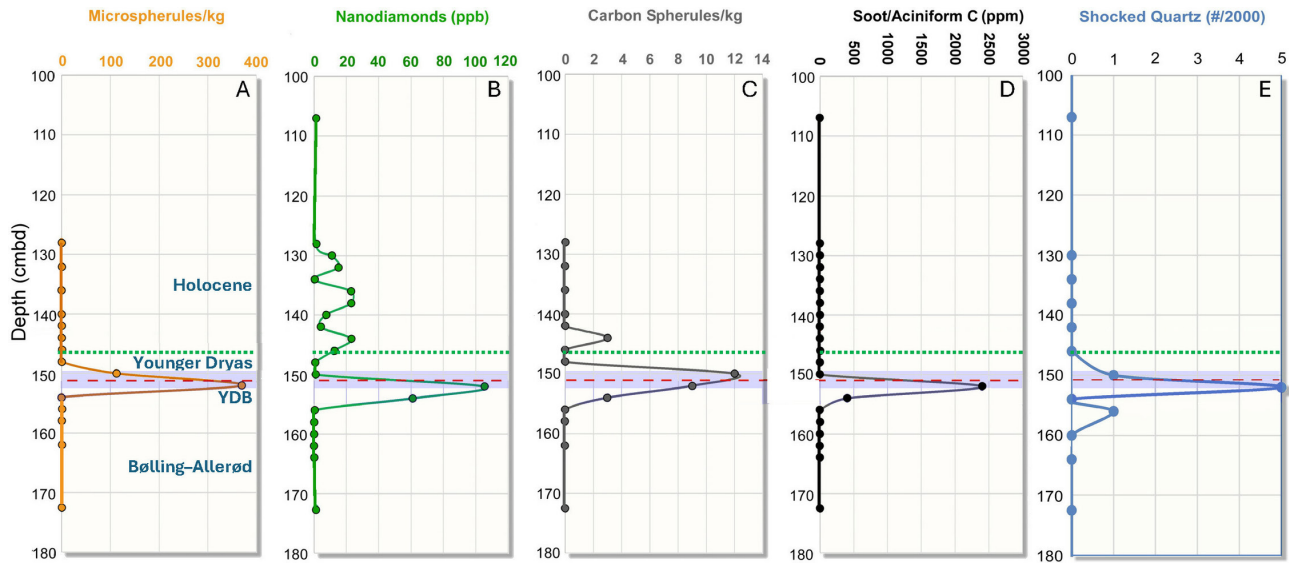


Figure 6: Stratigraphic profiles of high-temperature impact proxies. (A) spherules (per kg sediment), (B) nanodiamonds (ppb), (C) Carbon spherules (per kg sediment), (D) soot/aciniform carbon (ppm), (E) shocked quartz (number per ~2000 grain aliquots), plotted against depth. The dashed red line indicates a major lithologic transition at 151 cmbs, the light blue bar represents the modeled YDB interval, and the green dashed line indicates the ~Holocene boundary. All four proxies exhibit distinct peaks above the background level coincident with the YDB, marked by maximum abundances of carbon spherules, Fe- and silica-rich microspherules, and nanodiamonds, as well as elevated soot concentrations. Data tables are in Supporting Information, Tables S8 and S9 (<https://zenodo.org/uploads/19501481>).

as high-temperature melt products recovered from impact proxies in North America [36]. The coexistence of Fe-rich and aluminosilicate spherules with secondary impacts indicates a dynamic environment of ejecta collision, fragmentation, and rapid melt-resurfacing and solidification, which is difficult to reconcile with slow, low-temperature diagenetic formation alone.

The occurrence of 10–20 μm spherules at Hall's Cave argues against a local volcanic origin as the primary source, given the absence of geologically young volcanic vents on the Edwards Plateau. Furthermore, while distal volcanic aerosols can travel long distances, the presence of Fe-rich and alloyed spherules are not commonly reported from distal volcanic sources, although volcanic and anthropogenic analogs exist [36]. Moreover, Fe-rich spherules occur in the YDB layer at Hall's Cave without a documented coeval tephra layer. The closest volcanic features, such as Pilot Knob near Austin and the Uvalde and Trans-Pecos volcanic fields, formed during the Late Cretaceous to early Cenozoic, tens of millions of years before the Younger Dryas (~12.8 ka) [46, 47]. Volcanic spherules produced in basaltic fountains (Pele's tears) typically fall only within a few kilometers from the vent due to their high density and ballistic trajectories, making long-range dispersal implausible [48].

The presence of YDB age spherules in Hall's Cave aligns with broader evidence for a widespread YDB spherule layer at ~12.8 ka, containing nanodiamonds, platinum anomalies, and extraordinary biomass burning proxies [17, 18, 32]. Together, these findings support the interpretation that Hall's

Cave preserves impact-derived materials associated with the onset of the YD, coincident with abrupt regional aridification and ecosystem disruption [33, 35].

Shocked quartz as a diagnostic indicator of high-energy impact processes at the YDB at Hall's Cave

Shocked quartz grains were identified in the YDB layer at Hall's Cave, with their highest abundance at 152 cm depth (Figure 8 and Supporting Information, Table S8; <https://zenodo.org/uploads/19501481>). Analytical techniques included electron backscatter diffraction (EBSD) using the Pattern Region of Interest Analysis System (PRIAS) from EDAX, Inc., as well as image quality (IQ) and inverse pole figure (IPF) mapping to reveal and document crystallographic damage. Transmission electron microscopy (TEM) was used to resolve nanoscale planar features. These combined methods enable the discrimination of high-temperature vesiculation from shock-related planar deformation features (PDFs), providing evidence consistent with shock deformation features typically associated with impact processes.

Interpretation

An average of ~2000 quartz grains were thin-sectioned and examined for shocked quartz in each of 15 intervals from 15 to 172.5 cm. Shocked grains were only observed in the following 3 intervals: 150 cm (1 grain), 152 cm (5 grains), and 156 cm (1 grain) (see Figure 6E and Supporting Table S8). The highest abundance, at 152 cm, coincides with peaks

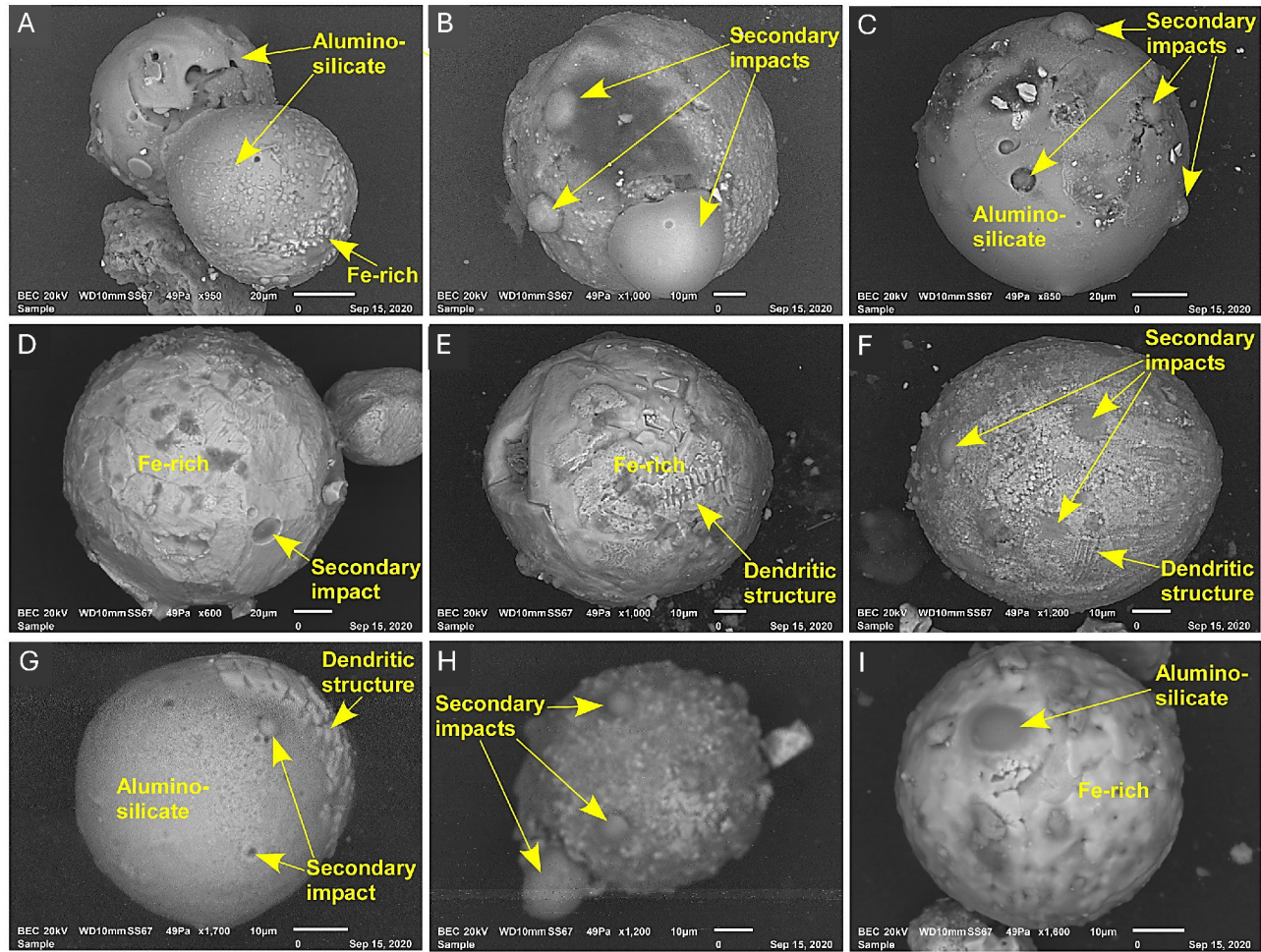


Figure 7: Scanning electron microscope (SEM) images of spherules from Hall's Cave. Panels A–I show a range of spherule morphologies observed at the YDB interval. Textural features include: (A–C) aluminosilicate spherules, often displaying smooth to vesicular surfaces; (D–F) dendritic Fe-rich spherules, indicative of rapid quenching; (A, F–H) mixed aluminosilicate and Fe-rich spherules; (A–I) abundant secondary impacts suggesting high-energy collisions among molten droplets. Scale bars are 10–20 μm . Collectively, these morphologies are consistent with rapid melting, ejection, and cooling during high-temperature events.

in other impact proxies at Hall's Cave, indicating a concentrated depositional horizon.

The EBSD maps (C–F) reveal strong crystallographic disruption, including vesiculated domains and extensive PDFs. TEM imaging (A–B) confirms that the fine, closely spaced lamellae are diagnostic of shock metamorphism rather than tectonic deformation, which produces wider and less regularly spaced features [49]. The co-occurrence of vesiculation and PDFs indicates exposure to both extreme pressures and high temperatures, conditions consistent with a cosmic airburst/impact. Importantly, these lamellae are restricted to crystallographically controlled orientations, including (0001), and $\{10\bar{1}1\}$. The $\{10\bar{1}1\}$ rhombohedral planes represent one of the most frequently observed PDF orientations in experimentally shocked quartz, while (0001) basal PDFs are far rarer and form only under unusually high shock pressures. The presence of both orientations in the same grain is therefore a strong

indicator of hypervelocity impact [21]. By contrast, tectonic deformation lamellae are typically irregular, widely spaced, lack such strict crystallographic control, and do not contain melted silica [21], arguing against a tectonic origin for the Hall's Cave features. Volcanism is not known to be a source of shocked minerals [49].

Shocked quartz is widely regarded as one of the most reliable diagnostic markers of impact events because PDFs form only under the extreme pressure conditions generated during hypervelocity impacts and nuclear detonations, and not under endogenic geologic processes [49]. Their occurrence at Hall's Cave therefore provides direct mineralogical evidence consistent with shock metamorphism in the YDB layer. Although reworking of shocked quartz from older, non-YDB impact deposits (e.g., the K–Pg event) cannot be entirely ruled out, the confinement of shocked quartz to the YDB horizon, with no occurrences above or below, is difficult to reconcile with a reworked origin.

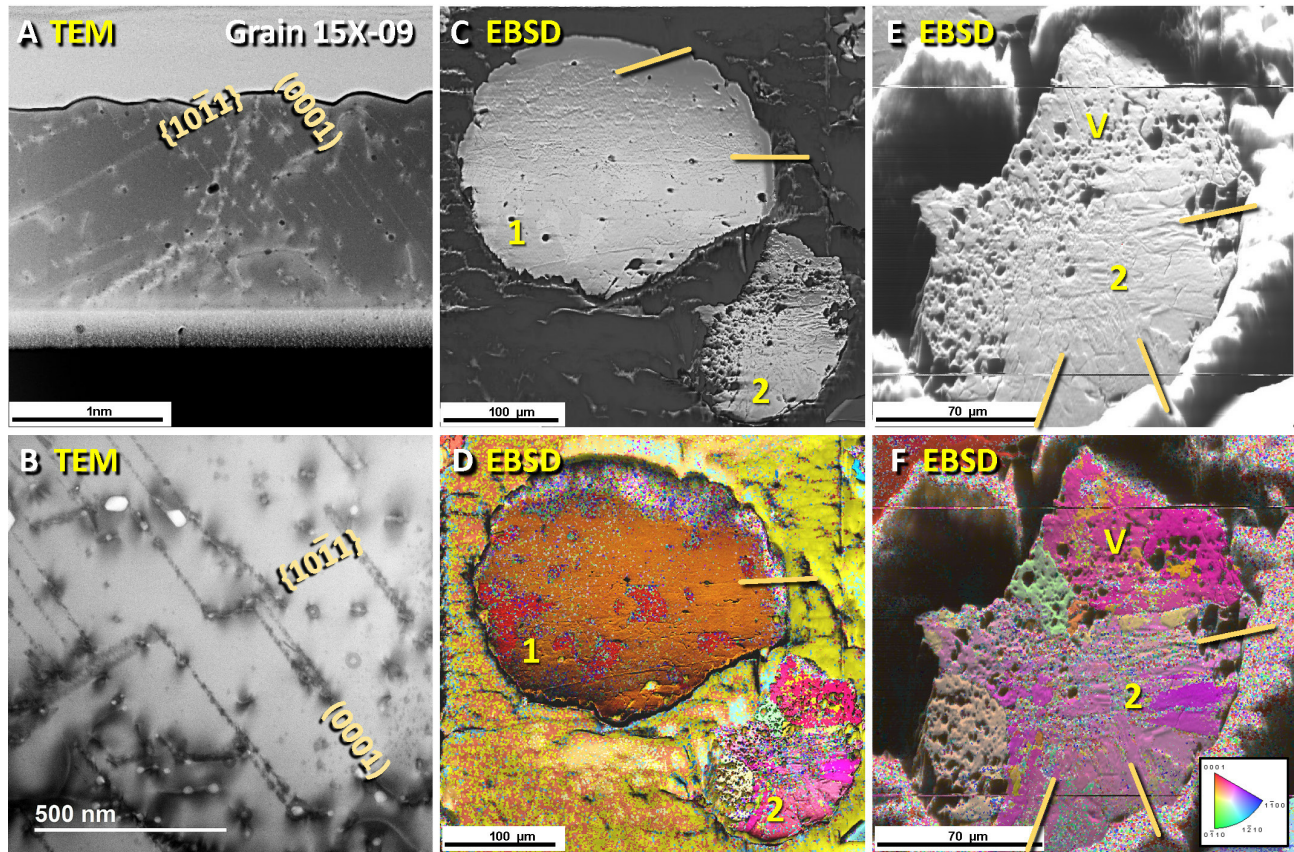


Figure 8: Shocked quartz grain from 152 cm depth in Hall's Cave. (A) TEM image of representative grain 15x-09 showing closely spaced parallel lamellae interpreted as PDFs. Lamellae spacing is $<2\ \mu\text{m}$, consistent with shock deformation. (B) TEM image showing fine lines indicating PDFs at the nanoscale. (C) EBSD image acquired using the PRIAS technique, showing two adjacent quartz grains (1 and 2). (D) IQ and IPF map of the same grains, with contrasting colors reflecting lattice disorder. (E) EBSD PRIAS image of grain 2. (F) Corresponding IPF map showing widespread color variation and vesiculated quartz (V) across more than half the grain, consistent with exposure to extreme temperatures. The remainder of the grain exhibits multiple sets of planar deformation features (PDFs). The inset indicates crystallographic orientation. Scale bars: C–D = $100\ \mu\text{m}$; E–F = $70\ \mu\text{m}$; A = $1\ \text{nm}$; B = $500\ \text{nm}$. The observed PDFs occur along $\{10\bar{1}1\}$ and (0001) orientations, both diagnostic of shock metamorphism. The distribution of shocked quartz grains are shown in Figure 6E and Supporting Information, Table S8 (<https://zenodo.org/uploads/19501481>).

Comparable discoveries of shocked quartz have been reported in YDB-age sediments from multiple localities, including Syria [50]; Argentina [51]; South Carolina, New Jersey, Maryland, USA [52]; and California, Arizona, New Mexico [29]. In each case, shocked quartz is stratigraphically confined to the YDB layer, consistent with its formation during a singular, high-energy event. The occurrence of PDFs at Hall's Cave thus reinforces the broader, geographically widespread evidence consistent with a cosmic impact or airburst that produced shocked minerals and other high-temperature proxies at $\sim 12.8\ \text{ka}$.

The association of shocked quartz with contemporaneous peaks in microspherules, soot, and nanodiamonds across YDB sites suggests that the Hall's Cave grains are part of a larger continental-scale depositional event [32, 45]. Their stratigraphic confinement to the boundary interval supports the interpretation that an extraterrestrial impact contributed to abrupt Younger Dryas cooling through atmospheric

perturbation, including the injection of dust, aerosols, and carbonaceous material [17, 18, 53].

Carbonaceous spherules and soot

Microscopic and nanoscopic carbonaceous materials were also identified from the YDB interval at Hall's Cave using optical microscopy for carbon spherules, transmission electron microscopy (TEM) for carbon nano-spherules, and scanning electron microscopy (SEM) for aciniform carbon (soot) (Figure 9 and Supporting Table S6). Their distinct morphologies are diagnostic of high-temperature formation processes.

Interpretation

The co-occurrence of carbon spherules, carbon nano-spherules, and aciniform carbon (soot) within the Hall's Cave YDB layer supports evidence for widespread high-temperature processes contemporaneous with the onset of the YD.

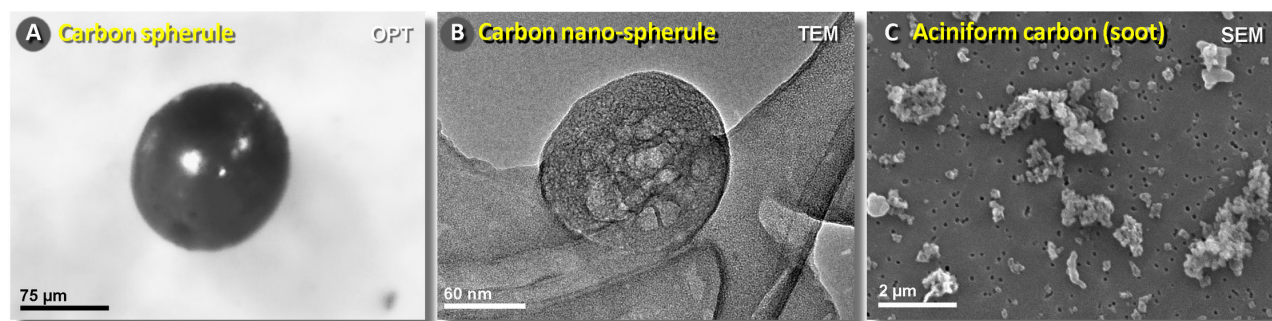


Figure 9: Carbonaceous particles from the Younger Dryas Boundary at Hall's Cave. (A) Optical micrograph of a carbon spherule displaying a smooth, glassy exterior consistent with melting and quenching. (B) TEM image of a carbon nano-spherule exhibiting concentric internal structure. (C) SEM image of aciniform carbon (soot) clusters showing aggregated spheroids typical of high-temperature incomplete combustion. Scale bars: A = 75 µm; B = 60 nm; C = 2 µm. See Supporting Table S8 (<https://zenodo.org/uploads/19501481>).

Carbon spherules and nano-spherules exhibit morphologies consistent with rapid melting and quenching, indicative of formation in intense heat, while the aggregated soot particles suggest incomplete combustion at high temperatures. These features are consistent with biomass burning and elevated thermal conditions, which may be associated with a range of high-energy environmental processes, as has been documented at other YDB sites [17, 18, 32, 36]. While large-scale wildfires can explain soot and carbon spherules, they do not readily explain the co-occurrence of high-temperature metallic nanoparticles, PGEs, and Ni–Fe alloys, which require far higher formation temperatures than terrestrial combustion processes can achieve. At Hall's Cave, soot concentrations peak at 2400 ppm at a depth of 152 cm, with carbon spherule abundances (12/kg) peaking at 150 cm, thus representing a distinct increase in carbonaceous proxies in the YDB layer (see Figure 6C).

Such carbonaceous proxies have been widely reported in the YDB across North America and beyond, where they form part of a consistent suite of impact-related markers including microspherules, nanodiamonds, and elevated platinum-group elements [17–19, 45, 51, 54, 55]. Therefore, their presence at Hall's Cave strengthens the case for synchronous continent-wide wildfire activity (e.g., conflagration) triggered by a cosmic airburst or impact event at ~12.8 ka. These high-energy events are hypothesized to have contributed to the abrupt climatic cooling at the onset of the Younger Dryas through injection of soot and aerosols into the atmosphere, thereby reducing solar insolation [32, 35].

Nanodiamonds in the YDB

We used a range of techniques to identify, classify, and count carbon nanoparticles in the sequence. These include electron microscopy (TEM) with energy-dispersive X-ray spectroscopy (EDS), selected-area electron diffraction (SAD), high-resolution TEM (HRTEM), electron energy-loss spectroscopy (EELS), and dynamic conical dark-field imaging (Figures 10–12 and Supporting S8 and S9). We counted

particles in each image by structural class, cubic/*n*-diamond, lonsdaleite-like, and *i*-carbon, and plotted these counts by depth. Nanodiamond abundance peaks sharply in the YDB layer (HC364, 153–151 cm; midpoint 152 cm), with few to none above and below (see Figure 6B). TEM-EDS indicates compositions of >98 wt% C and <2 wt% O for all particles analyzed; SAD ring spacings match published polytypes; and EELS C–K edges confirm dominantly sp³-bonded carbon consistent with nanodiamond.

Interpretation

The stratigraphic confinement of multiple nanodiamond polytypes (cubic/*n*-diamond, lonsdaleite-like, and *i*-carbon) to the YDB layer at Hall's Cave, with a sharp peak at 153–151 cm (HC364), is consistent with a discrete depositional event rather than simply background inputs. EELS C–K edge fine structure (dominant σ^* at ~292 eV with minimal π^* pre-edge) and SAD/HRTEM lattice spacings together support sp³-rich nanodiamond domains rather than graphitic soot aggregates. At the same time, carbon-only EDS argues against mineral contamination, including by copper, whose d-spacings are similar to *n*-diamond. Similar nanodiamond enrichments at YDB horizons have been documented at multiple sites [20, 32, 54], and the Hall's Cave occurrence is consistent with those earlier reports.

The coexistence of polytypes, including lonsdaleite-like and *i*-carbon, is consistent with formation under short-lived, high-temperature conditions, potentially involving elevated pressures and rapid quenching, processes consistent with cosmic airburst/impact scenarios proposed for the YDB [36, 45]. Independent geochemical markers at YDB, such as the platinum abundance in Greenland ice [53] and synchronous, continent-scale biomass-burning proxies [17, 18], provide contextual support for an energetic event capable of dispersing carbon nanophases and altering climate.

In the aftermath of an impact-induced wildfire, the transient environment may include high local temperatures,

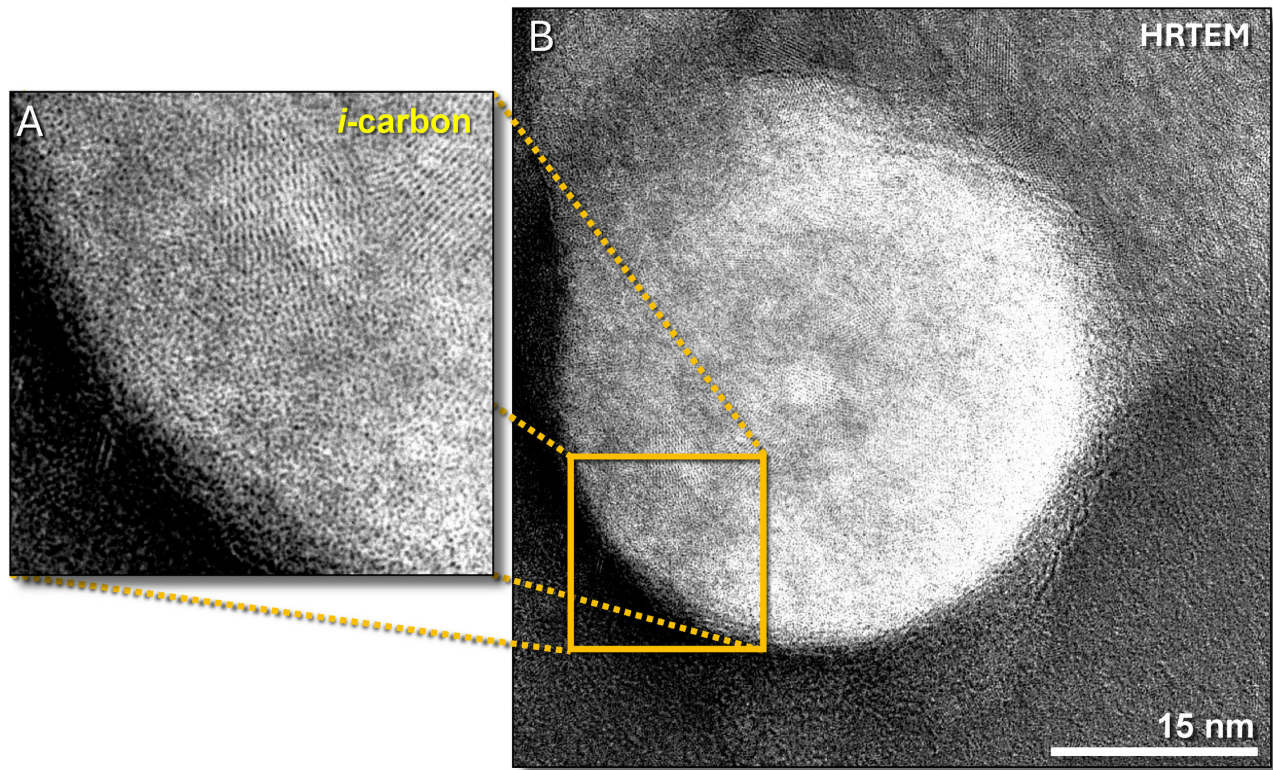


Figure 10: Polycrystalline *i*-carbon sphere composed of nanodiamond-bearing domains. (A-B) HRTEM image and enlarged inset of a rounded carbon nanoparticle with polycrystalline (mosaic) nanodomains and locally diamond-like lattice spacings. TEM-EDS confirms carbon-only composition for this particle. Scale bars as indicated.

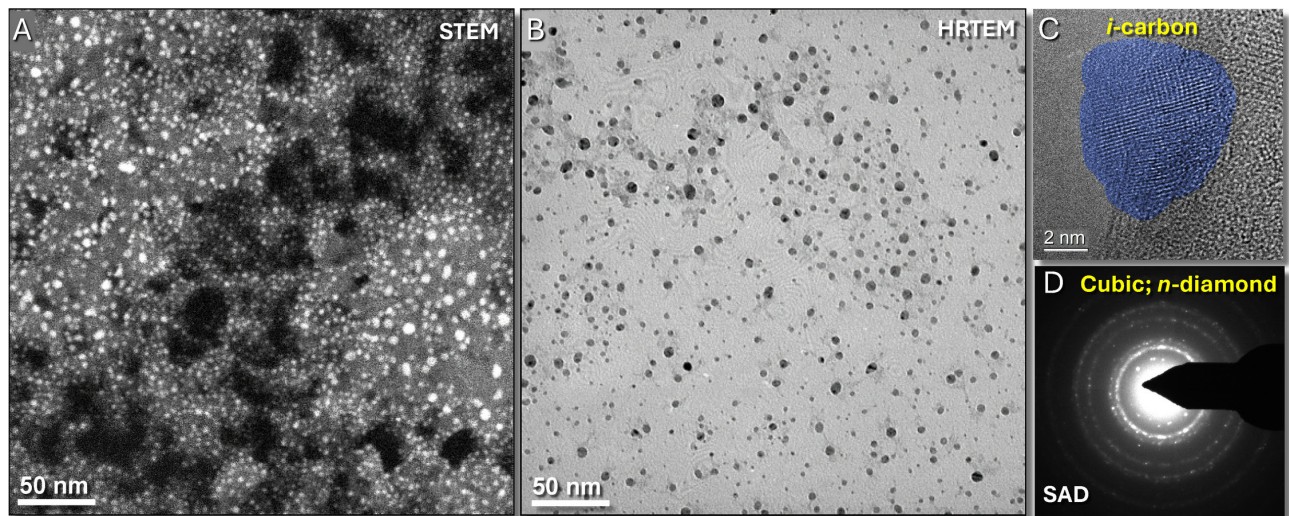


Figure 11: STEM, HRTEM, and SAD evidence for nanodiamonds at the YDB. (A) Scanning transmission electron microscopy (STEM) overview from the YDB layer showing abundant, discrete carbon nanoparticles. (B) High-resolution TEM (HRTEM) field with lattice fringes consistent with diamond-related structures. (C) HRTEM image of *i*-carbon. (D) Selected-area electron diffraction (SAD) rings indexing to cubic/*n*-diamond spacings, confirming polycrystalline order. Analytical confirmation by TEM-EDS shows carbon-only spectra (≥ 98 wt% C, ≤ 2 wt% O) for particles in all panels. Scale bars as indicated.

vaporized or radical carbon species, and steep cooling gradients. Under such circumstances, one might imagine a process roughly analogous to chemical vapor deposition

(CVD) in which carbon vapor or radicals deposit onto pre-existing carbon nuclei (e.g., char, soot, or graphite fragments) and reorganize into more ordered sp^3 (diamond-like)

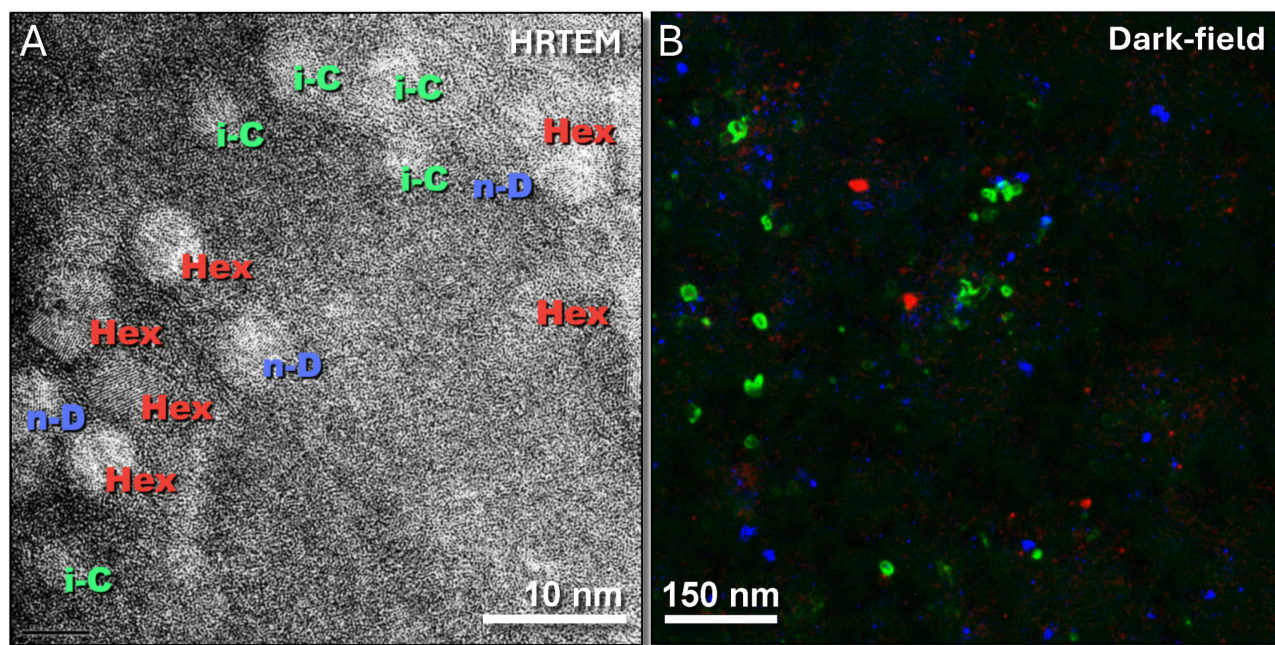


Figure 12: HRTEM and dynamic conical dark-field (DCDF) imaging showing different diamond-related polytypes. **(A)** HRTEM micrographs illustrating domains with distinct lattice spacings diagnostic of diamond-related phases, as labeled. **(B)** DCDF (RGB composite) of the same field, highlighting contrasting scattering responses that enable *in situ* polytype discrimination (e.g., *n*-diamond, lonsdaleite-like, *i*-carbon). TEM-EDS acquired from the imaged particles records carbon-only compositions with no other detectable elements. Scale bars as indicated.

structures. If the predominant diamond-like forms in a given sample were “*n*-diamond” or “*i*-carbon,” it is conceivable (though unproven) that such CVD-type deposition might help explain their presence. However, to date there is no direct experimental or natural-system evidence demonstrating large-scale diamond growth by vapor deposition in high-temperature wildfire or impact settings. Laboratory CVD methods produce diamond under carefully controlled conditions of pressure, gas composition, and plasma environment (e.g., Butler & Sumant [56]; Nebel et al. [57]), and other work has shown transformation pathways from graphitic precursors under plasma or ion bombardment (e.g., Robertson [58]).

At the same time, we acknowledge an ongoing debate over nanodiamonds as impact proxies, especially as related to the YDB impact theory. Critics have questioned identification protocols and preservation pathways [59, 60]. Alternative explanations considered here include onion-like carbon (carbon onions/diaphite), beam-induced graphitization of diamond, or detrital/pyrolytic carbon aggregates that mimic some SAD/EELS characteristics. In the present material, the concurrence of (i) sp^3 -dominant EELS, (ii) diagnostic d-spacings for diamond-related phases, (iii) dynamic conical dark-field polytype discrimination, (iv) carbon-only EDS, and (v) a narrow stratigraphic peak argues against these alternatives, though we view the lonsdaleite assignment as “lonsdaleite-like,” pending further diffraction/EELS mapping at higher spatial resolution. Overall, the Hall’s Cave nanodiamond concentration provides supporting evidence

for a high-energy process at the YDB consistent with the proposed YD impact event.

Depth-resolved nanoparticle phase assemblages across the YDB

The Hall’s Cave sequence provides a high-resolution record of nanoparticle assemblages that capture the YDB spherule layer and its aftermath, as determined by single-particle inductively coupled plasma time-of-flight mass spectrometry (SP-ICP-TOF-MS). Most non-carbonate particles in the cave sediments are likely allochthonous, meaning they were transported into the cave by runoff or wind rather than forming *in situ*, and therefore may reflect changes in external depositional environments. By tracking shifts in phase assemblages across successive horizons, we distinguish baseline Fe-Al detrital input from anomalous fallout and dust events. The resulting stratigraphy documents a two-step sequence, a condensed YDB event layer, followed immediately by an early YD dust pulse, superimposed upon background of Fe-Al-dominated deposition (Figure 13 and Supporting Information, Table S10).

Interpretation

The five stratigraphic units at Hall’s Cave, as described below, define a coherent narrative of environmental change spanning the onset of the Younger Dryas. Such Ni–Fe–Cr–Ir enrichments are not commonly reported in volcanic or authigenic contexts, and anthropogenic input is unlikely given the stratigraphic context and age and isolation. Moreover,

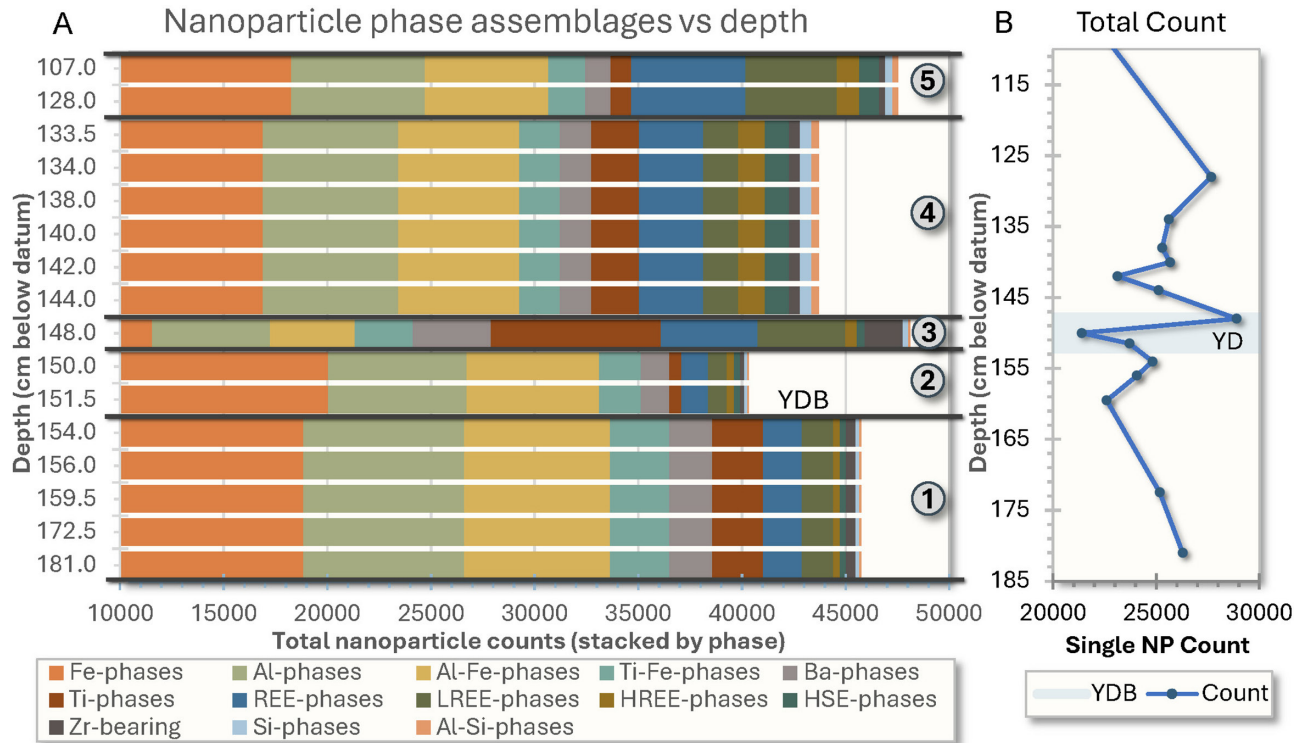


Figure 13: Depth-resolved nanoparticle phase assemblages across the YDB. (A) Stacked bars show the per-sample counts of single nanoparticles, measured by SP-ICP-TOF-MS, partitioned into operational phases: Fe-, Al-, Al-Fe-, Ti-, Ti-Fe-, Ba-, rare earth (REE-), light REE (LREE-), heavy REE (HREE-), highly siderophile elements (HSE-), Zr-bearing, Si-, and Al-Si phases. The YDB layer (~151.5–150 cm; Horizon 2) is marked by a condensed, Fe-Al-dominated dust minimum, while the overlying 148-cm layer displays the most abundant and compositionally diverse dust in the profile, enriched in Ti-, Zr-, and Ba-phases with a steep LREE/HREE ratio. Depths are given in cm below datum. Because light elements such as Ca, Mg, Na, K, C, N, and O were not measured using SP-ICP-TOF-MS, the mineral phases identified represent potential carriers of the detected elements but should not be considered definitive identifications. (B) Total single-particle counts measured by SP-ICP-TOF-MS plotted by depth. A sharp peak at ~148 cm (Horizon 3), just above the YDB event bed, marks a brief but intense increase in nanoparticle abundance. This short-lived pulse likely reflects enhanced atmospheric dust loading during early Younger Dryas aridification, followed by a rapid return to background levels. See SP-ICP-TOF-MS data in Supporting Information, Table S10 (<https://zenodo.org/uploads/19501481>). The numbers within the circles in panel A indicate the different stratigraphic horizons.

volcanic fallout commonly yields diffuse PGE enrichments with radiogenic Os signatures, and diagenetic or sedimentary processes do not produce co-concentrated PGEs, Fe–Ni alloys, or high-temperature spherules. These distinctions are consistent with an extraterrestrial origin over volcanic or post-depositional alternatives.

Pre-YDB (Horizon 1, 181–154 cm)

This interval is dominated by Fe–Al assemblages with relatively low contributions from Ti, Zr, Ba, and highly siderophile element (HSE) phases, suggesting wetter conditions, stable soils, and consistent hydrologic input. These conditions align with late Quaternary evidence for episodic moisture and thicker soils on the Edwards Plateau during the end of the Glacial and Bølling–Allerød (BA) periods [1, 8].

YDB event bed (Horizon 2, 151.5–150 cm)

A condensed fine-fallout layer coincident with the YDB exhibits a decrease in sediment accumulation, Fe–Al

dominance, and scarcity of Ti-, Zr, Ba-, and HSE phases and the presence of high-temperature proxies including nanodiamonds, shocked quartz, glassy spherules, and aciniform carbon. Overall, this association is most consistent with scenarios involving a high-energy depositional event at the YDB, including but not limited to an extraterrestrial impact event that is marked by widespread platinum anomalies and other cosmic impact markers in sediments across North America and beyond [32, 36, 45, 61, 62].

Early Younger Dryas dust pulse (Horizon 3, 148 cm)

Immediately above YDB event bed 2, nanoparticle counts increased sharply, dominated by Ti-, Zr-, and Ba-bearing phases and accompanied by an elevated LREE/HREE ratio (Figure 13). This compositional shift is consistent with an increased influx of heavy-mineral dust sourced from felsic crustal materials, most plausibly reflecting enhanced aeolian entrainment and transport rather than volcanism [4, 8, 63]. The abrupt rise in total nanoparticle abundance, together

with the predominance of Ti-rich and Zr-bearing phases, may reflect changes in sediment availability, transport processes, or atmospheric conditions on the Edwards Plateau during the earliest Younger Dryas. Similar evidence for increased dust mobilization and/or landscape instability during late-glacial climatic transitions has been reported in parts of the southern Great Plains and adjacent regions [64]. However, hydroclimate conditions during the Younger Dryas were spatially heterogeneous across midcontinental North America, and multiple records indicate locally higher effective moisture and relative humidity during this interval [65]. For example, the Cupola Pond record suggests warming in the Ozark region of southern Missouri during the Younger Dryas while areas farther north and east cooled [66]. Within Hall's Cave, the 148-cm post-YDB interval (Horizon 3) is also marked by a short-lived decline in Fe-rich nanoparticles coincident with a pronounced enrichment in Ti-bearing phases (Figure 13A). This abrupt phase shift immediately above the impact-proxy layer is consistent with transient high-temperature fractionation and carrier-phase sorting, in which highly siderophile elements preferentially partition into metallic and sulfide nanoparticles that settle rapidly following cooling and condensation. The stratigraphic position of this excursion aligns with other high-temperature indicators at the YDB, including nanodiamonds, Fe–Si spherules, aciniform carbon, and shocked quartz collectively indicating a high-temperature event is consistent with impact-related processes.

Recovery (Horizon 4 and Horizon 5, 144–133.5 cm)

Subsequent horizons show a return to Fe–Al dominance, higher accumulation rates, and reduced heavy-mineral input, reflecting partial moisture recovery, stabilized soils, and attenuated dust transport. Small excursions in Ti- and Zr-bearing phases indicate brief pulses of heavy-mineral dust but do not represent the overall recovery return to background sedimentary processes at Hall's Cave.

Notably, while some have suggested a volcanic source to account for YDB anomalies [5], the Hall's Cave record lacks any discrete tephra bed. The 148-cm horizon (Figure 13) is best interpreted as a felsic dust episode, although distal and minor volcanic aerosols may have mixed with continental dust elsewhere. Thus, volcanic input appears minimal, although additional geochemical and isotopic analyses may help resolve the degree of any volcanic contribution.

Synthesis

The nanoparticle assemblages at Hall's Cave are consistent with a two-step YDB signal: (i) a condensed impact fallout bed coinciding with extraterrestrial impact proxies, followed by (ii) a local short-lived dust pulse reflecting early YD aridity represented by a nanoparticle phase shift consistent with increasing dust abundance (Fig. 13; Horizon 3). These findings reinforce the interpretation that the YDB event may have included an extraterrestrial influx with cascading ecological consequences, while also capturing a regional increase in

aridity during the YD. Although volcanic or lightning-generated processes cannot be entirely excluded, the absence of associated Pt–Os isotopic anomalies at this site does not strongly support volcanic alternatives, although such signals can be spatially variable.

Possible extraterrestrial nanoparticles concentrated at the YDB

To further test whether the Younger Dryas Boundary (YDB) contains extraterrestrial (ET) material, we used SP-ICP-TOF-MS to identify and count individual nanoparticles that included two elements of interest (Ni–Fe, Fe–Si, Co–Fe, Al–Ir, and Ti–Ir) (Figure 14 and Supporting Information, Table S10; <https://zenodo.org/uploads/19501481>). Multi-element nanoparticle identification enables recognition of alloyed phases potentially consistent with meteoritic input. We focused on combinations of platinum-group elements (PGEs) with lithophile or siderophile metals that rarely co-occur in terrestrial sediments but are common in meteoritic alloys and high-temperature condensates. ET-like nanoparticle abundances peak within the YDB layer at Hall's Cave, consistent with an extraterrestrial influx at the onset of YD climate change. The phase assemblage data indicates an abrupt and anomalous shift in sediment composition at ~12.8 ka.

Several non-impact mechanisms could potentially contribute to anomalous nanoparticles at a single horizon, including (1) sediment reworking/stratigraphic mixing, (2) shifts in local detrital sediment source, (3) diagenetic/redox-driven metal concentration, (4) volcanic input or cryptotephra, (5) wildfire-only deposition, (6) anthropogenic or laboratory contamination, and (7) background micrometeorite (cosmic dust) rain. However, these alternatives are disfavored because the Hall's Cave peak is stratigraphically discrete (not smeared as would be expected from mixing), is accompanied by PGE enrichment and unradiogenic Os (not readily produced by ordinary detrital or diagenetic processes), shows no supporting volcanic signature (e.g., no Hg anomaly), and includes multi-element nanoparticle assemblages involving Ir-bearing combinations that are difficult to generate through low-temperature terrestrial processes or wildfire alone. These constraints make simple single-process terrestrial explanations less consistent with the full proxy suite observed at the YDB horizon. Given the presence of multiple independent impact proxies, no known terrestrial process readily accounts for the full suite of observations.

Interpretation

We identified multi-element nanoparticles, Ni–Fe, Fe–Si, Co–Fe, Al–Ir, and Ti–Ir, that display sharp increases beginning in the YDB layer (Figure 14). These particles were not detected in the pre YDB horizon. Ni–Fe alloys represent the canonical meteoritic signature (e.g., kamacite, taenite, tetraetaenite). Their presence represents one of the more compelling indicators potentially consistent with extraterrestrial

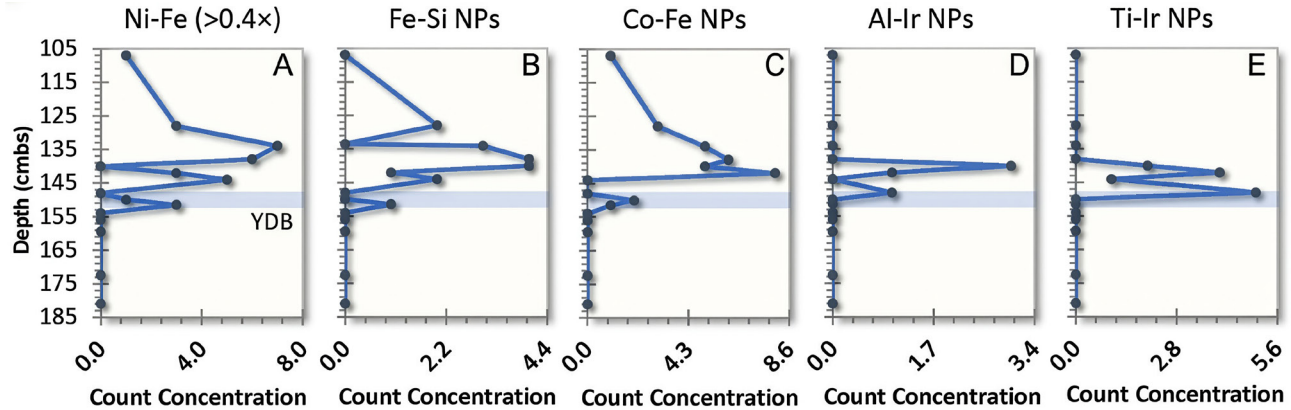


Figure 14: Multi-elemental nanoparticles enriched in platinum-group elements (PGEs) and siderophile alloys within and above the YDB. (A–E) SP-ICP-TOF-MS was used to identify and count multi-element nanoparticles (count concentration [per gram]) that contained in each case, both of the investigated elements: Ni-Fe, Fe-Si, Co-Fe, Al-Ir, and Ti-Ir. Some multi-element nanoparticles contain/consist of unusual combinations of siderophile and lithophile elements. These elemental assemblages are consistent with compositions observed in meteoritic alloys and high-temperature condensation products. Concentrations peak between ~151.5 and 138 cm depth. They span the interval from the YDB layer ($\sim 12,780 \pm 170$ cal BP) through the Younger Dryas and into the earliest Holocene. Bayesian modeling of the radiocarbon series using OxCal v4.4 with the IntCal20 calibration confirms that the event layer is statistically indistinguishable from the Greenland GISP2 Pt anomaly dated to 12,836–12,815 cal BP (Petaev et al. [53]). For consistency with our age model, the YD termination is $\sim 11,600$ cal BP. The shaded blue band marks the YD interval (~ 152 – 147 cm), including the YDB layer at ~ 151 cm. See SP-ICP-TOF-MS data in Supporting Information, Table S10 (<https://zenodo.org/uploads/19501481>).

input (Figure 14A). Although further mineralogical imaging would help confirm alloy structures, their stratigraphic confinement and element pairing strongly support an ET source.

Fe–Si nanoparticles are consistent with meteoritic silicides such as hapatite (Fe_2Si), suessite (Fe_3Si), and naquite (FeSi), which are uncommon in ordinary sediments but occur in meteorites and impact products (Figure 14B). These identifications are based on element associations and should be regarded as compositional analogs pending direct crystallographic verification.

Co–Fe alloys strengthen the case for meteoritic metal since cobalt is significantly enriched in meteoritic Fe relative to terrestrial iron phases (Figure 14C). Reported elemental ratios (0.1–0.33) overlap with those for wairauite and Fe–Ni–Co alloys found in meteorites.

Al–Ir nanoparticles represent an anomalous association of lithophile Al with highly siderophile Ir (Figure 14D). These elements are much more highly enriched in ET material where PGEs condense onto aluminosilicate substrates in high-temperature plumes [67, 68].

Ti–Ir nanoparticles likewise indicate condensation of PGE-enriched vapor onto Ti-oxide nuclei, consistent with vaporized meteoritic material (Figure 14E). These are difficult to generate through ordinary terrestrial fractionation [69]. Because Al–Ir and Ti–Ir combinations are exceptionally rare, additional analyses (e.g., TEM–EDS) would help verify these as true condensate phases.

Nickel–iron (Ni–Fe) alloys are among the most widely recognized mineralogical indicators of extraterrestrial material. Metallic Ni–Fe is abundant in iron meteorites, ordinary

chondrites, and micrometeorites, where it occurs as phases such as kamacite, taenite, and tetrataenite [70]. Its presence in terrestrial sediments is unusual, as native metallic iron is thermodynamically unstable under oxidizing surface conditions. Significantly, Ni–Fe alloys have been documented at several confirmed impact structures, including the Chicxulub crater at the K/T boundary (63 Ma), where meteoritic Ni–Fe fragments were recovered [71], and the Ries crater (~ 15 Ma), where Fe–Ni metal occurs in impact melt breccias [72]. Ni–Fe spherules and grains have also been reported at multiple YDB sites, in association with nanodiamonds, meltglass, and platinum-group element anomalies [36, 45]. Because of its rarity in ordinary sediments and its abundance in meteoritic material, the detection of Ni–Fe at Hall’s Cave provides additional strong evidence for an extraterrestrial contribution.

Iron silicides (Fe–Si phases) are exceptionally rare in terrestrial sediments but are increasingly recognized at impact sites and in meteoritic materials. At Blackville, South Carolina, trigonal Fe_2Si was recently discovered in a buried YDB-aged glass layer, associated with suessite and other high-temperature phases [73]. The occurrence of Fe–Si at Blackville is consistent with earlier reports of Fe–Si-rich spherules, platinum, iridium, nanodiamonds, and meltglass at multiple YDB sites, which were interpreted as products of hypervelocity shock processes [36]. A systematic review of natural iron silicides documented their presence in meteorites, lunar samples, and confirmed or proposed terrestrial impact structures, underscoring their association with extreme reduction environments [74]. More recently,

Ernstson et al. [75] reported a prominent Fe–Si strewn field in the Chiemgau impact region of southeast Germany, where thousands of Fe–Si particles, including gupeite, xifengite, hapkeite, naquite, and linzhite, were recovered and shown to carry microstructural evidence of shock metamorphism. Comparable Fe–Si phases occur in multiple extraterrestrial contexts, including Fe–Si in ureilites [76], hapkeite in lunar regolith breccias [77], and Fe–Si silicides captured from comet 81P/Wild 2 in Stardust aerogel tracks [78].

Collectively, these studies reinforce that Fe–Si phases are unlikely to form during ordinary sediment deposition but are instead characteristic of high-temperature, high-pressure impact environments [36, 73, 75, 79]. In particular, Fe–Si phases form under extreme reducing and high-temperature conditions typical of impacts, fulgurites, or unusual mantle-derived melts [76–78], which provides further support for interpreting their occurrence at Hall’s Cave as evidence of extraordinary depositional processes at the onset of the Younger Dryas. Fulgurite formation from lightning remains a possibility but is unlikely given the stratigraphic confinement of shocked quartz and melt-glass to the YDB layer.

The increasing abundance of these elemental phases beginning in the YDB layer, and their similarity to known meteoritic phases argue against volcanic or diagenetic origins and support an extraterrestrial input at the YD onset [36, 73, 75, 79]. The most parsimonious explanation is atmospheric fallout from one or more extraterrestrial impacts or airbursts at ~12,780 cal BP, consistent with PGE anomalies and Ir-rich horizons documented at other YD impact sites [67, 68]. Seeding of the surrounding landscape at Hall’s Cave with ET nanoparticles followed by episodic slopewash and aeolian sedimentation of sediments into the cave would inherently produce a lag in multi-elemental nanoparticles seen in the data (Figure 14). Similar delayed fallout of nanoparticles beginning in YDB dated sediments and continuing post YDB have been documented in ocean cores from Baffin Bay [80]. These results add to evidence linking the YDB layer to a cosmic event that contributed to abrupt cooling and ecological disruption during the YD [32, 35].

Depth profiles of key elemental mass ratios within multi-element nanoparticles across the YDB

To evaluate whether geochemical ratios are indicative of an extraterrestrial (ET) influx at Hall’s Cave, we analyzed individual nanoparticles using single-particle inductively coupled plasma time-of-flight mass spectrometry (SP-ICP-TOF-MS) (see Supporting Information, Table S10). For each particle, we computed mass-concentration ratios among platinum-group elements (PGEs; a subset of highly siderophile elements) and key transition metals, Pd/Pt, Pd/Os, Co/Pd, Co/Ni, Au/Pt, Ni/Pd, Ni/Cr, Ni/Au, Cr/Au, and Au/Co, and plotted them by depth (Figure 15; Supporting Information, Table S10). These elemental ratios are widely used to screen for meteoritic input, because PGEs and other siderophile

elements are strongly depleted in Earth’s crust but enriched in chondritic and meteoritic sources [67, 68].

While these siderophile-element ratios (e.g., Pd/Pt, Ni/Pt, Ni/Cr, Co/Ni) are consistent with chondritic compositions, similar enrichments can occasionally arise from crustal or anthropogenic sources. Therefore, we interpret these patterns as consistent with, but not uniquely diagnostic of, extraterrestrial material, emphasizing their confinement to a narrow YD stratigraphic horizon. These ratios are best viewed as contextually diagnostic, when combined with independent Pt–Os isotopic and nanoparticle evidence. The Pd/Pt and Ni/Cr ratios fall within the range observed in chondritic meteorites, though confirmation of a meteoritic source would require isotopic evidence currently lacking for this study due to particle size limitations for isotopic work. These data nonetheless align with patterns expected from high-temperature condensation of impact-derived aerosols.

Interpretation

Several depth-resolved elemental ratios exhibit pronounced anomalies that coincide with the YDB (~152–150 cm) and, in some cases, remain elevated at lower levels through the early Younger Dryas (YD) interval (~152–147 cm). The PGE-sensitive ratios Pd/Pt, Pd/Os, and Au/Pt rise sharply at the base of the YDB and remain elevated until ~11,900 cal BP (see Bayesian age/depth model) before declining toward background values. Ni- and Co-bearing systematics show parallel structure: Ni/Pd and Co/Pd increase across the boundary, while Co/Ni resolves a boundary-centered excursion in the relative abundance of Co versus Ni. Additional Au- and Cr-normalized contrasts, Ni/Au, Cr/Au, Au/Co, and Ni/Cr, depart from baseline at the same depth, marking a coordinated shift in the relative abundance of Ni-, Co-, Cr-, and Au-bearing nanoparticles. Although elevated Au/Pt and Au/Co ratios could partly reflect post-depositional remobilization under reducing conditions, the restricted stratigraphic occurrence and high-temperature elemental associations of the Au-bearing nanoparticles suggest condensation in a vapor-phase plume rather than diagenetic enrichment. While ratios alone cannot uniquely distinguish impact fallout from rare volcanic aerosols, their confinement and coherence with Pt–Os anomalies (discussed below) strengthen an ET interpretation. Taken together, the co-stratified PGEs; a subset of highly siderophile elements and key transition metals anomalies centered within the narrow YDB and YD interval are difficult to explain by routine volcanic or ordinary sedimentary fractionation (Figure 15) and instead is more consistent with an ET impact event, though limited distal volcanic aerosol input is present elsewhere in the section.

The combined evidence demonstrates that the YDB and YD layer at Hall’s Cave is marked by distinctive nanoparticle ratios characteristic of extraterrestrial material. These anomalies bolster findings from other sites where platinum and PGE enrichments have been identified in the YDB layer [32, 36, 62]. The minor persistence of elevated nanoparticle

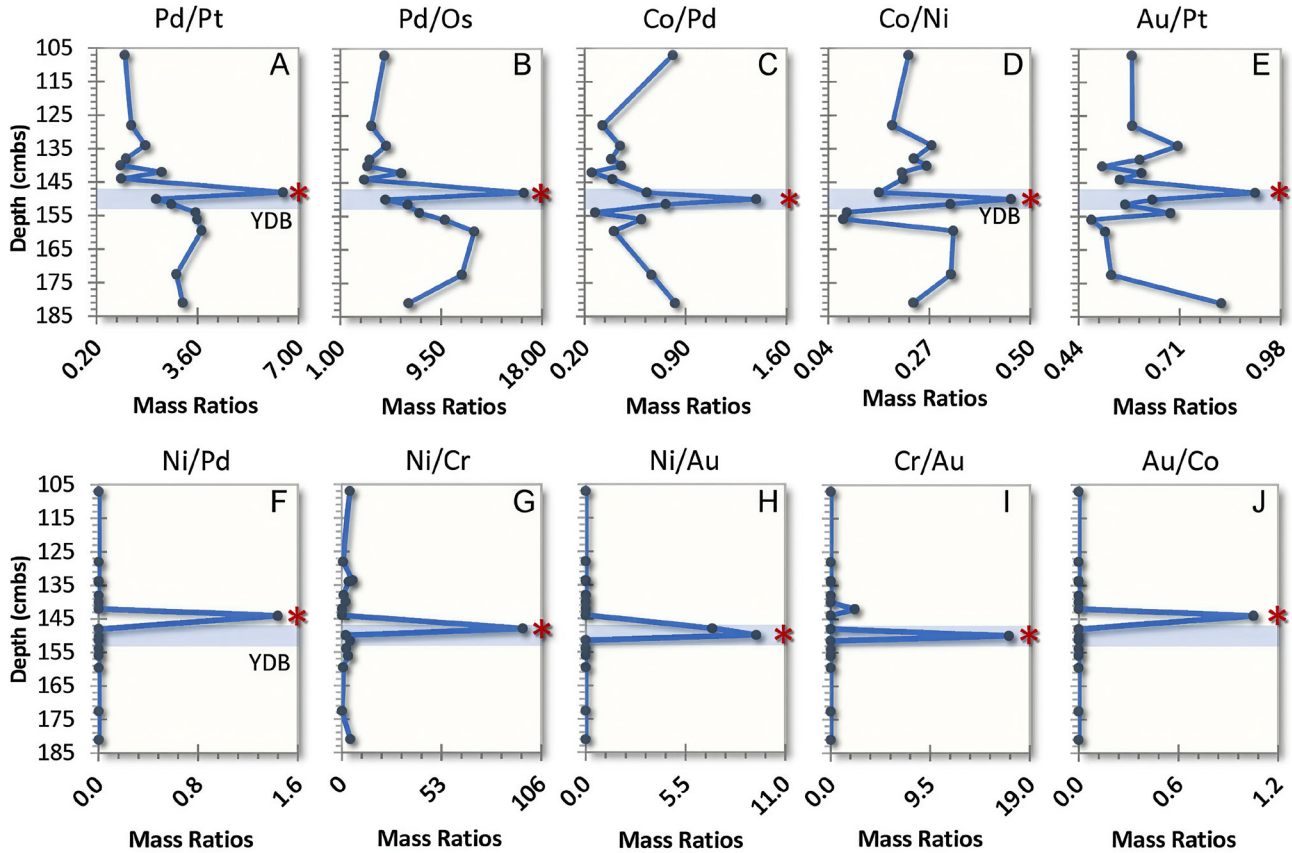


Figure 15: Depth-resolved ratios of the total mass concentration of elements within nanoparticles measured by SP-ICP-TOF-MS. SP-ICP-TOF-MS was used to calculate mass-concentration ratios for the following element pairs in single nanoparticles: Pd/Pt, Pd/Os, Co/Pd, Co/Ni, Au/Pt, Ni/Pd, Ni/Cr, Ni/Au, Cr/Au, and Au/Co. The depth profiles track variability above and below the sequence and highlight anomalies centered on the YD interval (~152–147 cm). Concentrations peak between ~151.5 and 138 cm depth. They span the interval from the YDB layer (~12,780 ± 170 cal BP) through the Younger Dryas and into the earliest Holocene. For consistency with our age model, the YD termination is ~11,600 cal BP. Ratio data are derived from single-particle measurements; see Supporting Information, Table S10 (<https://zenodo.org/uploads/19501481>) for particle counts and mass conversions. The shaded blue band marks the YD interval (~152–147), including the YDB layer at ~151 cm.

anomalies into the early YD suggests either prolonged atmospheric and surrounding landscape residence of ET-rich dust, repeated pulses of fallout, or secondary reworking from surface soils that were later washed into the cave, thereby broadening the apparent duration of the anomalies. This process could have broadened the apparent duration of the anomalies, making them appear more protracted than the primary fallout event. Even with this consideration, the presence and stratigraphic restriction of these anomalies strengthen the interpretation that an extraterrestrial influx contributed to the abrupt climate change at the onset of the YD, including widespread cooling and ecological disruption [32, 35].

Mixed extraterrestrial and volcanic geochemical signals at the YDB

To evaluate competing interpretations of anomalous geochemical signals at the Younger Dryas Boundary (YDB), we synthesized bulk ICP-MS elemental and osmium

isotopic data from Hall's Cave to differentiate potential extraterrestrial (ET) and volcanic contributions. Published elemental and isotopic datasets from Sun et al. [5], measured by inductively coupled plasma mass spectrometry (ICP-MS) and negative thermal ionization mass spectrometry (N-TIMS), were re-examined alongside the subsequently restored 153 cm sample by Young [81]. Figure 16 presents $^{187}\text{Os}/^{188}\text{Os}$ and Pt concentrations from the continuous HC16 core series, including this previously omitted interval (see Supplementary Table S11).

It is important to note that Figure 1 in Sun et al. [5] merges data from multiple, discontinuous Hall's Cave sampling episodes rather than representing a single stratigraphically coherent profile. As emphasized by Young [81], the Sun et al. dataset combined samples from at least three campaigns (HC15, HC16, HC17), with varying vertical resolutions and laterally offset positions, which we argue produced apparent duplication of osmium peaks and artificial excursions in $^{187}\text{Os}/^{188}\text{Os}$. This offset is due to the fact that the

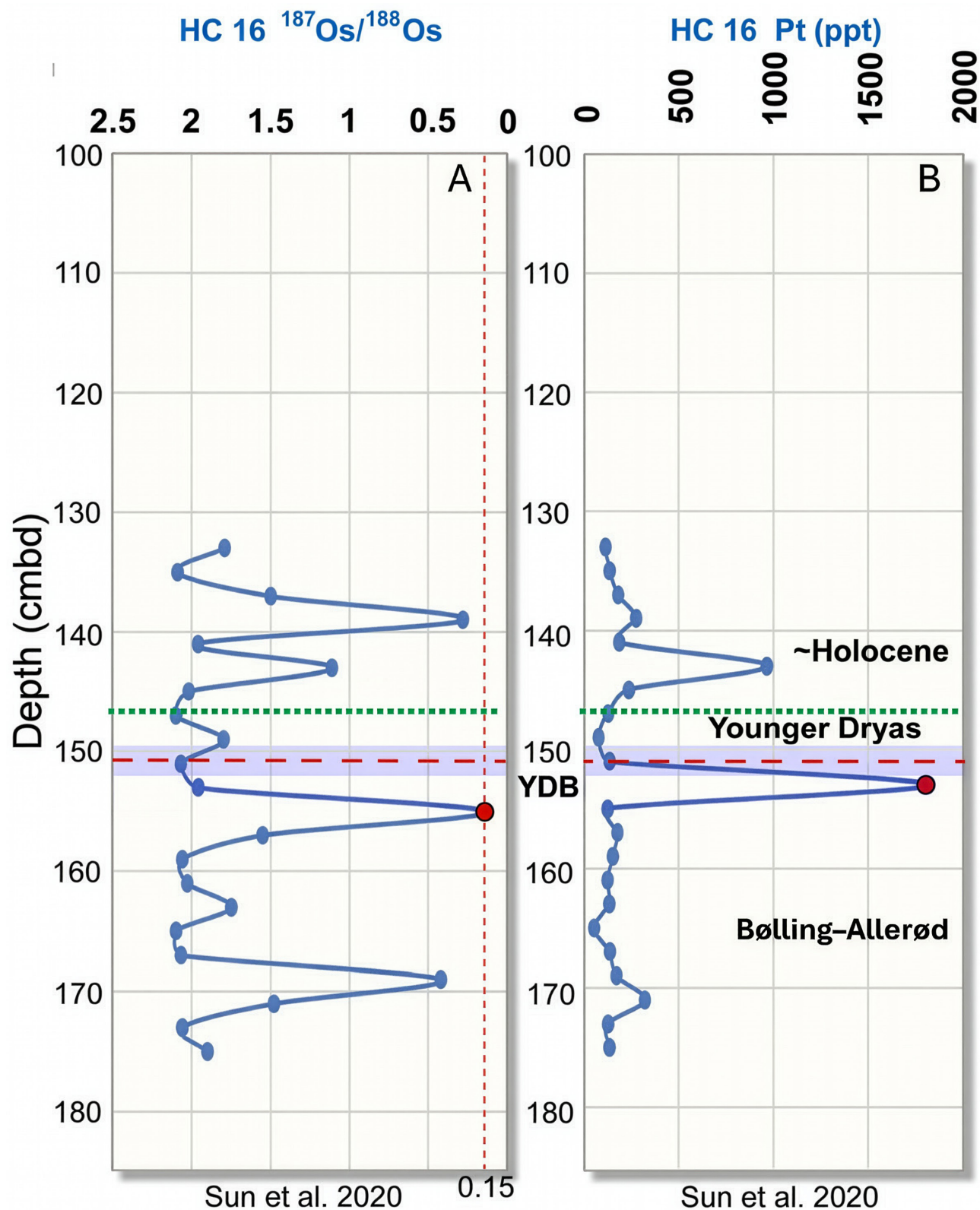


Figure 16: Changes in osmium isotope ratios and platinum concentrations across the Younger Dryas Boundary (YDB) at Hall's Cave. **(A)** $^{187}\text{Os}/^{188}\text{Os}$ values by depth, showing variation between radiogenic (>1.1) and highly unradiogenic (<0.2) compositions that are more characteristic of an extraterrestrial (ET) source. **(B)** Platinum (Pt) concentrations (parts per trillion) by depth, displaying a sharp, narrow peak near 153 cm after inclusion of the previously omitted sample from Sun et al. [5] restored by Young [81]. The dashed red line marks a lithologic break at 153 cm, the shaded band indicates the modeled Younger Dryas interval, and the dashed green line represents the Holocene onset. Volcanic

fallout typically yields diffuse enrichments and intermediate-to-radiogenic $^{187}\text{Os}/^{188}\text{Os}$ values ($\sim 0.3\text{--}1.1$) through mantle–crust mixing, whereas the Hall's Cave interval exhibits an extremely unradiogenic minimum (~ 0.15) nearly coincident with a high-amplitude Pt anomaly ($\sim 1,807$ ppt). This coupled pattern is atypical of volcanic aerosol deposition and instead supports rapid input of meteoritic material during a brief, high-energy depositional pulse near the onset of the Younger Dryas. Data are from Sun et al. [5] (HC16 core), including the reanalyzed 153 cm sample by Young [81]; see Supplementary Table S11.

lithostratigraphic boundary representing the YD onset in this profile undulates slightly which means separate sampling columns intersect this boundary at slightly different depths relative to the site datum. When the dataset is restricted to the continuous HC16 core, the record becomes internally consistent and reveals three rather than five unradiogenic Os events, none coinciding with the YDB layer itself (Figure 16). Critically, inclusion of the previously omitted 153 cm sample, recovered from the HC16 series and reinstated by Young [81], reveals the highest Pt concentration in the entire sequence ($\sim 1,807$ ppt), directly associated with a shallow, highly unradiogenic Os minimum just below the YDB. These results demonstrate that the broad unradiogenic anomaly portrayed in the composite of Sun et al. [5] is likely an artifact of stratigraphic mixing and sample overlap rather than a discrete signal at the Younger Dryas Boundary. The complete and properly ordered Sun et al. HC16 dataset, as reanalyzed here, instead supports a tightly coupled Pt–Os relationship indicative of rapid deposition of extraterrestrial material near the onset of the Younger Dryas.

Interpretation

Sun et al. [5] interpreted Pt–PGE enrichments and unradiogenic excursions as volcanic in origin. However, inclusion of the missing 153 cm sample reveals a very narrow, high-amplitude Pt peak ($\sim 1,807$ ppt) positioned directly above an extremely unradiogenic Os minimum (~ 0.15). This coupled pattern, an abrupt, stratigraphically confined Pt spike with a sharp Os isotopic trough, is atypical of volcanic fallout, which generally produces diffuse enrichment profiles and moderately radiogenic bulk signatures over broader intervals. Nevertheless, possible volcanic and diagenetic sources were quantitatively evaluated and found inconsistent with the stratigraphic sharpness and magnitude of the coupled Pt–Os excursion (Figure 16). Volcanic fallout generally produces broader enrichment profiles with moderately radiogenic Os values ($0.3\text{--}1.1$), unlike the isolated unradiogenic minimum (0.15) observed here. Volcanic gases and ash incorporate mantle-like Os that mixes with continental crust during eruption and transport, yielding fallout with $\sim 0.3\text{--}1.1$ $^{187}\text{Os}/^{188}\text{Os}$ rather than discrete, single-sample Pt spikes of the magnitude observed here [82–84].

In contrast, impact-related fallout layers commonly exhibit sharp, centimeter-scale PGE spikes coupled with extremely unradiogenic Os values ($\sim 0.12\text{--}0.20$) that match meteoritic or standard chondritic-mantle compositions, as documented at the Cretaceous–Paleogene (K–Pg) boundary and several YDB sites [82–85]. Although Sun et al.

[5] favored a volcanic explanation, the combination of an extremely unradiogenic minimum and a narrow Pt spike at ~ 153 cm is inconsistent with volcanic aerosol deposition and instead most consistent with an extraterrestrial component. Given possible post-depositional mobility of Os along organic or sulfidic pathways, the magnitude and brevity of the Pt anomaly, its approximate coincidence with the unradiogenic Os trough, and the absence of broader diffusion collectively indicate a brief, high-energy depositional pulse rather than prolonged fallout. The data indicates a short-duration depositional sequence comprising two closely timed phases, a primary fallout bed followed by a brief dust-enrichment pulse.

This interpretation is further supported by the SP-ICP-TOF-MS nanoparticle data (Figures 13–15), which document co-occurring metallic Fe–Ni–Cr–Pt nanoparticles and siderophile-enriched clusters inconsistent with volcanic aerosols but characteristic of high-temperature vapor condensation. Possible anthropogenic or modern contamination sources were evaluated and excluded based on sedimentary context (deeply stratified), particle compositions (co-occurring metallic phases), and stratigraphic confinement (large peaks only within the YDB-dated zone). The analyzed nanoparticles enrichments begin within the Bayesian modeled YDB and YD ($\sim 152\text{--}147$ cm), indicating a primary depositional origin rather than intrusive or modern contamination. When considered with established YDB impact markers at Hall's Cave, including nanodiamonds, microspherules, aciniform carbon, and shocked quartz (Figure 6), the geochemical and mineralogical evidence favors an extraterrestrial influx near ~ 12.8 ka.

In summary, Hall's Cave records a stratigraphically discrete event characterized by co-occurring Pt enrichment and Os isotopic excursion near the onset of the Younger Dryas. Although minor volcanic or background contributions may be present, these geochemical features are best explained by a predominantly extraterrestrial influx of PGE-rich material at ~ 12.8 ka. The Pt–Os systematics thus reinforce interpretation of a short-lived, impact-related depositional episode superimposed on otherwise gradual deglacial sedimentation.

Comparison of YDB nanoparticle ratios with extraterrestrial materials

To test whether anomalous nanoparticles at Hall's Cave correspond to known extraterrestrial sources, we analyzed single nanoparticles using single-particle inductively coupled plasma time-of-flight mass spectrometry (SP-ICP-TOF-MS).

For each particle, we calculated elemental ratios of highly siderophile and transition metals, normalized them to CI chondrites, and compared them against a reference library of >2000 elemental values from comets, chondrites, iron meteorites, micrometeorites (MMs), interplanetary dust particles (IDPs), lunar and Martian meteorites, and refractory metal nuggets (RMNs) (Figure 17). We then identified the four best matches for each ET category at each depth horizon. This approach enables us to determine whether the anomalous ratios at the YDB layer originated from a homogeneous impactor (e.g., iron or chondrite) or a heterogeneous, possibly cometary source.

Interpretation

The comparison demonstrates that nanoparticles from the YDB horizon at Hall's Cave (~151–148 cm) yield strong geochemical matches with multiple classes of extraterrestrial material.

Peak anomalies at the YDB

ET-like nanoparticle ratios reach a distinct maximum at the YDB, coincident with the occurrence of nanodiamonds, shocked quartz, meltglass, magnetic spherules, and soot previously reported at this site and others [32, 35, 45, 54].

Heterogeneous matches

Hall's Cave nanoparticle ratios do not align uniquely with a single impactor type. Instead, they overlap with several classes of extraterrestrial material, including comets, micrometeorites, and ureilites, indicating a heterogeneous impactor composition, which falls within a range of ~1× to 2× of the reference composition ranges. This heterogeneity argues against a purely homogeneous iron or ordinary chondrite impactor. Taken together, these results most plausibly indicate an extraterrestrial influx at ~12.8 ka, although additional isotopic and microstructural confirmation would further strengthen this interpretation.

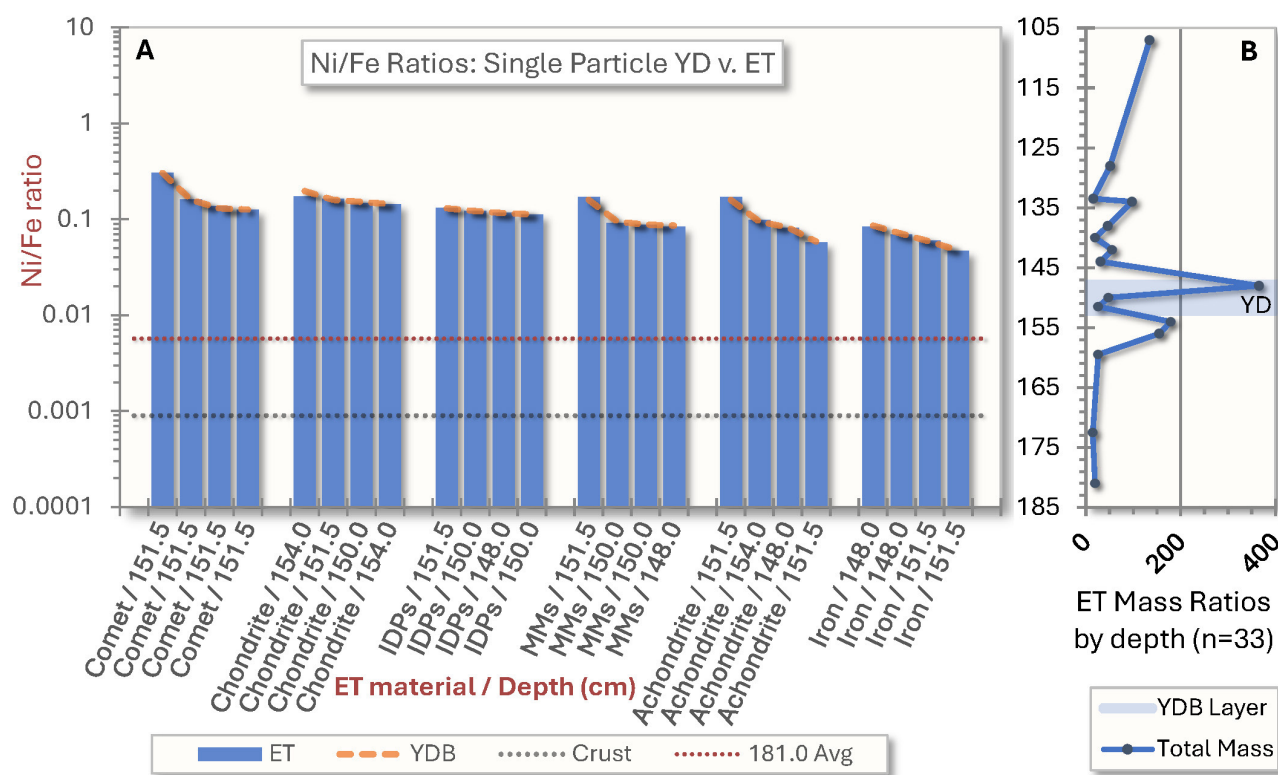


Figure 17: Comparison of elemental ratios within single multi-element nanoparticles at Hall's Cave with known extraterrestrial (ET) materials. Nanoparticles were analyzed using single-particle inductively coupled plasma time-of-flight mass spectrometry (SP-ICP-TOF-MS). Elemental ratios (Ni/Fe) from individual nanoparticles (154.0 to 148.0 cm depth) were compared to a reference library of >2,000 extraterrestrial elemental ratios. **(A)** Comparative line plot shows the best Hall's Cave matches (by sample depth) against six classes of ET materials, including comets, chondrites, interplanetary dust particles (IDPs), micrometeorites (MMs), achondrites, and iron meteorites. Most YD elemental ratios from Hall's Cave fall within 0.94 to 1.13× ET reference values, indicating strong compositional correspondence. The red dotted line represents the mean Ni/Fe ratio 181.0 cm depth, the bottom of the sampled column. Those values are >10× lower than values across the YDB from 154.0 to 148.0 cm. The black dotted line represents the mean Ni/Fe crustal ratio with values are >100× lower than values across the YDB from 154.0 to 148.0 cm. **(B)** Total counts of ET-like single nanoparticles with anomalous ratios by depth at Hall's Cave, showing a distinct peak in the Younger Dryas Boundary (YDB; ~151–148 cm). See Supporting Information Table S10 for SP-ICP-TOF-MS data and Table S12 for comparative ET datasets (<https://zenodo.org/uploads/19501481>).

Impactor type

In this context the closest correspondence is to cometary material, which can be expected to incorporate diverse components (metal-rich phases, refractory nuggets, organics, and silicates). We cannot pin down the exact impactor type from elemental ratios alone, but the overall compositional diversity is more consistent with a mixed or cometary source than with any single homogeneous meteorite class. The presence of carbon spherules and nanodiamonds further supports a carbon-rich bolide, consistent with a comet but little else [28, 86].

Broader implications

The data indicates that the YDB anomaly at Hall's Cave reflects deposition of a heterogeneous extraterrestrial object, most consistent with a cometary airburst/impact event rather than a homogeneous impactor, such as a chondritic body. A dispersed multi-impactor event could disperse PGEs, nanodiamonds, shocked quartz, soot, and metallic nanoparticles across wide regions, consistent with the globally distributed YDB "spherule layer" documented at multiple sites. The results support the Younger Dryas Impact Hypothesis, indicating impacts by bolides of mixed composition likely contributed to abrupt climate change and ecological disruption close to 12,800 cal BP [53, 62].

Nanoparticle elemental signatures consistent with cometary and meteoritic sources

To further evaluate whether nanoparticles in the Younger Dryas (YD) layer at Hall's Cave include an extraterrestrial component, we compared Fe/Ni and Fe/Cr elemental ratios of individual nanoparticles using single-particle inductively coupled plasma time-of-flight mass spectrometry (SP-ICP-TOF-MS). Only nanoparticles that contained Fe, Ni, and Cr were included, as these elements are widely used in cosmic spherule and micrometeorite studies to distinguish extraterrestrial material from terrestrial crustal sources, given that Ni and Cr are significantly enriched in many meteoritic phases relative to average crustal compositions [85, 87, 88]. When plotted together, the Fe/Ni and Fe/Cr values define compositional fields help with differentiating between meteoritic and cometary dust and background crustal sediments. Here, we compare nanoparticle ratios from the YD-age interval at Hall's Cave (152–147) with published extraterrestrial reference fields for cometary material (Wild 2 Stardust samples) [89] and Antarctic micrometeorites [90–92], allowing direct assessment of whether the Hall's Cave nanoparticles fall within compositional ranges expected for extraterrestrial material. The results are displayed in Figure 18 (See SP-ICP-TOF-MS data in Supporting Information, Table S10).

Interpretation

The Fe/Ni and Fe/Cr values of most Hall's Cave YD-layer nanoparticles cluster within, or lie close to, compositional fields defined by extraterrestrial materials, including Wild

2 cometary dust [89] and Antarctic micrometeorite dust [90–92]. In contrast, terrestrial crustal reference values are consistently offset, with higher Fe/Cr values and lower Ni concentrations, highlighting the geochemical distinction between crustal inputs and extraterrestrial material. The Hall's Cave dataset, therefore, is consistent with the suggestion that a significant fraction of the YD nanoparticles share geochemical signatures with meteoritic and cometary particles, supporting an extraterrestrial source. This evidence parallels other YDB sites where meteoritic geochemical signatures, nanodiamonds, shocked quartz, magnetic spherules, and high-temperature meltglass co-occur [32, 36, 45, 62], reinforcing the interpretation that the YDB layer records fallout from an extraterrestrial impact or airburst. The correspondence with cometary and micrometeorite fields is especially notable, as it suggests the proposed impactors were heterogeneous and comet-like, consistent with a body containing both metal-rich and carbon-rich phases, capable of dispersing soot, organics, and platinum-group element anomalies at ~12.8 ka. Future isotopic or microstructural analyses will be valuable to further verify the extraterrestrial interpretation of these nanoparticles.

Discussion

The geochemical and nanoparticle anomalies identified at Hall's Cave occur within the Bayesian-modeled interval corresponding to the onset of Greenland Stadial 1 (GS-1), the Younger Dryas (YD) cooling event. In Greenland ice cores, this transition is marked by rapid declines in $\delta^{18}\text{O}$ values and pronounced increases in dust and ammonium flux, reflecting enhanced atmospheric loading at ~12.8 ka. The coeval enrichment of platinum-group and siderophile elements, together with the appearance of high-temperature spherules and nanoparticles at Hall's Cave, indicates that local depositional processes were influenced by the same broad pulse of atmospheric dust documented in high-latitude records. These correlations suggest that the Hall's Cave boundary layer records part of a hemispheric-scale episode of rapid environmental change associated with the onset of GS-1.

The stratified fossil vertebrate record at Hall's Cave provides one of the most continuous and well-dated terrestrial sequences of biotic and ecological change spanning the YD interval in North America. Faunal data indicate substantial reorganization of mammalian communities near the onset of the YD (~12.8 ka), including the disappearance or extirpation of several small- to mid-sized taxa. Toomey [1] documented abrupt losses of prairie dogs (*Cynomys*), moles (*Scalopus*), woodrats (*Neotoma*), and cold-adapted rodents (*Mictomys*, *Lemmings*), many of which had been common during the preceding Bølling–Allerød interstadial. These extirpations occur stratigraphically near the Younger Dryas Boundary (YDB) and within a narrow time interval defined by multiple radiocarbon dates, suggesting that the biotic

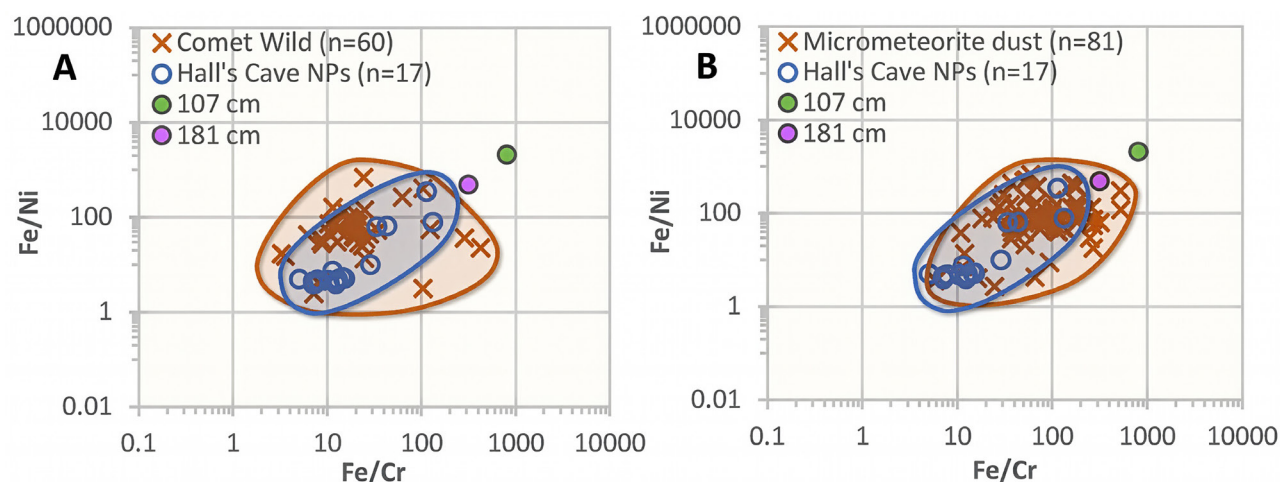


Figure 18: Bivariate plot of Fe/Ni versus Fe/Cr mass ratios within individual multi-element nanoparticles containing the three elements for YD-layer single nanoparticles, compared to compositions of extraterrestrial materials. Nanoparticles were analyzed using SP-ICP-TOF-MS, and only particles containing Fe, Ni, and Cr were included. **(A)** Hall's Cave YD-age NPs (blue circles) compared to reference fields for cometary material from Wild 2 samples returned by the Stardust mission (orange X's) [89]. **(B)** The same Hall's Cave dataset compared with Antarctic micrometeorites representing cometary and meteoritic dust (orange X's) [90–92]. For context, values for NPs from non-YDB layers are shown (a green dot for 107 cm and a purple dot for 181 cm), highlighting higher relative Cr and Ni relative to Fe in the YDB v. other layers in the cave. Hall's Cave nanoparticles primarily cluster within or adjacent to the extraterrestrial reference fields. See SP-ICP-TOF-MS data in Supporting Information, Table S10 and comparative ET data in Table S12 (<https://zenodo.org/uploads/19501481>).

response was both rapid and temporally coincident with other environmental changes. Although such faunal turnover has been interpreted by some studies as consistent with an abrupt catastrophic trigger, Late Pleistocene extinctions and extirpations in North America have also been widely attributed to rapid climate-driven habitat change and/or cumulative anthropogenic pressures [93, 94].

Stable-isotope data from faunal collagen [9] and magnetic susceptibility records [10] lend further support for a pronounced climatic shift at the onset of the YD. These proxies indicate cooler, drier conditions with decreased rainfall and reduced sediment influx into the cave. Charcoal and pollen data similarly record increased fire activity and vegetation turnover at this time [13]. Collectively, this evidence points to a period of environmental and ecological stress for both flora and fauna in the Hall's Cave region.

The magnitude and abruptness of the sedimentary, geochemical, environmental, and biotic changes recorded at Hall's Cave imply a high-energy trigger that could be consistent with a cosmic impact or major volcanic eruption. At the modeled sedimentation rate for Unit II (~ 0.01 cm yr⁻¹), a 0.5 cm depth uncertainty corresponds to < 50 years—well within the 2σ chronological envelope for the GS-1 onset [95]. Previous investigations have reported impact-related proxies in the YDB layer at Hall's Cave, including magnetic spherules, meltglass, nanodiamonds, soot, and trace-element anomalies (Pt, Ir, Fe-rich particles) [6]. These have been interpreted as evidence for a cosmic impact event, although alternative volcanic interpretations have also been advanced.

Sun et al. [5] re-evaluated several YDB proxies from Hall's Cave and proposed that volcanic processes such as phreatomagmatic eruptions, volcanic lightning, and ash-plume condensation might reproduce similar mineralogical and geochemical signatures. Their reinterpretation relies primarily on analogy rather than on stratigraphic or isotopic evidence for coeval volcanism at the site. While volcanic aerosols can carry unradiogenic Os from mantle sources, they normally incorporate mantle Os (~ 0.13 – 0.16) mixed with continental crust, producing bulk fallout with intermediate to radiogenic $^{187}\text{Os}/^{188}\text{Os}$ values (~ 0.3 – 1.1). Even large basaltic eruptions, including the Deccan Traps and Icelandic fissure events, yield broad, low-contrast PGE enrichments rather than discrete, high-amplitude spikes such as those observed at Hall's Cave. Moreover, Os and PGE profiles in volcanic sediments are diffuse and show minimal fractionation, reflecting slower depositional processes rather than short-duration condensation events [82–84].

In contrast, the Hall's Cave YDB horizon exhibits a sharply defined, high-amplitude Pt peak ($\sim 1,807$ ppt) directly above an extremely unradiogenic Os minimum (~ 0.15), a pattern indicative of rapid accumulation of PGE-rich, high-temperature condensates of extraterrestrial origin. Comparable Pt–Os relationships are observed at other YDB sites and at the Cretaceous–Paleogene (K–Pg) boundary, where impact-derived ejecta produce centimeter-scale PGE enrichments coupled with Os isotopic minima characteristic of chondritic sources [86]. The slightly deeper stratigraphic position of the unradiogenic $^{187}\text{Os}/^{188}\text{Os}$ anomaly at 155

cmbd likely reflects limited post-depositional mobility of Os along organic or sulfide pathways. Collectively, the abruptness of the Pt spike, its close association with the $^{187}\text{Os}/^{188}\text{Os}$ anomaly, and its alignment with multiple independent impact proxies support a brief depositional event rather than prolonged fallout.

This interpretation is further supported by new SP-ICP-TOF-MS nanoparticle analyses (Figures 13–15), which document stratigraphically restricted enrichments in metallic Fe–Ni–Cr–Pt nanoparticles, Fe–Si and Co–Fe alloys, and PGE-bearing combinations consistent with vapor-phase condensation in an impact plume but inconsistent with volcanic aerosol formation. These assemblages co-occur with established impact markers, nanodiamonds, microspherules, aciniform soot, and shocked quartz, demonstrating a multiproxy signature most consistent with an extraterrestrial influx of high-temperature material at ~12.8 ka.

Collectively, these geochemical, isotopic, and mineralogical indicators align stratigraphically with abrupt paleoenvironmental and faunal changes, supporting interpretation of the Hall's Cave YDB layer as a discrete event horizon. Although minor volcanic or background dust inputs may have contributed, the dominant signal reflects a short-duration, high-energy depositional event that we interpret as an extraterrestrial airburst or impact that coincided with the onset of the Younger Dryas. Hall's Cave thus represents one of the most stratigraphically secure terrestrial records for evaluating a possible Younger Dryas Boundary event in North America.

The Hall's Cave record contributes new resolution to the Younger Dryas debate by delineating a stratigraphically discrete, multiproxy-defined event layer that includes high-temperature impact proxies, unradiogenic Os, and extraterrestrial nanoparticles. This two-step depositional sequence, a fallout bed followed by a secondary dust pulse, is consistent with delayed nanoparticle settling reported at sites such as Baffin Bay. Unlike previous studies based on lower-resolution or composite records, this integrated analysis from a single, well-dated profile reduces age uncertainties and allows confident attribution of environmental changes to specific depositional episodes. These results strengthen interpretation of the Hall's Cave YDB stratigraphic zone as a temporally constrained horizon marked by high-energy depositional signatures and coincident abrupt ecological and climatic change.

Conclusions

Hall's Cave preserves a well-dated, stratigraphically coherent record of environmental change across the Younger Dryas Boundary (YDB) in central Texas. The Bayesian-modeled radiocarbon chronology places this interval at $12,780 \pm 170$ cal BP, overlapping within uncertainty with independent age estimates for the onset of the Younger Dryas.

Multiproxy analyses identify a two-part stratigraphic sequence consisting of: (i) a discrete boundary layer containing nanodiamonds, shocked quartz, Fe- and Si-rich spherules, aciniform carbon, and stratigraphically restricted Fe–Ni–Cr–Pt-bearing nanoparticles, coincident with reduced sedimentation rates; followed by (ii) an overlying interval characterized by increased nanoparticle abundance and compositional shifts consistent with enhanced dust input and changing depositional conditions during the early Younger Dryas.

Bulk geochemical proxies ($\delta^{15}\text{N}$, C/N, Hg/TOC, magnetic susceptibility) indicate changes in nitrogen cycling, sediment input, and hydroclimate across this interval. The absence of a distinct Hg/TOC enrichment at the YDB does not provide evidence for a local volcanic signal at this site, although it does not exclude volcanic or wildfire-related contributions regionally. In contrast, the occurrence of highly siderophile element-bearing nanoparticles and associated geochemical signatures along with the presence of high-temperature and high-pressure (shocked quartz) materials is consistent with a meteoritic impact component.

Faunal indicators, including declines in *Sporormiella* and changes in species occurrence, record ecological disruption within the same general stratigraphic interval. These biotic patterns are consistent with environmental stress during the Younger Dryas but do not independently resolve the relative contributions of climatic, ecological, or other forcing mechanisms.

Taken together, the Hall's Cave record documents a temporally constrained, multiproxy anomaly at ~12.8 ka that reflects a combination of high-temperature and high-pressure materials, environmental change, and ecological reorganization. The co-occurrence of these signals within a narrow stratigraphic interval is unlikely to be entirely coincidental and is consistent with a short-lived disturbance superimposed on broader climatic transitions. These observations are compatible with a high-energy extraterrestrial impact event.

As a well-resolved cave sequence with independent chronological control, Hall's Cave provides a valuable regional archive for evaluating the timing and nature of environmental changes at the Younger Dryas onset. The record contributes to ongoing efforts to distinguish among competing explanations, including extraterrestrial meteorite impact, volcanism, and internal climate dynamics, by documenting the structure, composition, and stratigraphic context of this transition at high resolution.

Supporting information

SI: Supporting information. Additional figures, tables, and methods. (PDF)

<https://zenodo.org/uploads/19501481>

Supporting Tables: <https://zenodo.org/records/17475244>

Acknowledgments

We thank the South Carolina Institute for Archaeology and Anthropology (SCIAA), the Southeastern Paleoamerican Survey (SEPAS), the College of Arts and Sciences at the University of South Carolina (USC), Columbia, South Carolina. We also thank Thomas W. Stafford, Jr. (Stafford Research Laboratories, Inc.) and Ernest L. Lundelius (University of Texas, Austin) for assistance collecting samples and for providing radiocarbon dates used in this study. We also thank the Hall family, especially Lee and Fran, for permitting us to take samples at the site. The Comet Research Group (CRG) provided funding for various analyses. The authors used ChatGPT (OpenAI, GPT-5) to assist with language refinement and clarity improvements during manuscript preparation, in compliance with ACI guidelines. Finally, we wish to thank Eugene Jhong, Brian Muraresku and the Athanatos Foundation for providing generous gifts to the University of South Carolina and University of California, Santa Barbara to support this research.

Funding

The study was funded mainly by the Comet Research Group (CRG) and with the generous support of Eugene Jhong and Brian Muraresku through the Athanatos Foundation, who provided substantial research gifts to the University of California, Santa Barbara (J.P.K.) and the University of South Carolina through the South Carolina Institute for Archaeology and Anthropology (C.R.M.).

References

- Toomey, R.S., III.; Blum, M.D.; Valastro, S., Jr. Late Quaternary Climates and Environments of the Edwards Plateau, Texas. *Glob. Planet. Change* **1993**, *7*, 299–320, doi: [10.1016/0921-8181\(93\)90003-7](https://doi.org/10.1016/0921-8181(93)90003-7).
- Waters, M.R.; Keene, J.L.; Prewitt, E.R.; Everett, M.E.; Laughlin, T.; Stafford, T.W., Jr. Late Quaternary Geology, Archaeology, and Geoarchaeology of Hall's Cave, Texas. *Quat. Sci. Rev.* **2021**, *274*, 107276, doi: [10.1016/j.quascirev.2021.107276](https://doi.org/10.1016/j.quascirev.2021.107276).
- Ryan, W.B.F.; Carbotte, S.M.; Coplan, J.O.; O'Hara, S.; Melkonian, A.; Arko, R.; Weissel, R.A.; Ferrini, V.; Goodwillie, A.; Nitsche, F.; et al. Global Multi-resolution Topography Synthesis. *Geochem. Geophys. Geosyst.* **2009**, *10*, doi: [10.1029/2008GC002332](https://doi.org/10.1029/2008GC002332).
- Cooke, M.J.; Stern, L.A.; Banner, J.L.; Mack, L.E.; Stafford, T.W., Jr.; Toomey, R.S., III. Precise Timing and Rate of Massive Late Quaternary Soil Denudation. *Geology* **2003**, *31*, 853–856, doi: [10.1130/G19749.1](https://doi.org/10.1130/G19749.1).
- Sun, N.; Brandon, A.D.; Forman, S.L.; Waters, M.R.; Befus, K.S. Volcanic Origin for Younger Dryas Geochemical Anomalies ca. 12,900 cal B.P. *Sci. Adv.* **2020**, *6*, eaax8587, doi: [10.1126/sciadv.aax8587](https://doi.org/10.1126/sciadv.aax8587).
- Stafford, T.W.; Lundelius, E.; Kennett, J.; Kennett, D.J.; West, A.; Wolbach, W.S. Testing Younger Dryas ET Impact (YDB) Evidence at Hall's Cave, Texas. In *AGU Fall Meeting Abstracts*, 2009; Volume 2009, pp. PP33B-08.
- Bourne, M.D.; Feinberg, J.M.; Stafford, T.W., Jr.; Waters, M.R.; Lundelius, E., Jr.; Forman, S.L. High-intensity Geomagnetic Field 'Spike' Observed at ca. 3000 cal BP in Texas, USA. *Earth Planet. Sci. Lett.* **2016**, *442*, 80–92, doi: [10.1016/j.epsl.2016.02.051](https://doi.org/10.1016/j.epsl.2016.02.051).
- Cooke, M.J.; Stern, L.A.; Banner, J.L.; Mack, L.E. Evidence for the Silicate Source of Relict Soils on the Edwards Plateau, Central Texas. *Quat. Res.* **2007**, *67*, 275–285, doi: [10.1016/j.yqres.2006.11.007](https://doi.org/10.1016/j.yqres.2006.11.007).
- Tomé, C.P.; Elliott Smith, E.A.; Lyons, S.K.; Newsome, S.D.; Smith, F.A. Changes in the Diet and Body Size of a Small Herbivorous Mammal (Hispid Cotton Rat, *Sigmodon Hispidus*) Following the Late Pleistocene Megafauna Extinction. *Ecography* **2020**, *43*, 604–619, doi: [10.1111/ecog.04596](https://doi.org/10.1111/ecog.04596).
- Ellwood, B.B.; Gose, W.A. Heinrich H1 and 8200 yr B.P. Climate Events Recorded in Hall's Cave, Texas. *Geology* **2006**, *34*, 753–756, doi: [10.1130/G22549.1](https://doi.org/10.1130/G22549.1).
- Smith, F.A.; Elliott Smith, E.A.; Villaseñor, A.; Tomé, C.P.; Lyons, S.K.; Newsome, S.D. Late Pleistocene Megafauna Extinction Leads to Missing Pieces of Ecological Space in a North American Mammal Community. *Proc. Natl. Acad. Sci. U. S. A.* **2022**, *119*, e2115015119, doi: [10.1073/pnas.2115015119](https://doi.org/10.1073/pnas.2115015119).
- Smith, F.A.; Tomé, C.P.; Elliott Smith, E.A.; Kathleen Lyons, S.; Newsome, S.D.; Stafford, T.W. Unraveling the Consequences

Data availability

All data files are available in this manuscript, Supporting Information, and from Zenodo.org.
<https://zenodo.org/uploads/19501481>
<https://zenodo.org/records/17475244>

Sample availability

Samples for this study are mostly depleted, but limited amounts may be available from the Corresponding Author.

Author contributions

C.R.M., A.W., J.P.K., and M.B. conceived and directed aspects of the project. All co-authors contributed data and/or technical analysis for the paper and wrote, edited, reviewed, and/or approved the manuscript.

Potential conflicts of interest

C.R.M., A.W., J.P.K., and M.A.L. volunteer their time as co-founders and directors of CRG. No co-author receives a salary, compensation, stock, or any other financial benefit from CRG, except for tax deductions for CRG donations by co-authors A.W., M.A.L., and T.W. All co-authors may receive reimbursements from their respective organizations for attending symposia on the research presented in this paper. A.W. is a co-author of a book about the Younger Dryas Impact Hypothesis; he donates all proceeds to the non-profit Comet Research Group. The authors declare that they have no other potential competing interests.

- of the Terminal Pleistocene Megafauna Extinction on Mammal Community Assembly. *Ecography* **2016**, *39*, 223–239, doi: [10.1111/ecog.01779](https://doi.org/10.1111/ecog.01779).
13. Cordova, C.E.; Johnson, W.C. An 18 ka to Present Pollen- and Phytolith-based Vegetation Reconstruction from Hall's Cave, South-central Texas, USA. *Quat. Res.* **2019**, *92*, 497–518, doi: [10.1017/qua.2019.17](https://doi.org/10.1017/qua.2019.17).
 14. Ramsey, C.B. Bayesian Analysis of Radiocarbon Dates. *Radiocarbon* **2009**, *51*, 337–360, doi: [10.1017/S0033822200033865](https://doi.org/10.1017/S0033822200033865).
 15. Reimer, P.J.; Austin, W.E.N.; Bard, E.; Bayliss, A.; Blackwell, P.G.; Ramsey, C.B.; Butzin, M.; Cheng, H.; Lawrence Edwards, R.; Friedrich, M.; et al. The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0–55 cal kBP). *Radiocarbon* **2020**, *62*, 725–757, doi: [10.1017/RDC.2020.41](https://doi.org/10.1017/RDC.2020.41).
 16. Dearing, J.A. Magnetic Susceptibility. In *Environmental Magnetism: A Practical Guide*; Arnold: London, 1999; pp. 35–62.
 17. Wolbach, W.S.; Ballard, J.P.; Mayewski, P.A.; Adedeji, V.; Bunch, T.E.; Firestone, R.B.; French, T.A.; Howard, G.A.; Israde-Alcántara, I.; Johnson, J.R.; et al. Extraordinary Biomass-burning Episode and Impact Winter Triggered by the Younger Dryas Cosmic Impact ~12,800 Years Ago. 1. Ice Cores and Glaciers. *J. Geol.* **2018**, *126*, 165–184, doi: [10.1086/695703](https://doi.org/10.1086/695703).
 18. Wolbach, W.S.; Ballard, J.P.; Mayewski, P.A.; Parnell, A.C.; Cahill, N.; Adedeji, V.; Bunch, T.E.; Domínguez-Vázquez, G.; Erlandson, J.M.; Firestone, R.B.; et al. Extraordinary Biomass-burning Episode and Impact Winter Triggered by the Younger Dryas Cosmic Impact ~12,800 Years Ago. 2. Lake, Marine, and Terrestrial Sediments. *J. Geol.* **2018**, *126*, 185–205, doi: [10.1086/695704](https://doi.org/10.1086/695704).
 19. LeCompte, M.A.; Goodyear, A.C.; Demitroff, M.N.; Batchelor, D.; Vogel, E.K.; Mooney, C.; Rock, B.N.; Seidel, A.W. Independent Evaluation of Conflicting Microspherule Results from Different Investigations of the Younger Dryas Impact Hypothesis. *Proc. Natl. Acad. Sci. U. S. A.* **2012**, *109*, E2960–E2969, doi: [10.1073/pnas.1208603109](https://doi.org/10.1073/pnas.1208603109).
 20. Kinzie, C.R.; Que Hee, S.S.; Stich, A.; Tague, K.A.; Mercer, C.; Razink, J.J.; Kennett, D.J.; DeCarli, P.S.; Bunch, T.E.; Wittke, J.H.; et al. Nanodiamond-rich Layer Across Three Continents Consistent with Major Cosmic Impact at 12,800 cal BP. *J. Geol.* **2014**, *122*, 475–506, doi: [10.1086/677046](https://doi.org/10.1086/677046).
 21. West, A.; Young, M.; Costa, L.; Kennett, J.P.; Moore, C.R.; LeCompte, M.A.; Kletetschka, G.; Hermes, R.E. Modeling Airbursts by Comets, Asteroids, and Nuclear Detonations: Shock Metamorphism, Meltglass, and Microspherules. *Airburs. Crater. Imp.* **2024**, *2*, e20240004, doi: [10.14293/aci.2024.0004](https://doi.org/10.14293/aci.2024.0004).
 22. Hermes, R.E.; Wenk, H.-R.; Kennett, J.P.; Bunch, T.E.; Moore, C.R.; LeCompte, M.A.; Kletetschka, G.; Victor Adedeji, A.; Langworthy, K.; Razink, J.J.; et al. Microstructures in Shocked Quartz: Linking Nuclear Airbursts and Meteorite Impacts. *Airburs. Crater. Imp.* **2023**, *1*, e20230001, doi: [10.14293/ACI.2023.0001](https://doi.org/10.14293/ACI.2023.0001).
 23. Alam, M.; Alshehri, T.; Wang, J.; Singerling, S.A.; Alpers, C.N.; Baalousha, M. Identification and Quantification of Cr, Cu, and As Incidental Nanomaterials Derived from CCA-treated Wood in Wildland-urban Interface Fire Ashes. *J. Hazard. Mater.* **2023**, *445*, 130608, doi: [10.1016/j.jhazmat.2022.130608](https://doi.org/10.1016/j.jhazmat.2022.130608).
 24. Baalousha, M.; Wang, J.; Erfani, M.; Goharian, E. Elemental Fingerprints in Natural Nanomaterials Determined Using SP-ICP-TOF-MS and Clustering Analysis. *Sci. Total Environ.* **2021**, *792*, 148426, doi: [10.1016/j.scitotenv.2021.148426](https://doi.org/10.1016/j.scitotenv.2021.148426).
 25. Wang, J.; Nabi, M.M.; Erfani, M.; Goharian, E.; Baalousha, M. Identification and Quantification of Anthropogenic Nanomaterials in Urban Rain and Runoff Using Single Particle-inductively Coupled Plasma-time of Flight-mass Spectrometry. *Environ. Sci. Nano* **2022**, *9*, 714–729, doi: [10.1039/D1EN00850A](https://doi.org/10.1039/D1EN00850A).
 26. Pace, H.E.; Rogers, N.J.; Jarolimek, C.; Coleman, V.A.; Higgins, C.P.; Ranville, J.F. Determining Transport Efficiency for the Purpose of Counting and Sizing Nanoparticles Via Single Particle Inductively Coupled Plasma Mass Spectrometry. *Anal. Chem.* **2011**, *83*, 9361–9369, doi: [10.1021/ac201952t](https://doi.org/10.1021/ac201952t).
 27. Gundlach-Graham, A.; Hendriks, L.; Mehrabi, K.; Günther, D. Monte Carlo Simulation of Low-Count Signals in Time-of-Flight Mass Spectrometry and its Application to Single-Particle Detection. *Anal. Chem.* **2018**, *90*, 11847–11855, doi: [10.1021/acs.analchem.8b01551](https://doi.org/10.1021/acs.analchem.8b01551).
 28. Kennett, J.P.; Kennett, D.J.; Culleton, B.J.; Aura Tortosa, J.E.; Bischoff, J.L.; Bunch, T.E.; Randolph Daniel, I., Jr.; Erlandson, J.M.; Ferraro, D.; Firestone, R.B.; et al. Bayesian Chronological Analyses Consistent with Synchronous Age of 12,835–12,735 Cal B.P. for Younger Dryas Boundary on Four Continents. *Proc. Natl. Acad. Sci. U. S. A.* **2015**, *112*, E4344–E4353, doi: [10.1073/pnas.1507146112](https://doi.org/10.1073/pnas.1507146112).
 29. Kennett, J.P.; LeCompte, M.A.; Moore, C.R.; Kletetschka, G.; Johnson, J.R.; Wolbach, W.S.; Mitra, S.; Maiorana-Boutillier, A.; Adedeji, V.; Young, M.D.; et al. RETRACTED: Shocked Quartz at the Younger Dryas Onset (12.8 ka) Supports Cosmic Airbursts/Impacts Contributing to North American Megafaunal Extinctions and Collapse of the Clovis Technocomplex. *PLoS One* **2025**, *20*, e0319840, doi: [10.1371/journal.pone.0319840](https://doi.org/10.1371/journal.pone.0319840).
 30. Rasmussen, S.O.; Bigler, M.; Blockley, S.P.; Blunier, T.; Buchardt, S.L.; Clausen, H.B.; Cvijanovic, I.; Dahl-Jensen, D.; Johnsen, S.J.; Fischer, H.; et al. A Stratigraphic Framework for Abrupt Climatic Changes During the Last Glacial Period Based on Three Synchronized Greenland Ice-core Records: Refining and Extending the INTIMATE Event Stratigraphy. *Quat. Sci. Rev.* **2014**, *106*, 14–28, doi: [10.1016/j.quascirev.2014.09.007](https://doi.org/10.1016/j.quascirev.2014.09.007).
 31. Meltzer, D.J.; Holliday, V.T. Would North American Paleoindians have Noticed Younger Dryas Age Climate Changes? *J. World Prehist.* **2010**, *23*, 1–41, doi: [10.1007/s10963-009-9032-4](https://doi.org/10.1007/s10963-009-9032-4).
 32. Kennett, D.J.; Kennett, J.P.; West, A.; West, G.J.; Bunch, T.E.; Culleton, B.J.; Erlandson, J.M.; Que Hee, S.S.; Johnson, J.R.; Mercer, C.; et al. Shock-synthesized Hexagonal Diamonds in Younger Dryas Boundary Sediments. *Proc. Natl. Acad. Sci. U. S. A.* **2009**, *106*, 12623–12628, doi: [10.1073/pnas.0906374106](https://doi.org/10.1073/pnas.0906374106).
 33. Steffensen, J.P.; Andersen, K.K.; Bigler, M.; Clausen, H.B.; Dahl-Jensen, D.; Fischer, H.; Goto-Azuma, K.; Hansson, M.; Johnsen, S.J.; Jouzel, J.; et al. High-resolution Greenland Ice Core Data Show Abrupt Climate Change Happens in Few Years. *Science* **2008**, *321*, 680–684, doi: [10.1126/science.1157707](https://doi.org/10.1126/science.1157707).
 34. Nordt, L.C.; Boutton, T.W.; Jacob, J.S.; Mandel, R.D. C4 Plant Productivity and Climate–CO₂ Variations in South-central Texas During the Late Quaternary. *Quat. Res.* **2002**, *58*, 182–188, doi: [10.1006/qres.2002.2344](https://doi.org/10.1006/qres.2002.2344).
 35. Firestone, R.B.; West, A.; Kennett, J.P.; Becker, L.; Bunch, T.E.; Revay, Z.S.; Schultz, P.H.; Belgia, T.; Kennett, D.J.; Erlandson, J.M.; et al. Evidence for an Extraterrestrial Impact 12,900 Years Ago that Contributed to the Megafaunal Extinctions and the Younger Dryas Cooling. *Proc. Natl. Acad. Sci. U. S. A.* **2007**, *104*, 16016–16021, doi: [10.1073/pnas.0706977104](https://doi.org/10.1073/pnas.0706977104).
 36. Bunch, T.E.; Hermes, R.E.; Moore, A.M.; Kennett, D.J.; Weaver, J.C.; Wittke, J.H.; DeCarli, P.S.; Bischoff, J.L.; Hillman, G.C.; Howard, G.A.; et al. Very High-temperature Impact Melt Products as Evidence for Cosmic Airbursts and Impacts 12,900 Years Ago. *Proc. Natl. Acad. Sci. U. S. A.* **2012**, *109*, E1903–E1912, doi: [10.1073/pnas.1204453109](https://doi.org/10.1073/pnas.1204453109).
 37. Gill, J.L.; Williams, J.W.; Jackson, S.T.; Lininger, K.B.; Robinson, G.S. Pleistocene Megafaunal Collapse, Novel Plant Communities, and Enhanced Fire Regimes in North America. *Science* **2009**, *326*, 1100–1103, doi: [10.1126/science.1179504](https://doi.org/10.1126/science.1179504).
 38. Raper, D.; Bush, M. A Test of *Sporormiella* Representation as a Predictor of Megaherbivore Presence and Abundance. *Quat. Res.* **2009**, *71*, 490–496, doi: [10.1016/j.yqres.2009.01.010](https://doi.org/10.1016/j.yqres.2009.01.010).
 39. Signor, P.W.; Lipps, J.H. Sampling Bias, Gradual Extinction Patterns and Catastrophes in the Fossil Record. In *Geological Implications of Impacts of Large Asteroids and Comets on the Earth*; 1982; pp. 291–296. doi: [10.1130/SPE190-p291](https://doi.org/10.1130/SPE190-p291).

40. Wang, S.C.; Marshall, C.R. Estimating Times of Extinction in the Fossil Record. *Biol. Lett.* **2016**, *12*, 20150989, doi: [10.1098/rsbl.2015.0989](https://doi.org/10.1098/rsbl.2015.0989).
41. Moore, C.R.; Brooks, M.J.; Goodyear, A.C.; Ferguson, T.A.; Perrotti, A.G.; Mitra, S.; Listekci, A.M.; King, B.C.; Mallinson, D.J.; Lane, C.S.; et al. Sediment Cores from White Pond, South Carolina, Contain a Platinum Anomaly, Pyrogenic Carbon Peak, and Coprophilous Spore Decline at 12.8 ka. *Sci. Rep.* **2019**, *9*, 15121, doi: [10.1038/s41598-019-51552-8](https://doi.org/10.1038/s41598-019-51552-8).
42. Seersholm, F.V.; Wernli, D.J.; Greal, A.; Johnson, T.; Keenan Early, E.M.; Lundelius E.L., Jr.; Winsborough, B.; Farr, G.E.; Toomey, R.; Hansen, A.J.; et al. Rapid Range Shifts and Megafaunal Extinctions Associated with Late Pleistocene Climate Change. *Nat. Commun.* **2020**, *11*, 2770, doi: [10.1038/s41467-020-16502-3](https://doi.org/10.1038/s41467-020-16502-3).
43. Courchamp, F.; Clutton-Brock, T.; Grenfell, B. Inverse Density Dependence and the Allee Effect. *Trends Ecol. Evol.* **1999**, *14*, 405–410, doi: [10.1016/S0169-5347\(99\)01683-3](https://doi.org/10.1016/S0169-5347(99)01683-3).
44. Barnosky, A.D.; Lindsey, E.L.; Villavicencio, N.A.; Bostelmann, E.; Hadly, E.A.; Wanket, J.; Marshall, C.R. Variable Impact of Late-Quaternary Megafaunal Extinction in Causing Ecological State Shifts in North and South America. *Proc. Natl. Acad. Sci. U. S. A.* **2016**, *113*, 856–861, doi: [10.1073/pnas.1505295112](https://doi.org/10.1073/pnas.1505295112).
45. Wittke, J.H.; Weaver, J.C.; Bunch, T.E.; Kennett, J.P.; Kennett, D.J.; Moore, A.M.; Hillman, G.C.; Tankersley, K.B.; Goodyear, A.C.; Moore, C.R.; et al. Evidence for Deposition of 10 Million Tonnes of Impact Spherules Across Four Continents 12,800 Y Ago. *Proc. Natl. Acad. Sci. U. S. A.* **2013**, *110*, E2088–E2097, doi: [10.1073/pnas.1301760110](https://doi.org/10.1073/pnas.1301760110).
46. Henry, C.D.; Price, J.G. Early Basin and Range Development in Trans-Pecos Texas and Adjacent Chihuahua: Magmatism and Orientation, Timing, and Style of Extension. *J. Geophys. Res. Solid Earth* **1986**, *91*, 6213–6224, doi: [10.1029/JB091iB06p06213](https://doi.org/10.1029/JB091iB06p06213).
47. Barnes, V.E. Geologic Atlas of Texas, Austin Sheet. *Bureau of Economic Geology*, University of Texas at Austin, 1983.
48. Moune, S.; Faure, F.; Gauthier, P.-J.; Sims, K.W.W. Pele's Hairs and Tears: Natural Probe of Volcanic Plume. *J. Volcanol. Geotherm. Res.* **2007**, *164*, 244–253, doi: [10.1016/j.jvolgeores.2007.05.007](https://doi.org/10.1016/j.jvolgeores.2007.05.007).
49. French, B.M.; Koeberl, C. The Convincing Identification of Terrestrial Meteorite Impact Structures: What Works, what Doesn't, and why. *Earth Sci. Rev.* **2010**, *98*, 123–170, doi: [10.1016/j.earscirev.2009.10.009](https://doi.org/10.1016/j.earscirev.2009.10.009).
50. Moore, A.M.T.; Kennett, J.P.; LeCompte, M.A.; Moore, C.R.; Li, Y.-Q.; Kletetschka, G.; Langworthy, K.; Razink, J.J.; Brogden, V.; van Devener, B.; et al. Abu Hureyra, Syria, Part 1: Shock-fractured Quartz Grains Support 12,800-year-old Cosmic Airburst at the Younger Dryas Onset. *Airburs. Crater. Imp.* **2023**, *1*(1), doi: [10.14293/ACI.2023.0003](https://doi.org/10.14293/ACI.2023.0003).
51. Mahaney, W.C.; Kalm, V.; Krinsley, D.H.; Tricart, P.; Schwartz, S.; Dohm, J.; Kim, K.J.; Kapran, B.; Milner, M.W.; Beukens, R.; et al. Evidence from the Northwestern Venezuelan Andes for Extraterrestrial Impact: The Black Mat Enigma. *Geomorphology* **2010**, *116*, 48–57, doi: [10.1016/j.geomorph.2009.10.007](https://doi.org/10.1016/j.geomorph.2009.10.007).
52. Moore, C.R.; Brooks, M.J.; Dunbar, J.S.; Hemmings, C.A.; Langworthy, K.A.; West, A.; LeCompte, M.A.; Adedeji, V.; Kennett, J.P.; Feathers, J.K. Platinum and Microspherule Peaks as Chronostratigraphic Markers for Onset of the Younger Dryas at Wakulla Springs, Florida. *Sci. Rep.* **2023**, *13*, 22738, doi: [10.1038/s41598-023-50074-8](https://doi.org/10.1038/s41598-023-50074-8).
53. Petaev, M.I.; Huang, S.; Jacobsen, S.B.; Zindler, A. Large Pt anomaly in the Greenland Ice Core Points to a Cataclysm at the Onset of Younger Dryas. *Proc. Natl. Acad. Sci. U. S. A.* **2013**, *110*, 12917–12920, doi: [10.1073/pnas.1303924110](https://doi.org/10.1073/pnas.1303924110).
54. Israde-Alcántara, I.; Bischoff, J.L.; Domínguez-Vázquez, G.; Li, H.C.; DeCarli, P.S.; Bunch, T.E.; Wittke, J.H.; Weaver, J.C.; Firestone, R.B.; West, A.; et al. Evidence from Central Mexico Supporting the Younger Dryas Extraterrestrial Impact Hypothesis. *Proc. Natl. Acad. Sci. U. S. A.* **2012**, *109*, E738–E747, doi: [10.1073/pnas.1110614109](https://doi.org/10.1073/pnas.1110614109).
55. Kurbatov, A.V.; Mayewski, P.A.; Steffensen, J.P.; West, A.; Kennett, D.J.; Kennett, J.P.; Bunch, T.E.; Handley, M.; Introne, D.S.; Que Hee, S.S.; et al. Discovery of a Nanodiamond-rich Layer in the Greenland Ice Sheet. *J. Glaciol.* **2010**, *56*, 747–757, doi: [10.3189/002214310794457191](https://doi.org/10.3189/002214310794457191).
56. Butler, J.E.; Sumant, A.V. The CVD of Nanodiamond Materials. *Chem. Vap. Depos.* **2008**, *14*, 145–160, doi: [10.1002/cvde.200700037](https://doi.org/10.1002/cvde.200700037).
57. Nebel, C.E. CVD Diamond: A Review on Options and Reality. *Funct. Diam.* **2023**, *3*, 2201592, doi: [10.1080/26941112.2023.2201592](https://doi.org/10.1080/26941112.2023.2201592).
58. Robertson, J. The Deposition Mechanism of Diamond-like a-C and a-C: H. *Diam. Relat. Mater.* **1994**, *3*, 361–368, doi: [10.1016/0925.9635\(94\)90186.4](https://doi.org/10.1016/0925.9635(94)90186.4).
59. Van Hoesel, A.; Hoek, W.Z.; Pennock, G.M.; Drury, M.R. The Younger Dryas Impact Hypothesis: A Critical Review. *Quat. Sci. Rev.* **2014**, *83*, 95–114, doi: [10.1016/j.quascirev.2013.10.033](https://doi.org/10.1016/j.quascirev.2013.10.033).
60. Daulton, T.L.; Pinter, N.; Scott, A.C. No Evidence of Nanodiamonds in Younger-Dryas Sediments to Support an Impact Event. *Proc. Natl. Acad. Sci. U. S. A.* **2010**, *107*, 16043–16047, doi: [10.1073/pnas.1003904107](https://doi.org/10.1073/pnas.1003904107).
61. Kennett, D.J.; Kennett, J.P.; West, A.; Mercer, C.; Hee, S.S.; Bement, L.; Bunch, T.E.; Sellers, M.; Wolbach, W.S. Nanodiamonds in the Younger Dryas Boundary Sediment Layer. *Science* **2009**, *323*, 94, doi: [10.1126/science.1162819](https://doi.org/10.1126/science.1162819).
62. Moore, C.R.; West, A.; LeCompte, M.A.; Brooks, M.J.; Daniel, I.R., Jr.; Goodyear, A.C.; Ferguson, T.A.; Ivester, A.H.; Feathers, J.K.; Kennett, J.P.; et al. Widespread Platinum Anomaly Documented at the Younger Dryas Onset in North American Sedimentary Sequences. *Sci. Rep.* **2017**, *7*, 44031, doi: [10.1038/srep44031](https://doi.org/10.1038/srep44031).
63. Holliday, V.T. Soils in Archaeological Research (Oxford University Press, Oxford, 2004).
64. Holliday, V.T. The Blackwater Draw Formation (Quaternary): A 1-4-plus-m.y. Record of Eolian Sedimentation and Soil Formation on the Southern High Plains. *Geol. Soc. Am. Bull.* **1989**, *101*, 1598–1607, doi: [10.1130/0016-7606\(1989\)101<1598:TBDFQA>2.3.CO;2](https://doi.org/10.1130/0016-7606(1989)101<1598:TBDFQA>2.3.CO;2).
65. Voelker, S.L.; Stambaugh, M.C.; Guyette, R.P.; Feng, X.; Grimley, D.A.; Leavitt, S.W.; Panyushkina, I.; Grimm, E.C.; Marsicek, J.P.; Shuman, B.; et al. Deglacial Hydroclimate of Midcontinental North America. *Quat. Res.* **2015**, *83*, 336–344, doi: [10.1016/j.ygres.2015.01.001](https://doi.org/10.1016/j.ygres.2015.01.001).
66. Jones, R.A.; Williams, J.W.; Jackson, S.T. Vegetation History Since the Last Glacial Maximum in the Ozark Highlands (USA): A New Record from Cupola Pond, Missouri. *Quat. Sci. Rev.* **2017**, *170*, 174–187, doi: [10.1016/j.quascirev.2017.06.024](https://doi.org/10.1016/j.quascirev.2017.06.024).
67. Alvarez, L.W.; Alvarez, W.; Asaro, F.; Michel, H.V. Extraterrestrial Cause for the Cretaceous-tertiary Extinction. *Science* **1980**, *208*, 1095–1108, doi: [10.1126/science.208.4448.1095](https://doi.org/10.1126/science.208.4448.1095).
68. Goderis, S.; Sato, H.; Ferrière, L.; Schmitz, B.; Burney, D.; Kaskes, P.; Vellekoop, J.; Wittmann, A.; Schulz, T.; Chernozhukhin, S.M.; et al. Globally Distributed Iridium Layer Preserved within the Chicxulub Impact Structure. *Sci. Adv.* **2021**, *7*, eabe3647, doi: [10.1126/sciadv.abe3647](https://doi.org/10.1126/sciadv.abe3647).
69. Payne, D. Iridium's Impact. *Nat. Chem.* **2016**, *8*, 392, doi: [10.1038/nchem.2486](https://doi.org/10.1038/nchem.2486).
70. Goldstein, J.I.; Scott, E.R.D.; Chabot, N.L. Iron Meteorites: Crystallization, Thermal History, Parent Bodies, and Origin. *Geochemistry* **2009**, *69*, 293–325, doi: [10.1016/j.chemer.2009.01.002](https://doi.org/10.1016/j.chemer.2009.01.002).
71. Kyte, F.T. A Meteorite from the Cretaceous/Tertiary Boundary. *Nature* **1998**, *396*, 237–239, doi: [10.1038/24322](https://doi.org/10.1038/24322).
72. Meyers, P.A. Preservation of Elemental and Isotopic Source Identification of Sedimentary Organic Matter. *Chem. Geol.* **1994**, *114*, 289–302, doi: [10.1016/0009-2541\(94\)90059-0](https://doi.org/10.1016/0009-2541(94)90059-0).
73. Bindi, L.; Kennett, J.P.; LeCompte, M.A.; Kletetschka, G.; Moore, C.R.; West, A. Trigonal Fe₂Si from the Blackville Site, South Carolina, USA: Occurrence, Composition and Determination of the Crystal Structure. *Mineral. Mag.* **2026**, *90*(1), 87–92. doi: [10.1180/mgm.2025.10130](https://doi.org/10.1180/mgm.2025.10130).

74. Rappenglück, M.A.; Ernstson, K.; Mayer, W.; Beer, R.; Benske, G.; Siegl, C.; Sporn, R.; Bliemetsrieder, T.; Schüssler, U. *The Chiemgau Impact event in the Celtic Period: Evidence of a Crater Strewnfield and a Cometary Impactor Containing Presolar Matter*. Chiemgau-Impakt c/o Kord Ernstson, 2004.
75. Ernstson, K.; Bauer, F.; Hiltl, M. A Prominent Iron Silicides Strewn Field and its Relation to the Bronze Age/Iron Age Chiemgau Meteorite Impact Event (Germany). *Earth Sci.* **2023**, *12*, 26–40, doi: [10.11648/j.earth.20231201.14](https://doi.org/10.11648/j.earth.20231201.14).
76. Ross, A.J.; Downes, H.; Herrin, J.S.; Mittlefehldt, D.W.; Humayun, M.; Smith, C. The Origin of Iron Silicides in Ureilite Meteorites. *Geochemistry* **2019**, *79*, 125539, doi: [10.1016/j.chemer.2019.125539](https://doi.org/10.1016/j.chemer.2019.125539).
77. Anand, M.; Taylor, L.A.; Nazarov, M.A.; Shu, J.; Mao, H.K.; Hemley, R.J. Space Weathering on Airless Planetary Bodies: Clues from the Lunar Mineral Hapkeite. *Proc. Natl. Acad. Sci. U. S. A.* **2004**, *101*, 6847–6851, doi: [10.1073/pnas.0401565101](https://doi.org/10.1073/pnas.0401565101).
78. Rietmeijer, F.J.M. Understanding the Comet Wild 2 Mineralogy in Samples from the Stardust Mission. *Powder Diffr.* **2008**, *23*, 74–80, doi: [10.1154/1.2912327](https://doi.org/10.1154/1.2912327).
79. Rappenglück, M.A. Natural Iron Silicides: A Systematic Review. *Minerals* **2022**, *12*, 188, doi: [10.3390/min12020188](https://doi.org/10.3390/min12020188).
80. Moore, C.R.; Tselmovich, V.A.; LeCompte, M.A.; West, A.; Culver, S.J.; Mallinson, D.J.; Baalousha, M.; Kennett, J.P.; Napier, W.M.; Bizimis, M.; et al. A 12,800-year-old layer with cometary dust, microspherules, and platinum anomaly recorded in multiple cores from Baffin Bay (expanded). *Airburs. Crater. Imp.* **2026**, *4*, e20260004, doi: [10.14293/ACI.2026.0004](https://doi.org/10.14293/ACI.2026.0004).
81. Young, M.D. Geochemical Re-evaluation Supports Cosmic Impact Rather than Volcanism at Younger Dryas Onset, Hall's Cave, Texas: Reply to Sun et al. 2020. *Airburs. Crater. Imp.* **2025**, *3*, 20250007, doi: [10.14293/ACI.2025.0007](https://doi.org/10.14293/ACI.2025.0007).
82. Peucker-Ehrenbrink, B.; Ravizza, G. The Marine Osmium Isotope Record. *Terra Nova* **2000**, *12*, 205–219, doi: [10.1046/j.1365.3121.2000.00295.x](https://doi.org/10.1046/j.1365.3121.2000.00295.x).
83. Ravizza, G.; Peucker-Ehrenbrink, B. The Marine $^{187}\text{Os}/^{188}\text{Os}$ Record of the Eocene–Oligocene Transition: The Interplay of Weathering and Glaciation. *Earth Planet. Sci. Lett.* **2003**, *210*, 151–165, doi: [10.1016/S0012-821X\(03\)00137-7](https://doi.org/10.1016/S0012-821X(03)00137-7).
84. Ravizza, G.; Peucker-Ehrenbrink, B. Chemostratigraphic Evidence of Deccan Volcanism from the Marine Osmium Isotope Record. *Science* **2003**, *302*, 1392–1395, doi: [10.1126/science.1089209](https://doi.org/10.1126/science.1089209).
85. Koeberl, C. Identification of Meteoritic Components in Impactites. *Geol. Soc. Lon. Spec. Publ.* **1998**, *140*, 133–153, doi: [10.1144/GSL.SP.1998.140.01.11](https://doi.org/10.1144/GSL.SP.1998.140.01.11).
86. Greshake, A.; Kloeck, W.; Arndt, P.; Maetz, M.; Flynn, G.J.; Bajt, S.; Bischoff, A. Heating Experiments Simulating Atmospheric Entry Heating of Micrometeorites: Clues to their Parent Body Sources. *Meteorit. Planet. Sci.* **1998**, *33*, 267–290, doi: [10.1111/j.1945.5100.1998.tb01632.x](https://doi.org/10.1111/j.1945.5100.1998.tb01632.x).
87. Rudnick, R.L.; Gao, S. *Composition of the Continental Crust*; Rudnick, R.L., Ed.; Elsevier, 2003; Volume 3, pp. 1–64.
88. Taylor, S.R.; McLennan, S.M. *The Continental Crust: Its Composition and Evolution*. Blackwell Scientific Publications, Oxford, 1985.
89. Flynn, G.J.; Bleuet, P.; Borg, J.; Bradley, J.P.; Brenker, F.E.; Brennan, S.; Bridges, J.; Brownlee, D.E.; Bullock, E.S.; Burghammer, M.; et al. Elemental Compositions of Comet 81P/Wild 2 Samples Collected by Stardust. *Science* **2006**, *314*, 1731–1735, doi: [10.1126/science.1136141](https://doi.org/10.1126/science.1136141).
90. Goderis, S.; Simonson, B.M.; McDonald, I.; Hassler, S.W.; Izmer, A.; Belza, J.; Terryn, H.; Vanhaecke, F.; Claeys, P. Ni-rich Spinel and Platinum Group Element Nuggets Condensed from a Late Archaean Impact Vapour Cloud. *Earth Planet. Sci. Lett.* **2013**, *376*, 87–98, doi: [10.1111/j.1945-5100.1998.tb01632.x](https://doi.org/10.1111/j.1945-5100.1998.tb01632.x).
91. Taylor, S. *Digital dataset (National Snow and Ice Data Center, Boulder, CO)*; U.S. Antarctic Program Data Center, 2002.
92. Genge, M.J.; Grady, M.M.; Hutchison, R. The Textures and Compositions of Fine-grained Antarctic Micrometeorites: Implications for Comparisons with Meteorites. *Geochim. Cosmochim. Acta* **1997**, *61*, 5149–5162, doi: [10.1016/S0016-7037\(97\)00308-6](https://doi.org/10.1016/S0016-7037(97)00308-6).
93. Koch, P.L.; Barnosky, A.D. Late Quaternary Extinctions: State of the Debate. *Annu. Rev. Ecol. Evol. Syst.* **2006**, *37*, 215–250, doi: [10.1146/annurev.ecolsys.34.011802.132415](https://doi.org/10.1146/annurev.ecolsys.34.011802.132415).
94. Meltzer, D.J. Overkill, Glacial History, and the Extinction of North America's Ice Age Megafauna. *Proc. Natl. Acad. Sci. U. S. A.* **2020**, *117*, 28555–28563, doi: [10.1073/pnas.2015032117](https://doi.org/10.1073/pnas.2015032117).
95. Rasmussen, S.O.; Andersen, K.K.; Svensson, A.M.; Steffensen, J.P.; Vinther, B.M.; Clausen, H.B.; Siggaard-Andersen, M.-L.; Johnsen, S.J.; Larsen, L.B.; Dahl-Jensen, D.; et al. A New Greenland Ice Core Chronology for the Last Glacial Termination. *J. Geophys. Res. Atmos.* **2006**, *111*, doi: [10.1029/2005JD006079](https://doi.org/10.1029/2005JD006079).