



Research Article

Microspherules, meltglass, and nanoparticles from the Younger Dryas boundary layer at White Pond, USA

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ABSTRACT

Sediment cores from White Pond, South Carolina, preserve a well-constrained Younger Dryas Boundary (YDB) interval dated by Bayesian age modeling to ~12,875–12,775 cal BP and previously shown to contain a platinum (Pt) anomaly, elevated Pt/Pd ratios, a peak in pyrogenic carbon, and a decline in coprophilous spores. Here we report additional high-temperature proxies from this same horizon, including microspherules, vesicular meltglass, and metal-bearing nanoparticles, integrating laser ablation ICP-MS (LA-ICP-MS) and single-particle ICP time-of-flight mass spectrometry (SP-ICP-TOF-MS) to evaluate their origin and carrier phases.

Scanning electron microscopy reveals Fe-rich and aluminosilicate microspherules exhibiting dendritic crystallization, quench textures, and vesiculation, together with vesicular meltglass, all confined to the YDB layer. Laser ablation ICP-MS analyses show that individual microspherules contain strongly elevated absolute platinum concentrations

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(up to $\sim 82\text{--}89\times$ upper continental crust) and correspondingly elevated Pt/Fe ratios. However, Fe-normalized Ni/Fe ratios remain within or near terrestrial compositional fields, indicating that the microspherules are dominantly derived from melted local sediment rather than from bulk meteoritic metal.

In contrast, SP-ICP-TOF-MS data document synchronous increases in platinum-group-element (PGE)–bearing (Ir, Pt, Pd, Os, Ru) and transition-metal–bearing (Ni, Co, Cr, V, Fe) nanoparticles at the YDB. This interval is marked by coincident peaks in total nanoparticle mass and number, together with a reduction in average mass per particle, indicating enrichment in numerous low-mass nanoparticles. This population structure is consistent with high-temperature processing and rapid formation of fine metal-rich particles during a short-lived depositional event, potentially involving vaporization and condensation processes, rather than accumulation of a small number of large particles. Nanoparticle Pt/Fe, Ir/Fe, and HSE/Ni ratios overlap fields defined by metal-rich extraterrestrial materials, including refractory metal nuggets and cometary matter, and show minimal overlap with magmatic or upper-crustal compositions.

Chondrite-normalized multi-element, rare-earth-element (REE), and PGE patterns show that the YDB layer does not reflect bulk meteoritic mixing or large-scale melt differentiation but instead records a subtle enrichment of background terrestrial sediment. The coexistence of terrestrial melt spherules and compositionally distinct metal-rich nanoparticles supports a two-population framework involving sediment melting alongside condensation or delivery of siderophile-enriched nanoparticles during a short-lived event. Absence of cryptotephra argues against a volcanic source. Together, these multiproxy observations are consistent with an abrupt, high-energy depositional pulse at the onset of the Younger Dryas and are compatible with processes proposed under the Younger Dryas Impact Hypothesis, including low-altitude airbursts or fragmented impacts by metal-bearing primitive bodies such as comets or rubble-pile asteroids.

KEYWORDS

Younger Dryas boundary, platinum anomaly, nanoparticles, microspherules, meltglass, SP-ICP-TOF-MS

Introduction and background

The Younger Dryas (YD), a period of abrupt climate cooling that began around ca. 12,800 years ago, represents one of the most significant and rapid climatic transitions of the Late Quaternary. It has been associated with widespread environmental change, including the extinction of megafauna and disruptions to human populations across North America [1–3]. The prevailing explanation attributes YD cooling to disruption of North Atlantic thermohaline circulation driven by meltwater discharge from the Laurentide Ice Sheet [4, 5]. Additional hypotheses propose that an abrupt external forcing, such as a cosmic impact or series of atmospheric airbursts, may have contributed to or amplified environmental and climatic instability at the YD onset, potentially through widespread biomass burning, short-lived atmospheric perturbations, and secondary effects on ice-sheet dynamics and freshwater fluxes relevant to Atlantic Meridional Overturning Circulation slowdown [6–8]. Numerous lines of evidence potentially consistent with the Younger Dryas Impact Hypothesis (YDIH) have been reported at dozens of sites worldwide. This body of evidence includes elevated concentrations of multiple impact-related proxies, such as magnetic microspherules [6, 9–16], platinum [11–15, 17–20], iridium [6, 11, 20–22], meltglass [11, 12, 23], nanodiamonds [11, 12, 20, 24–27], and combustion-related

materials, including aerosols and soot [11, 12, 19, 20, 27–29]. These proxies have been identified in sedimentary deposits dating to the lower Younger Dryas Boundary (YDB) across a broad geographic range, including North America [6], central Mexico [30], South America [31, 32], South Africa [33], Europe [6, 34–36], Greenland [21], the Middle East [11, 12, 20, 27], and within lacustrine, marine, and ice core records on a global scale [28, 29].

Geochemical signatures such as platinum (Pt) enrichment, microspherules, and elevated concentrations of pyrogenic carbon have thus been documented at multiple YDB sites, although taphonomic processes, depositional reworking, and chronological uncertainties have complicated interpretation at several localities. In this study, we analyze sediment cores from White Pond, South Carolina, an undisturbed, well-stratified lacustrine basin in the southeastern United States, to assess the stratigraphic integrity, timing, and geochemical characteristics of environmental disruption recorded at the onset of the Younger Dryas, and to evaluate the processes capable of producing the observed proxy assemblage.

Study site

White Pond is a natural, spring-fed, shallow lake located in north-central South Carolina (34.1680°N, –80.7760°W)

along the western margin of the Atlantic Coastal Plain (Figure 1). The 28-hectare basin contains shallow water, with depths rarely exceeding 2 m. It is surrounded by relict eolian and fluvial sands that overlie deeply weathered Cretaceous and Tertiary clay-rich substrates. A nearly 6-meter-thick sequence of peat, organic-rich mud, and silt has accumulated within the basin since before the Last Glacial Maximum (LGM), or possibly earlier. Recent coring by Krause et al. [37] identified basal sediments dating to approximately 31–32 ka at a depth of 5.5 m. The basin occupies a streamhead depression that likely formed through erosional scour followed by damming of local drainage by large Pleistocene sand dunes along the southern margin of the lake. Previous paleoenvironmental [19, 37, 38] and archaeological investigations demonstrate that the stratigraphy of White Pond preserves a diverse archive of biomarkers, stable isotopes, and discrete event layers.

Previous Work. Moore et al. [19] reported a series of geochemical and paleoecological changes centered around ~12,800 cal yr BP in sediment cores from White Pond, corresponding to the onset of the Younger Dryas (YD). A pronounced platinum (Pt) anomaly and elevated Pt/Pd ratios occur within a ~2-cm interval, with a Bayesian age model placing the horizon at $12,785 \pm 58$ cal yr BP [19].

This Pt enrichment is nearly coeval with a peak in pyrogenic carbon (soot) at $12,838 \pm 103$ cal BP, a decline in coprophilous fungal spores at $12,752 \pm 54$ cal BP, and a negative $\delta^{15}\text{N}$ excursion, all occurring within the Younger Dryas Boundary (YDB) layer as reported in Moore et al. [19] (see Supplementary Figure S23 and Table S1; <https://zenodo.org/records/18684761>). Together, these observations indicate rapid regional environmental disruption at the onset of the YD.

Watts [38] and Krause et al. [37] established the multi-proxy stratigraphic framework for White Pond through separate coring campaigns. The chronology used here follows the Bayesian age–depth model of Moore et al. [19], which incorporates additional radiocarbon constraints and was designed specifically to resolve the Younger Dryas Boundary interval.

Notably, Moore et al. [19] found no evidence of volcanic ash (cryptotephra) or anomalous mercury levels associated with the YD boundary, discounting a volcanogenic origin for the Pt anomaly. The study also identified a substantial depositional hiatus of approximately 2,400 years following the YD onset, complicating interpretations of megafaunal extinction timing at this site. However, the observed pre-hiatus decline in coprophilous spores aligns temporally with

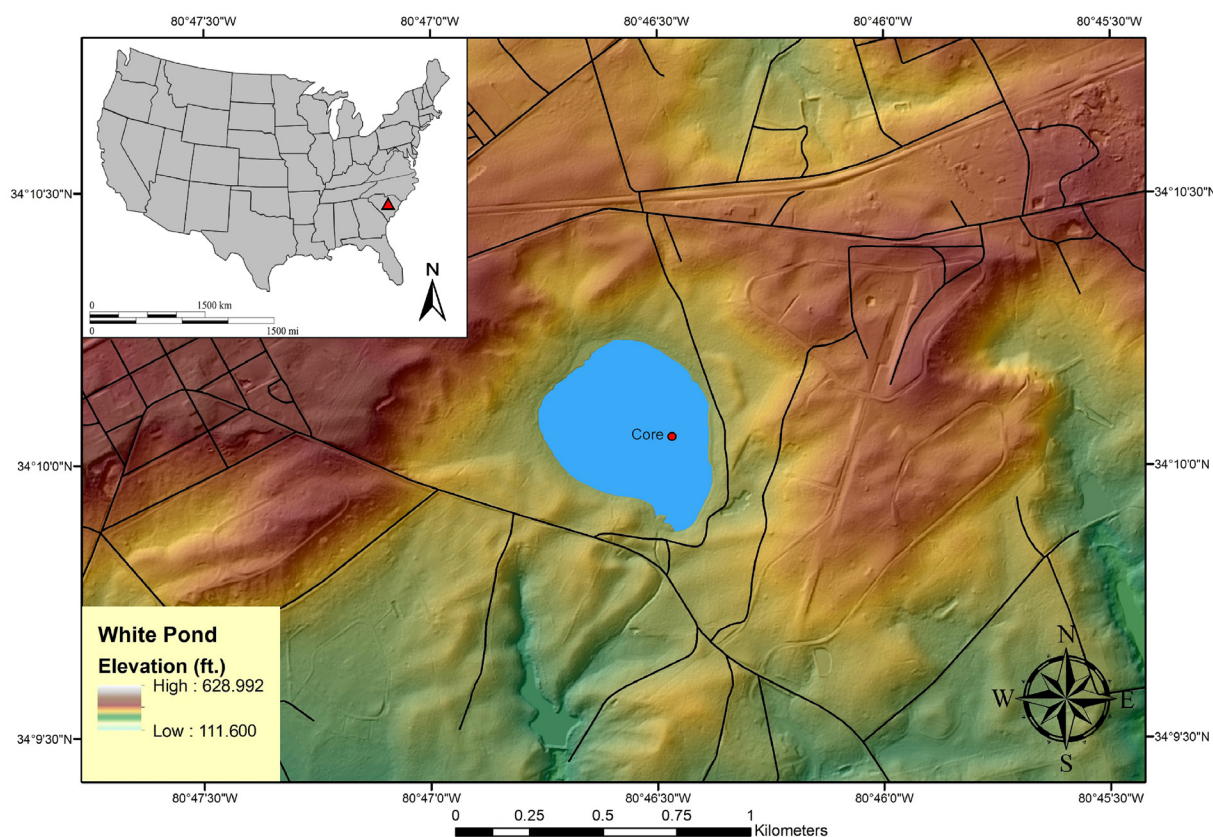


Figure 1: LiDAR image of White Pond near Elgin, South Carolina, showing the location of vibracores collected in 2016 (34.1680°N , -80.7744°W). The figure is from Moore et al. [19] licensed under CC BY 4.0. Cores were collected ~1 meter apart.

declines reported at other North American sites, suggesting a broader continental pattern [39–42].

Stable isotopes of carbon and nitrogen and magnetic susceptibility data at the YD onset at White Pond support a shift toward increased terrestrial biomass and changing watershed nutrient dynamics during and after the YD [19]. These patterns reinforce the interpretation of an abrupt climatic and ecological transition initiated at the boundary.

Results and interpretation

In 2019, Moore et al. [19] reported a pronounced spike in platinum concentration and a concurrent peak in pyrogenic carbon (soot) in core WP-16-2 within the YDB layer at White Pond. Similar platinum anomalies have been reported in YDB layers at sites across multiple continents and in the Greenland ice sheet, consistent with an extraterrestrial impact

event [17, 18, 43, 44]. Pyrogenic carbon is interpreted as evidence of widespread biomass burning, and large YDB peaks in pyrogenic carbon have been reported from ice cores, lake cores, and terrestrial cores globally [28, 29]. Moore et al. [19] also observed a marked decline in coprophilous fungal spores, including *Sporormiella*, in core WP-16-3, consistent with a rapid reduction in megafaunal biomass and ecological disruption at the onset of the Younger Dryas.

Microspherules and meltglass

Building on the work of Moore et al. [19], we sampled additional core intervals through the YDB to investigate microspherules and meltglass similar to those reported from other global YDB sites. Scanning electron microscopy of samples from cores WP-16-3 and WP-16-4 revealed the presence of high-temperature spherules and vesicular meltglass particles (Figures 2 and 3 and Supplementary Figures S1–22;

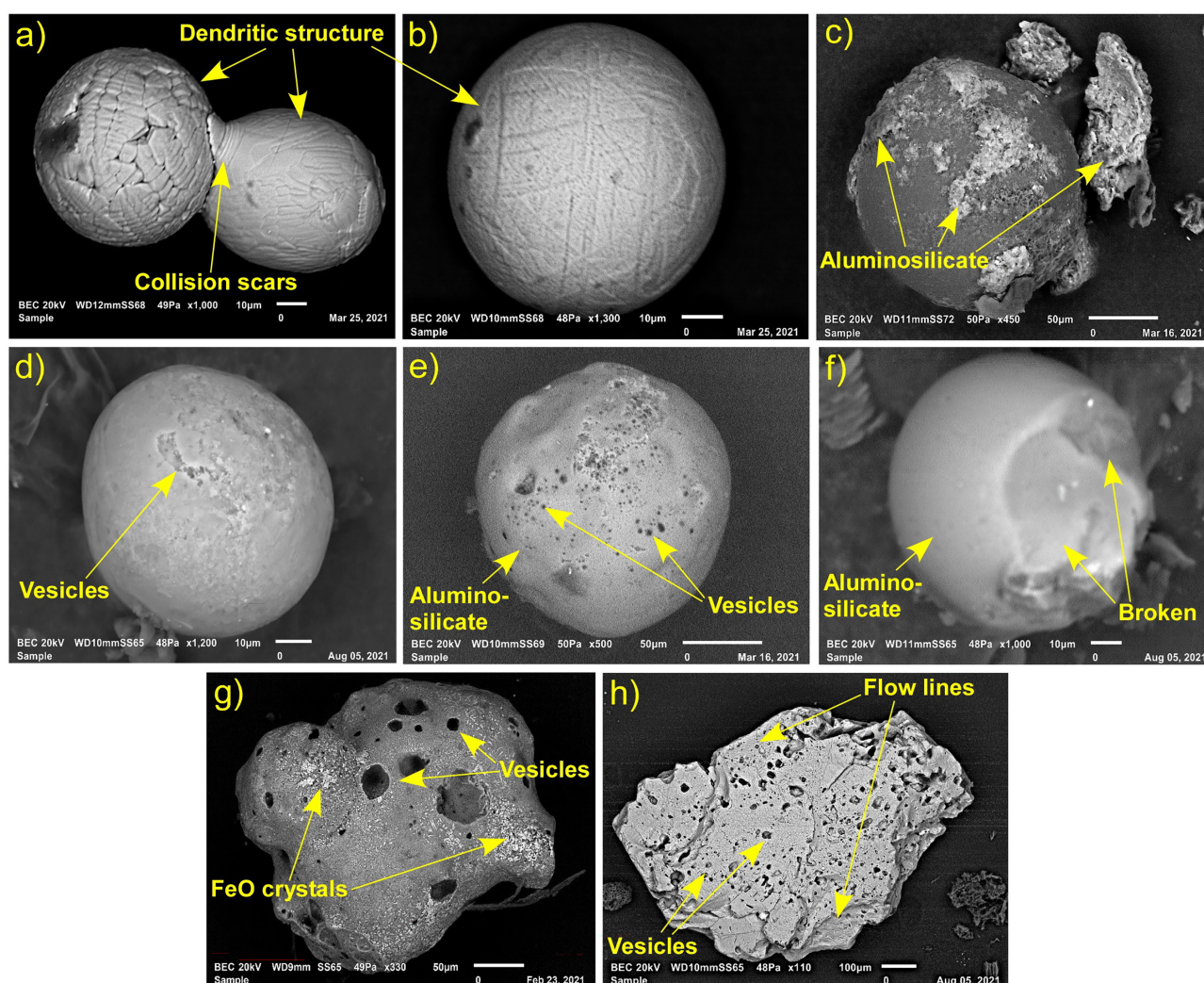


Figure 2: Examples of Fe-rich and silica-rich microspherules (a–f) and meltglass (g–h) from White Pond (cores WP-16-3 and WP-16-4). See Supplementary Figures S1–S22 for additional images and EDS data (<https://zenodo.org/records/18684761>). Dendritic crystals, vesicles, and flow lines indicative of high-temperature melting are visible. Spherules (d–f) are composed of aluminosilicate, with spherule (d) showing detectable Os enrichment in EDS spectra.

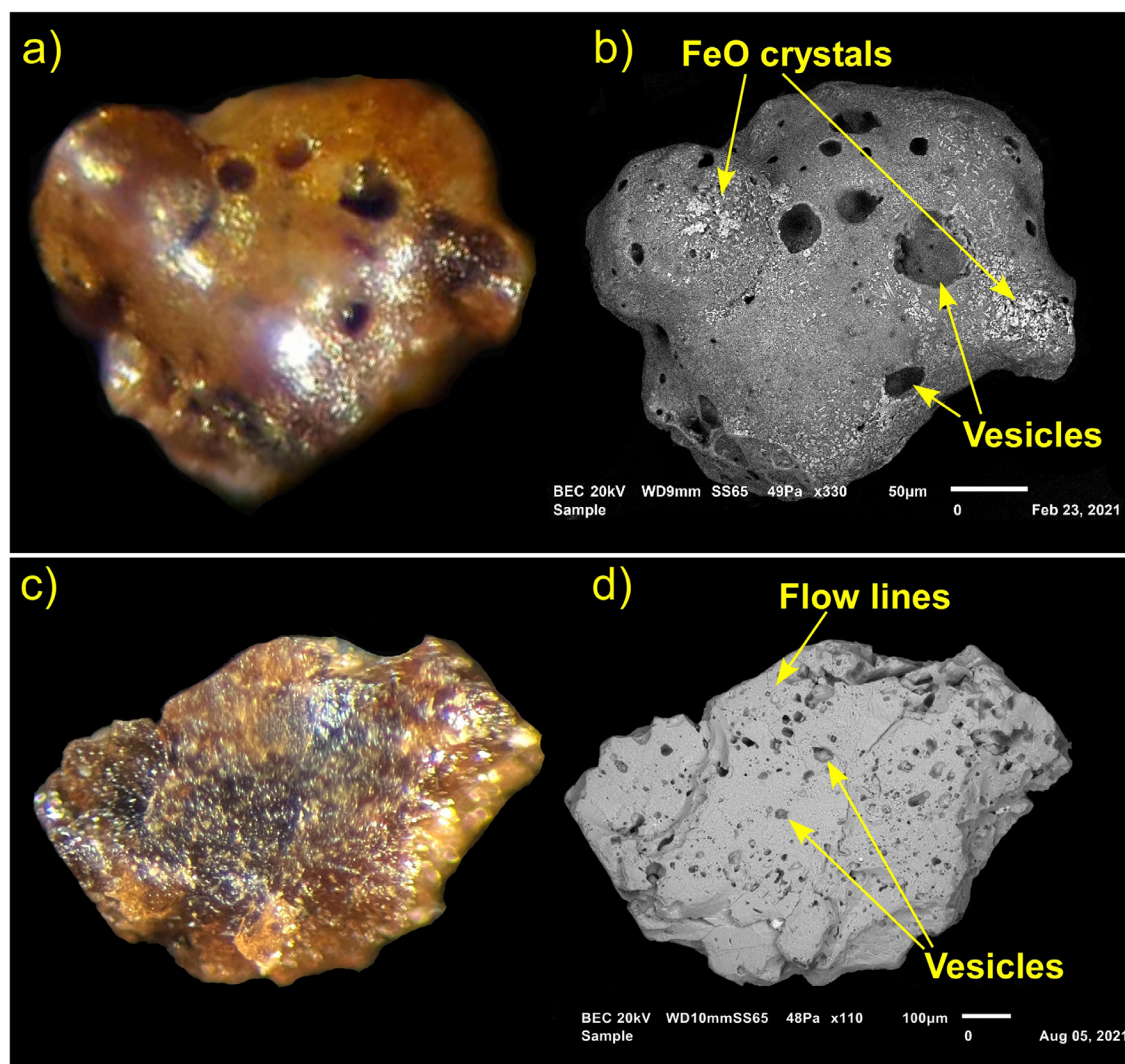


Figure 3: Optical (a, c) and SEM images (b, d) of meltglass from White Pond (Cores 3 and 4). See Supplementary Figures S16–22 for additional images and EDS data (<https://zenodo.org/records/18684761>). Note dendritic crystals, vesicles, and flow lines.

<https://zenodo.org/records/18684761>). Microspherules and meltglass were found exclusively within YD-onset age sediments (Figure 4 and Supplementary Table S2) and display morphologies and elemental compositions consistent with formation under extreme thermal conditions [23, 47]. Iron-rich spherules with quench textures and flow structures, an iron-rich dendritic spherule doublet with collisional deformation scars, carbon spherules embedded with aluminosilicate melt, and aluminosilicate spherules were found in Cores 3 and 4.

Trace platinum-group elements (Pt, Pd, and Os) were detected by EDS at the limits of detection in a limited subset of aluminosilicate melt spherules and meltglass fragments, whereas most spherules lack measurable PGEs. This heterogeneous distribution indicates that PGEs are not intrinsic to all spherules but occur selectively within certain high-temperature melt products, consistent with the incorporation

of minor PGE-bearing particulate material rather than bulk meteoritic mixing.

Laser ablation ICP-MS geochemistry of YDB spherules

To further characterize the geochemical composition of individual YDB microspherules, laser ablation ICP-MS (LA-ICP-MS) analyses were conducted on representative spherules from the White Pond cores, spherule WP16-3 A and spherule WP 16-3 B. Results are summarized in Table 1.

Platinum concentrations in the analyzed spherules are elevated relative to upper continental crust, reaching 41.5 ppb (WP16-3 B), and 45.1 ppb (WP16-3 A), corresponding to ~82–89× crustal abundance. Chromium and vanadium are also enriched (Cr up to 243.8 ppm; V up to 183.5 ppm), exceeding crustal values by factors of ~1.9–2.3. Nickel and

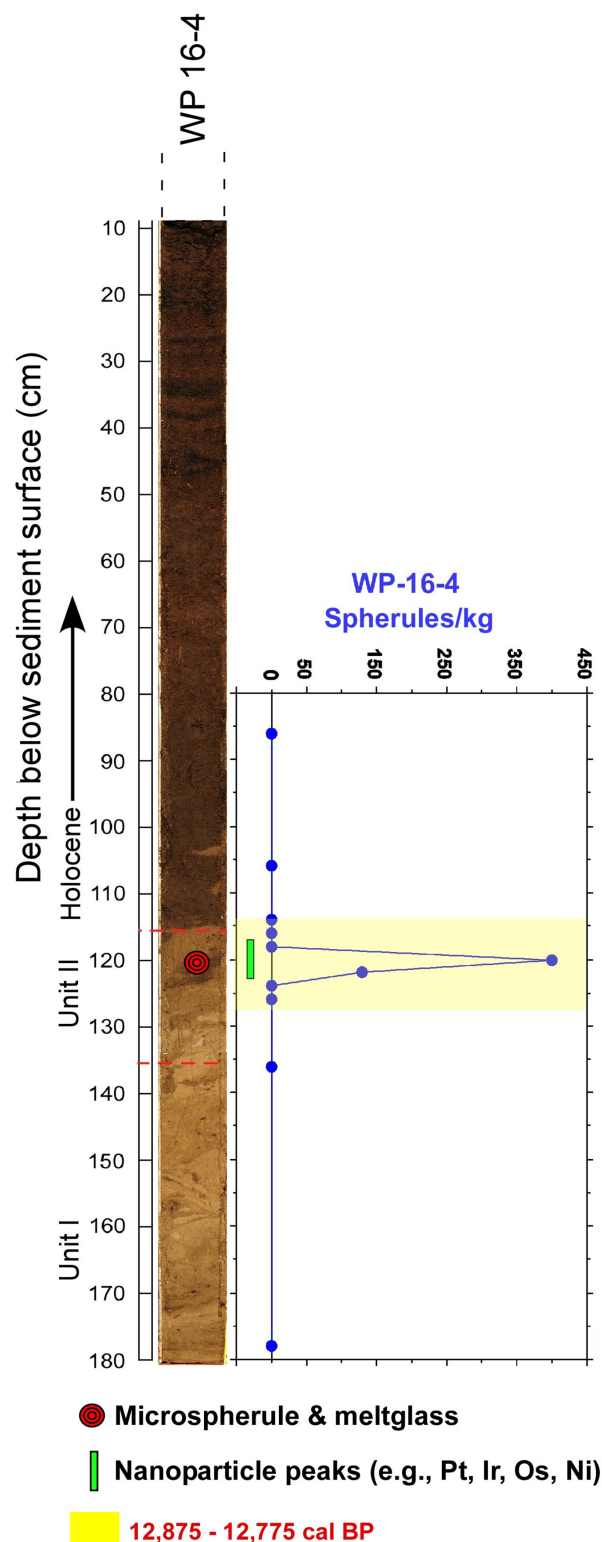


Figure 4: Microspherule abundance for WP-16-4 (spherules/kg). The yellow rectangle represents the Bayesian modeled YD onset (12,875–12,775 cal BP; IntCal20) [45, 46] determined by the age/depth model in Moore et al. [19] (see Supplementary Table S2 and Figure S23 that is adapted from Moore et al. [19]) (<https://zenodo.org/records/18684761>).

cobalt concentrations are modest (Ni = 113.8–140.0 ppm; Co = 27.8–48.4 ppm), with enrichments ranging from ~0.1–3.2× crust, depending on the sample.

Elemental ratios provide additional constraints. Ni/Fe ratios range from 1.23×10^{-3} to 2.63×10^{-3} (1.37–2.94× crust), whereas Pt/Fe ratios range from 3.97×10^{-7} to 9.61×10^{-7} (30–75× crust). Pt/Ni ratios are on the order of 3.2 – 3.6×10^{-4} . Despite elevated absolute Pt concentrations and Pt/Fe values greatly exceeding continental crust, Fe-normalized Ni ratios remain within or near terrestrial compositional fields and do not approach values characteristic of metal-rich meteoritic alloys.

These LA-ICP-MS data indicate that the analyzed spherules are chemically dominated by melted terrestrial sediment, with selective enrichment of certain trace metals but without bulk meteoritic metal signatures.

Nanoparticles

The elemental SP-ICP-TOF-MS nanoparticle data collected from above, below, and within the YDB in Core WP-16-4 are given in Table 2.

We compare sample WP 121–123 and WP 135–137 using a CI chondrite normalized multi-element spider diagram (Figure 5a, b). Sample WP 121–123 was collected from the YDB horizon, whereas WP 135–137 was collected approximately 12 cm below the YDB, representing sediment deposited prior to and unaffected by the hypothesized airburst event. Sample WP 135–137, therefore, serves as a local stratigraphic background, while WP 121–123 captures the chemical characteristics of the boundary layer itself. Together, these samples bracket the event horizon and allow evaluation of whether the YDB layer reflects bulk geochemical modification or a more limited overprint superimposed on pre-existing sedimentary material.

The spider diagram demonstrates that the two samples share nearly identical trace-element and rare-earth-element (REE) patterns (Figure 5b does not use a logarithmic y-axis to demonstrate the variations better in terms of the light elements), differing primarily in overall abundance rather than in shape. This close parallelism suggests that the YDB horizon did not undergo large-scale melt differentiation or melt–residue separation sufficient to measurably fractionate the REE system. In particular, the absence of significant REE slope changes or Eu anomalies argue against large-scale differentiation at any level and implies that any high-temperature processes associated with the event were localized and limited in mass.

At the same time, siderophile and transition-metal abundances (e.g., V–Ni) remain extremely subchondritic or maintain subchondritic end-member values in both samples, ruling out bulk meteoritic mixing as a dominant control on whole-rock chemistry. Any extraterrestrial contribution must therefore have been minor, particulate, and highly diluted within the sediment matrix. These data show that the YDB layer reflects a brief, externally driven thermal perturbation

Table 1: LA-ICP-MS elemental concentrations and selected elemental ratios for individual Younger Dryas Boundary (YDB) microspherules from White Pond (Core 16-3).

Element	Measured values		Times upper crust	
	WP16-3 A	WP 16-3 B	WP16-3 A	WP 16-3 B
Pt (ppb)	45.1	41.5	89.40	82.18
Cr (ppm)	243.8	136.3	3.32	1.85
Cu (ppm)	81.3	210.0	0.15	9.06
Ni (ppm)	140.0	113.8	0.11	3.24
Co (ppm)	48.4	27.8	0.20	1.79
V (ppm)	183.5	173.7	2.32	2.20
Ni/Fe	1.231E-03	2.634E-03	1.37	2.94
Pt/Ni	3.224E-04	3.646E-04	--	--
Pt/Fe	3.968E-07	9.605E-07	30.80	74.56

Measured concentrations are shown alongside enrichment factors relative to upper continental crust. Green-highlighted cells represent significant enrichment over crustal values. Platinum concentrations and Pt/Fe values are strongly elevated, but Ni/Fe ratios remain within or near terrestrial compositional ranges, indicating that the spherules are dominantly derived from melted terrestrial sediment rather than bulk meteoritic metal.

Table 2: SP-ICP-TOF-MS geochemical data for the samples collected from the Core WP-16-4 at various depths.

Element	WP 117-119		WP 119-121		WP 121-123		WP 123-125		WP 125-127		WP 135-137		WP 177-179	
	WP 113-115	WP 115-117	MQ	MQ	MQ	MQ	WP 123-125	WP 125-127	WP 135-137	MQ	WP 123-125	WP 125-127	WP 135-137	MQ
Al	37652.9	135230.2	148442.8	161874.6	433607.9	157415.5	176411.6	273713.7	384595.3					
Ti	7349.5	5430.8	9051.8	6413.6	26475.0	8714.0	9586.4	16870.6	15147.9					
V	35.0	24.9	52.9	49.8	54.5	29.3	35.7	42.2	56.8					
Cr	507.1	26.1	55.2	271.1	1083.7	180.8	72.7	43.1	46.3					
Mn	94.6	104.0	28.0	41.4	100.0	51.1	36.9	128.9	104.0					
Fe	9887.0	36951.3	13924.6	29772.3	42128.1	15093.1	24501.4	31037.0	33545.1					
Co	13.7	11.5	9.2	8.6	12.4	8.7	5.2	10.6	7.7					
Ni	385.6	44.1	44.8	107.4	488.6	84.5	140.2	55.7	57.7					
Cu	123.4	94.8	65.9	56.1	159.5	99.7	56.4	57.4	46.8					
Zn	70.3	65.6	132.5	124.9	50.9	40.6	41.4	84.6	126.4					
As	146.8	105.0	119.3	112.5	120.9	134.7	96.1	107.4	68.6					
Zr	31.1	39.7	51.2	58.4	180.5	68.2	20.2	63.6	334.6					
Nb	15.2	12.4	27.2	13.8	33.2	16.7	21.5	15.7	26.8					
Ru	24.0	16.8	33.5	23.6	16.6	14.9	27.4	19.8	20.5					
Rh	7.9	8.6	5.8	5.3	5.4	5.3	5.3	4.1	2.9					
Pd	62.4	52.4	44.5	57.5	51.9	45.4	67.5	44.9	62.7					
Sn	29.3	22.9	22.9	24.8	14.4	23.7	20.1	24.7	25.1					
Sb	23.0	12.7	23.7	26.0	16.8	11.0	12.8	7.8	14.6					
Ba	72.5	167.5	190.5	241.6	685.0	222.5	312.5	346.2	535.4					
La	18.4	33.9	37.5	75.8	252.8	67.1	60.0	95.2	106.0					
Ce	40.1	94.9	111.4	210.9	776.5	159.3	160.6	266.0	347.4					
Pr	7.3	9.1	10.2	18.4	53.0	13.9	11.8	17.0	25.3					
Nd	34.5	41.0	45.1	100.8	297.4	46.0	57.9	67.4	122.5					
Sm	25.3	23.1	18.0	19.9	33.6	19.6	17.7	18.2	21.7					
Eu	10.0	10.6	8.1	7.8	9.7	7.7	7.9	8.3	7.3					
Gd	23.6	22.5	16.0	24.9	33.6	18.9	18.0	15.9	19.0					
Tb	5.0	4.5	5.1	4.5	5.2	4.7	4.4	4.4	3.9					
Dy	12.9	17.9	13.0	15.1	14.6	19.3	16.4	16.1	11.7					
Ho	6.9	5.6	5.9	4.7	4.1	6.1	3.2	3.0	4.0					
Er	15.5	14.6	12.3	15.7	14.9	17.0	7.8	11.8	6.9					
Tm	4.7	4.4	4.2	5.5	4.1	3.7	3.7	3.7	4.3					
Yb	17.2	15.5	13.9	14.4	15.5	18.1	14.0	11.9	10.2					
Lu	5.9	4.9	4.9	2.6	3.4	4.4	3.7	3.8	4.0					
Hf	20.3	17.4	18.3	18.5	12.6	14.4	16.7	10.2	17.1					
Ta	38.1	6.4	5.8	5.2	7.2	6.5	6.3	3.3	5.9					
W	26.1	23.2	25.2	22.9	20.3	23.9	19.5	24.2	19.0					
Re	7.8	9.8	6.0	5.8	6.7	7.8	5.5	4.3	6.4					
Os	7.8	8.1	17.2	21.4	11.3	5.9	9.1	6.7	10.8					
Ir	12.7	11.6	14.2	10.7	7.5	12.8	9.0	13.3	8.5					
Pt	35.1	39.2	51.4	39.7	28.2	26.9	25.2	26.3	25.3					
Au	22.1	23.3	47.9	33.8	34.8	11.8	18.5	12.9	48.1					

Table 2: Continued

Element	WP 113-115		WP 117-119		WP 119-121		WP 121-123		WP 123-125		WP 125-127		WP 135-137		WP 177-179	
	WP 113-115	WP 115-117	MQ	MQ	MQ	MQ	MQ	MQ	WP 123-125	WP 125-127	WP 135-137	MQ	WP 135-137	MQ	WP 177-179	MQ
Pb	22.0	36.6	39.6	87.2	249.1	68.7	74.4	97.8	123.6							
Th	10.0	10.8	11.8	16.9	54.6	16.6	17.1	26.7	15.4							
U	8.3	7.5	6.5	5.8	7.1	9.9	8.1	6.6	4.7							

Note. All data are given in $\text{ng/g} \times 10^9$ (i.e., the values were multiplied by 10^9 to enhance visualization). MQ stands for the filtration technique used (Millipore filters). Depth is in cm below the sediment surface.

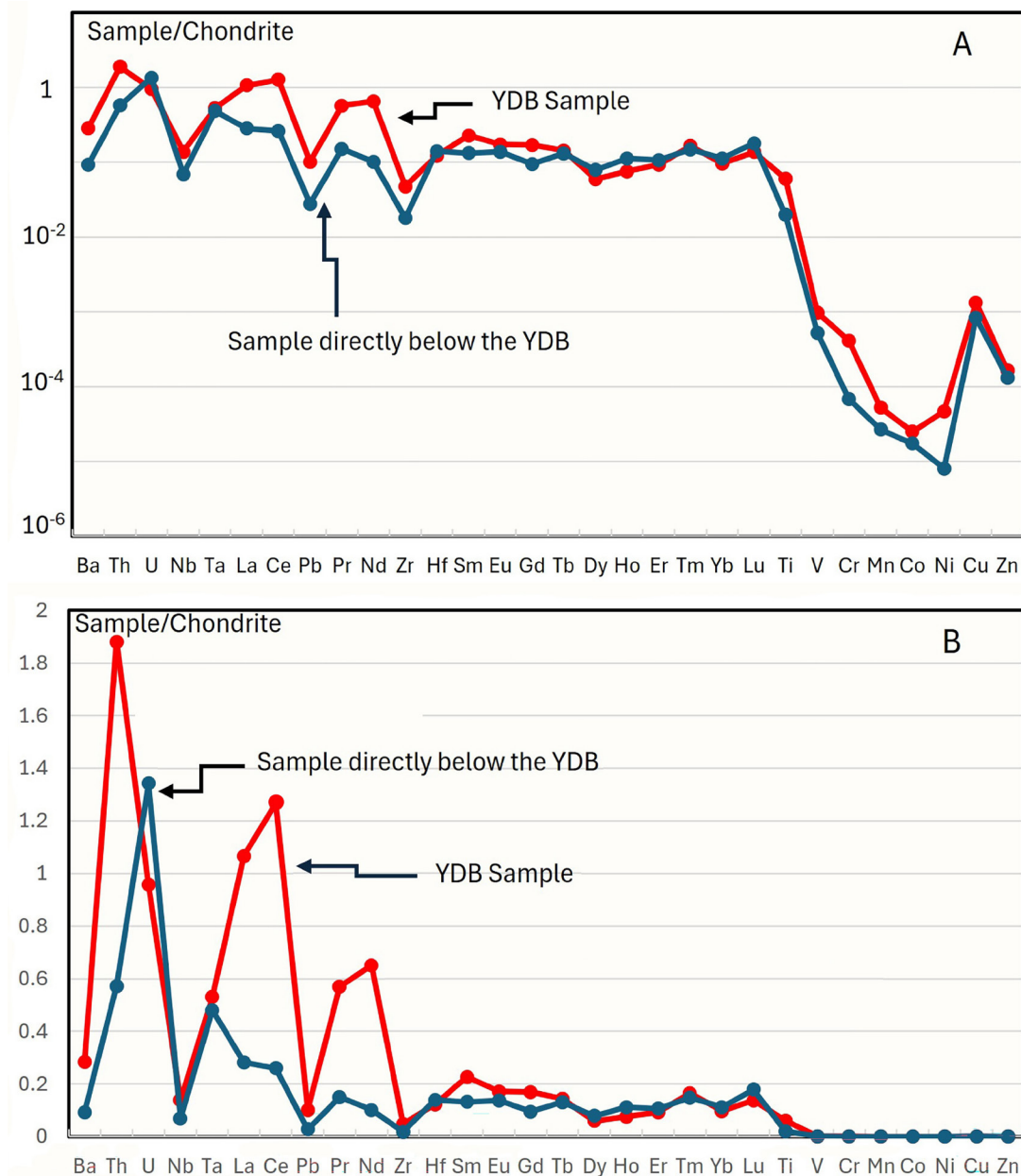


Figure 5: a) Chondrite-normalized multi-element spider diagram. b) Chondrite-normalized multi-element spider diagram without logarithmic y-axis. C1 chondrite normalizing values are from McDonough and Sun [48]. Sample WP 121-123 is within the YDB while sample WP 135-137 is below the YDB. All calculations used NP values in $\text{ng/g} \times 10^9$, i.e., all raw NP values were multiplied by 10^9 before CI-normalization (see Table 2).

that produced discrete melt products (e.g., spherules) but did not reset or homogenize the bulk geochemical signature of the enclosing sedimentary system. This is consistent with

our interpretation of a distal sedimentary archive recording atmospheric fallout from a short-lived high-energy event, rather than as a proximal impact site.

CI chondrite-normalized rare earth element (REE) patterns for samples WP 121–123 (YDB horizon) and WP 135–137 (12 cm below the YDB) display smooth, subparallel REE patterns from La through Lu, with no pronounced anomalies (Figure 6).

The close similarity in pattern shape indicates that the REE system was not significantly fractionated at the YDB horizon. In particular, the absence of an Eu anomaly suggests that large-scale melt–residue separation did not occur, including plagioclase fractionation. Likewise, the lack of strong LREE–HREE decoupling argues against involvement of garnet-bearing residues or extensive igneous-style differentiation.

Sample WP 121–123 exhibits slightly higher overall REE abundances relative to WP 135–137, but the preservation of parallel trends implies that this difference reflects minor enrichment or dilution effects (e.g., subtle grain-size or sedimentary heterogeneity) rather than a change in REE source or mineralogical control. Consequently, the data support the conclusion that any high-temperature processes associated with the YDB were localized and limited in mass, consistent with the formation of discrete melt products without resetting the bulk REE signature of the host sediment (Figure 6).

The direct comparison of WP 121–123 to WP 135–137 REE data isolates the REE system from other trace elements and demonstrates, independently, that the YDB horizon does not record bulk melting or geochemical differentiation (Figure 6). Together with the full multi-element spider diagram, it shows that the primary YDB signal is physical and microtextural, rather than a wholesale chemical transformation of the sediment.

Samples WP 121–123 and WP 135–137 exhibit uniformly subchondritic abundances of the refractory PGEs (Os, Ir,

Ru), further indicating that bulk meteoritic mixing did not occur at the YDB (Figure 7). In contrast, Pd (and to a lesser extent Au) is relatively enriched with respect to Os–Ir–Ru, producing a fractionated, non-chondritic PGE pattern. The broadly parallel patterns observed above and below the YDB indicate that the boundary layer represents a modest chemical overprint on an existing sedimentary PGE background rather than the introduction of a new PGE reservoir, consistent with a short-lived phenomenon affecting only a small fraction of the total sediment mass.

The PGE systematics are characterized by $\text{Pd} \gg \text{Pt} > \text{Ir–Os}$, a fractionated distribution inconsistent with simple chondritic mixing, in which refractory PGEs typically covary with Pd [49]. The clear decoupling of Pd from Os–Ir–Ru, which remain uniformly subchondritic, strongly argues against simple bulk meteoritic addition and instead points to volatility-controlled PGE fractionation during a high-temperature vapor or plume phase [50, 51]. Experimental and cosmochemical constraints show that Pd is significantly more volatile and more readily mobilized during high-temperature vaporization than the most refractory PGEs, such as Ir and Os, which remain largely immobile [52, 53]. During subsequent cooling, condensation preferentially incorporates Pd into fine particulates, producing Pd-rich signatures without corresponding refractory PGE enrichment. Comparable fractionated PGE patterns have been reported from impact-related ejecta and impactite contexts [54], documented airburst deposits such as those associated with the Tunguska event [55], and high-temperature aerosol systems, where Pd-rich particulate transport is well established [56, 57]. Together with the presence of melt spherules, these observations support the interpretation of the YDB PGE signal as reflecting localized, short-lived thermal processing

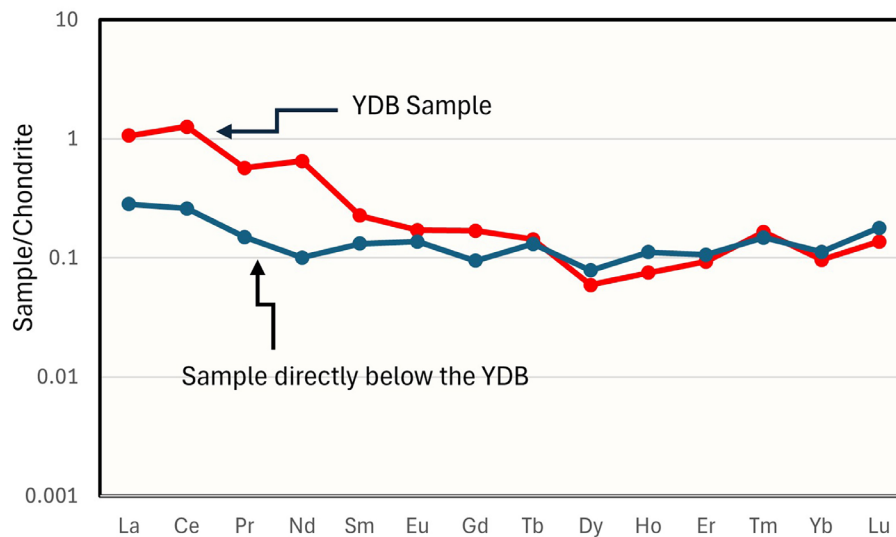


Figure 6: Chondrite-normalized rare-earth element diagram. C1 chondrite normalizing values are from McDonough and Sun [48]. All calculations used NP values in $\text{ng/g} \times 10^9$, i.e., all raw NP values were multiplied by 10^9 before CI-normalization. Sample WP 121–123 is within the YDB while sample WP 135–137 is below the YDB.

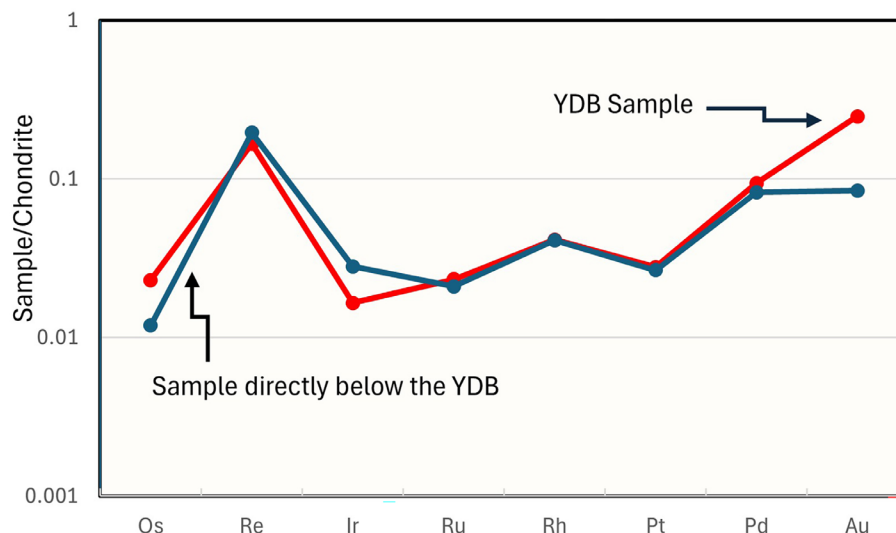


Figure 7: Chondrite-normalized diagram of platinum-group elements (PGEs) and related elements. C1 chondrite normalizing values are from McDonough and Sun [48]. All calculations used NP values in $\text{ng/g} \times 10^9$, i.e., all raw NP values were multiplied by 10^9 before CI-normalization. Sample WP 121-123 is within the YDB while sample WP 135-137 is below the YDB.

and plume-mediated redistribution, rather than *in situ* bulk chemical modification of the host sediment.

Using SP-ICP-TOF-MS, nanoparticle depth profiles from core WP-16-4 (Figures 8 and 9) reveal distinct, synchronous increases in platinum-group element (PGE) bearing nanoparticles (Ir, Pt, Pd, Os, Ru) centered within the Bayesian-modeled Younger Dryas onset interval in Unit II (~114.5–127 cm), with maximum values clustered near ~118–123 cm. The nanoparticle number-ratio profiles provide an additional constraint on source variability across the boundary interval. Increases in Pt/Pd and Pt/Ni values within the YDB horizon indicate that platinum enrichment is not simply tracking bulk changes in transition-metal-bearing nanoparticles but reflects a distinct PGE-bearing nanoparticle component. This behavior is consistent with prior work at White Pond, which shows a Pt/Pd anomaly at the YD onset, and supports the interpretation of an exogenic contribution superimposed on a local lithogenic background.

To further evaluate the geochemical characteristics of nanoparticles associated with the Younger Dryas Boundary (YDB) at White Pond, we examined these PGE profiles together with selected transition metals (Ni, Co, Cr, V, Fe) (Figure 9). Platinum-group elements are highly diagnostic tracers of extraterrestrial material, whereas Ni, Co, Cr, V, and Fe provide complementary context for metal-rich nanoparticle assemblages and allow assessment of stratigraphic coherence with independently identified microspherules, meltglass, and the modeled YD onset.

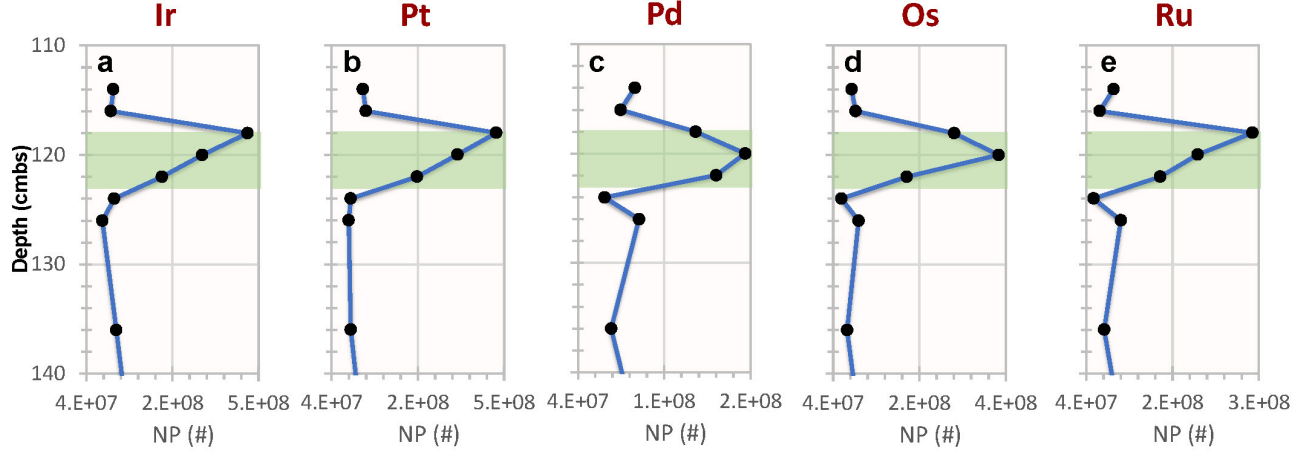
The SP-ICP-TOF-MS nanoparticle dataset provides an independent, particle-scale perspective on the Younger Dryas Boundary (YDB) at White Pond, complementing bulk geochemical anomalies and microspherule observations

(see Methods for definitions of mass and number concentrations). Nanoparticle mass, particle number, and average mass per particle vary with depth, allowing assessment of whether observed enrichments reflect increased nanoparticle flux, changes in particle size, or both (Figure 10). Diagnostic elemental ratios (Pt/Fe and Ir/Fe) measured in YDB nanoparticles closely correspond with ratios obtained from LA-ICP-MS analyses of YDB microspherules and with representative terrestrial and extraterrestrial compositional fields (Figure 11). This integrated comparison allows evaluation of whether spherules and nanoparticles represent a single geochemical population or distinct carrier phases. Together, these data constrain the nature of the YDB particle assemblage and provide insight into source components, phase segregation, and formation processes.

Discussion

Previous high-resolution stratigraphic analysis of vibrocores WP-16-1 through WP-16-4 from White Pond, South Carolina, identified a discrete (~12.5 cm) sedimentary layer containing a suite of coeval proxies marking the Younger Dryas Boundary (YDB) (Figure 12). This horizon lies within Unit II, a dark, organic-rich, silty unit underlain by late Pleistocene laminated clays and unconformably overlain by early Holocene muddy peat [19]. Bayesian age modeling places the Younger Dryas onset within Unit II at ~211.5–224 cm in core WP-16-3 and ~114.5–127 cm in core WP-16-4, corresponding to ~12,875–12,775 cal BP [45] using IntCal20 [46]; Figures 3 and 12; Supplementary Figure S23; Supplementary Table S1; <https://zenodo.org/records/18684761>). Variation in the depth of Unit II and the

Nanoparticles, total number concentration



Nanoparticles, total number ratios

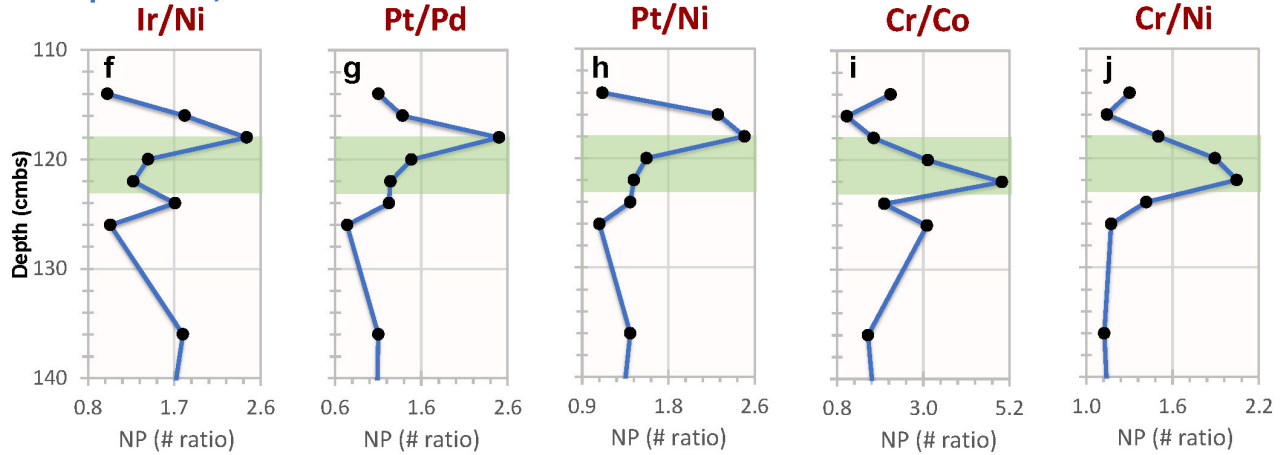


Figure 8: SP-ICP-TOF-MS nanoparticle number concentration (total particle counts) and number-ratio profiles for platinum-group elements in White Pond core WP-16-4 determined by SP-ICP-TOF-MS. Panels (a–e) show total nanoparticle number concentrations (NP #) for Ir, Pt, Pd, Os, and Ru plotted against sediment depth (cm below surface). Panels (f–j) show nanoparticle number ratios (Ir/Ni, Pt/Pd, Pt/Ni, Cr/Co, and Cr/Ni). Green shading indicates the stratigraphic interval of Unit II, where impact-related microspherules and meltglass were identified in cores WP-16-3 and WP-16-4. Platinum-group element-bearing nanoparticles show pronounced, synchronous increases between ~118 and 123 cm depth, and Pt/Pd and Pt/Ni values also rise across this boundary interval. The Bayesian-modeled Younger Dryas onset (12,875–12,775 cal BP; IntCal20) [45, 46] occurs between ~114.5 and 127 cm in core WP-16-4 (see Supplementary Figure S23; <https://zenodo.org/records/18684761>). Nanoparticle data are provided in Table 2. Nanoparticle number concentration represents the count of element-bearing nanoparticles ($\# \text{ g}^{-1}$), normalized to sediment mass.

overlying Holocene peat among cores reflects a gentle basin dip from right (Core 4) to left (Core 1), resulting in various proxies appearing slightly deeper in Unit II as cores deepen (Figure 12).

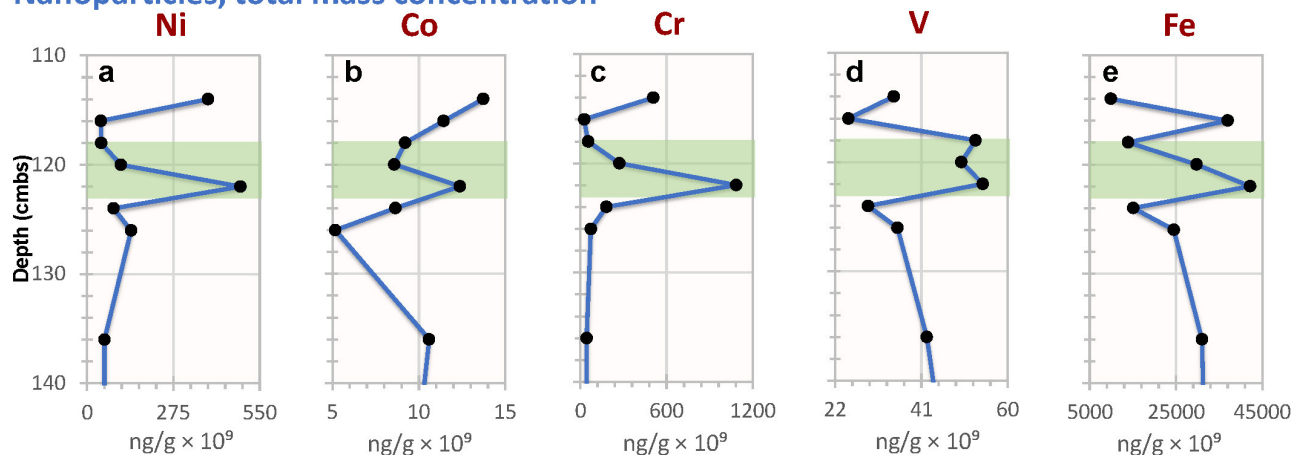
Moore et al. [19] further identified a stratigraphic hiatus above the YDB at the top of Unit II, consistent with a regional, climate-driven interval of non-deposition or erosion rather than a coring artifact. Comparable stratigraphic discontinuity across the YD–Holocene transition has been documented at multiple Coastal Plain archaeological and paleoenvironmental sites [58], consistent with Younger Dryas conditions, including reduced effective moisture, lowered lake levels, and possible subaerial exposure. This hiatus occurs above the YDB and does not compromise the stratigraphic integrity

or chronological placement of the YDB proxy assemblage preserved within Unit II.

Microspherules and meltglass

Microspherules and meltglass co-occur within the YDB interval at White Pond together with peaks in platinum and soot. These microspherules are primarily composed of aluminosilicate and FeO, as confirmed by SEM–EDS analyses (Supplementary Figures S1–S22), and are consistent with previous studies showing that YDB microspherules largely derive from melted terrestrial sediment with only a minor (<2%) extraterrestrial contribution [10]. Many exhibit dendritic or segmented “soccer-ball” textures resulting from Fe crystallization during magnetite melting

Nanoparticles, total mass concentration



Nanoparticles, total number concentration

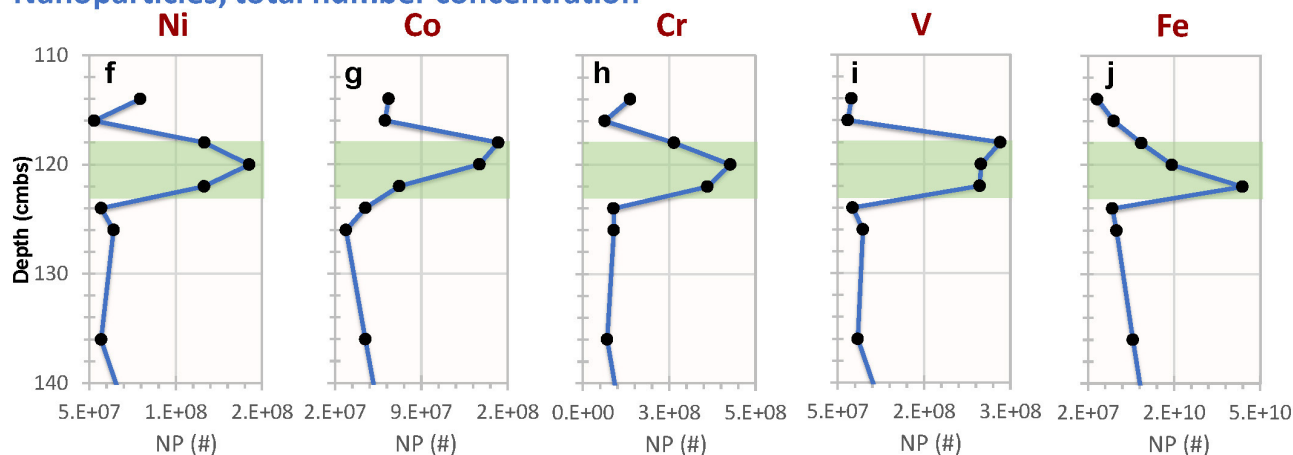


Figure 9: SP-ICP-TOF-MS nanoparticle depth profiles from White Pond showing total nanoparticle mass concentrations and total nanoparticle number concentrations for Ni, Co, Cr, V, and Fe plotted against sediment depth (cm below surface). Panels (a–e) show nanoparticle mass concentrations ($\text{ng g}^{-1} \times 10^9$; values multiplied by 10^9 to enhance visualization), while panels (f–j) show nanoparticle number concentrations (NP #). Green shading indicates the stratigraphic interval of Unit II, where impact-related microspherules and meltglass were identified in cores WP-16-3 and WP-16-4. All five elements exhibit pronounced, stratigraphically coherent peaks in both mass and number concentrations within this interval, indicating a discrete enrichment of metal-bearing nanoparticles coincident with the boundary layer. The Bayesian-modeled Younger Dryas onset ($\sim 12,875$ – $12,775$ cal BP; IntCal20) [45, 46] occurs between ~ 114.5 and 127 cm in core WP-16-4 (see Supplementary Figure S23; <https://zenodo.org/records/18684761>). Nanoparticle data are provided in Table 2. Nanoparticle mass concentration represents the summed elemental mass of a given element hosted within nanoparticles, normalized to sediment mass (ng g^{-1}), and Nanoparticle number concentration represents the count of nanoparticles containing a given element detected by SP-ICP-TOF-MS, normalized to sediment mass and reported as $\# \text{ g}^{-1}$.

(microkrystites). Comparable silica-rich microtektites and Fe-rich microkrystites have been documented at YDB sites across multiple continents and depositional environments [47, 59, 60].

Moore et al. [19] found no cryptotephra within the White Pond YDB interval, arguing against a volcanic source for the observed microspherules, meltglass, and platinum enrichment. Consistent with this interpretation, SP-ICP-TOF-MS analyses of core WP-16-4 document synchronous increases in platinum-group-element (PGE)–bearing nanoparticles (Ir, Pt, Pd, Os, Ru; Figure 8) and transition-metal–bearing nanoparticles (Ni, Co, Cr, V, Fe; Figure 9), indicating deposition during a short-lived event at the YDB.

Several non-impact processes have been proposed as potential sources of microspherules and meltglass, including intense wildfires, volcanism, lightning-related melting, diagenetic mineral growth, sediment reworking, and anthropogenic contamination. At White Pond, large-scale biomass burning can account for soot and some carbonaceous particles but cannot readily explain Fe-rich and aluminosilicate spherules or vesicular meltglass exhibiting dendritic crystallization, quench textures, vesiculation, and surface micro-impacts, which require temperatures and cooling rates exceeding those achieved in terrestrial fires. A volcanic origin is further disfavored by the absence of cryptotephra, the lack of coeval volcanic centers, and the confinement of both spherules and meltglass to a

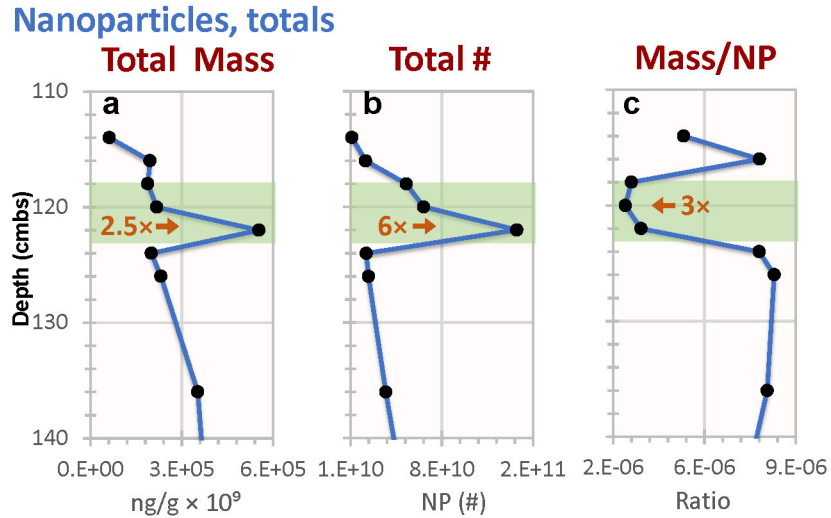


Figure 10: SP-ICP-TOF-MS nanoparticle depth profiles from White Pond showing total nanoparticle mass concentration, total nanoparticle number concentration, and mass per nanoparticle plotted against sediment depth. Panel (a) shows total nanoparticle mass concentration ($\text{ng g}^{-1} \times 10^9$), panel (b) shows total nanoparticle number concentration (NP #), and panel (c) shows mass per nanoparticle, calculated as total elemental mass divided by total nanoparticle number. All parameters display pronounced, stratigraphically coherent anomalies within the YDB interval (123–118 cm), corresponding to the Bayesian-modeled Younger Dryas onset ($\sim 12,875$ – $12,775$ cal BP; IntCal20) [45, 46]. The coincidence of mass and number peaks indicates that the enrichment reflects an increased flux of nanoparticles rather than dominance by a small number of unusually large particles. Green shading marks the YDB interval defined by independent age–depth modeling and the stratigraphic occurrence of microspherules and meltglass. Mass per nanoparticle reflects changes in nanoparticle population structure rather than physical particle size. Nanoparticle mass concentration represents the summed elemental mass of a given element hosted within nanoparticles, normalized to sediment mass (ng g^{-1}).

discrete stratigraphic horizon rather than a diffuse ash-derived background. Lightning-generated melts are typically localized and irregular in form and do not produce laterally continuous, basin-wide spherule or meltglass layers, while diagenetic or authigenic processes do not generate glassy melt textures or high-temperature quench morphologies. Sediment reworking would be expected to smear these materials across multiple horizons, and anthropogenic contamination is highly unlikely given the late-Pleistocene age of the deposits and the absence of industrial markers. Collectively, these constraints indicate that ordinary terrestrial processes are insufficient to account for the observed spherule and meltglass assemblage at White Pond.

Nanoparticle abundance and population structure

The nanoparticle dataset is evaluated using a complementary framework that integrates population-level mass and number concentrations with elemental number-ratio profiles (Figures 8–10). The YDB interval is marked by stratigraphically coherent enrichments in both total nanoparticle mass and total nanoparticle number, demonstrating a true increase in nanoparticle flux rather than enrichment driven by rare large particles or analytical artifacts. This interpretation is reinforced by the synchronous behavior of multiple platinum-group elements together with parallel peaks in nanoparticle mass and number across several transition metals, a pattern difficult to reconcile with either selective diagenetic

remobilization or simple concentration effects driven by reduced siliciclastic sedimentation.

Changes in bulk sedimentation rate can influence elemental concentrations expressed per gram of sediment; however, our interpretation does not rely solely on concentration data. Instead, we emphasize nanoparticle elemental ratios (e.g., Pt/Pd, Pt/Ni, Ir/Ni) and nanoparticle population structure, which are largely insensitive to simple dilution by reduced siliciclastic input. A dilution-only mechanism would elevate concentrations while leaving nanoparticle elemental ratios approximately unchanged. The observed ratio excursions therefore provide an internal test that distinguishes true nanoparticle influx from bulk sediment dilution. In contrast, the YDB interval exhibits pronounced excursions in PGE/transition-metal nanoparticle ratios together with synchronous increases in total nanoparticle number and total elemental mass, coupled with a decrease in average mass per particle. This combination demonstrates a compositional and population-structure change in the nanoparticle assemblage, consistent with the addition of numerous fine, PGE-enriched nanoparticles rather than concentration effects driven solely by reduced sediment accumulation. Where sufficiently resolved age–depth constraints permit, conversion of these data to mass accumulation rates could further quantify nanoparticle flux, but the observed ratio and population signals alone require a real change in nanoparticle source or carrier phase at the YDB.

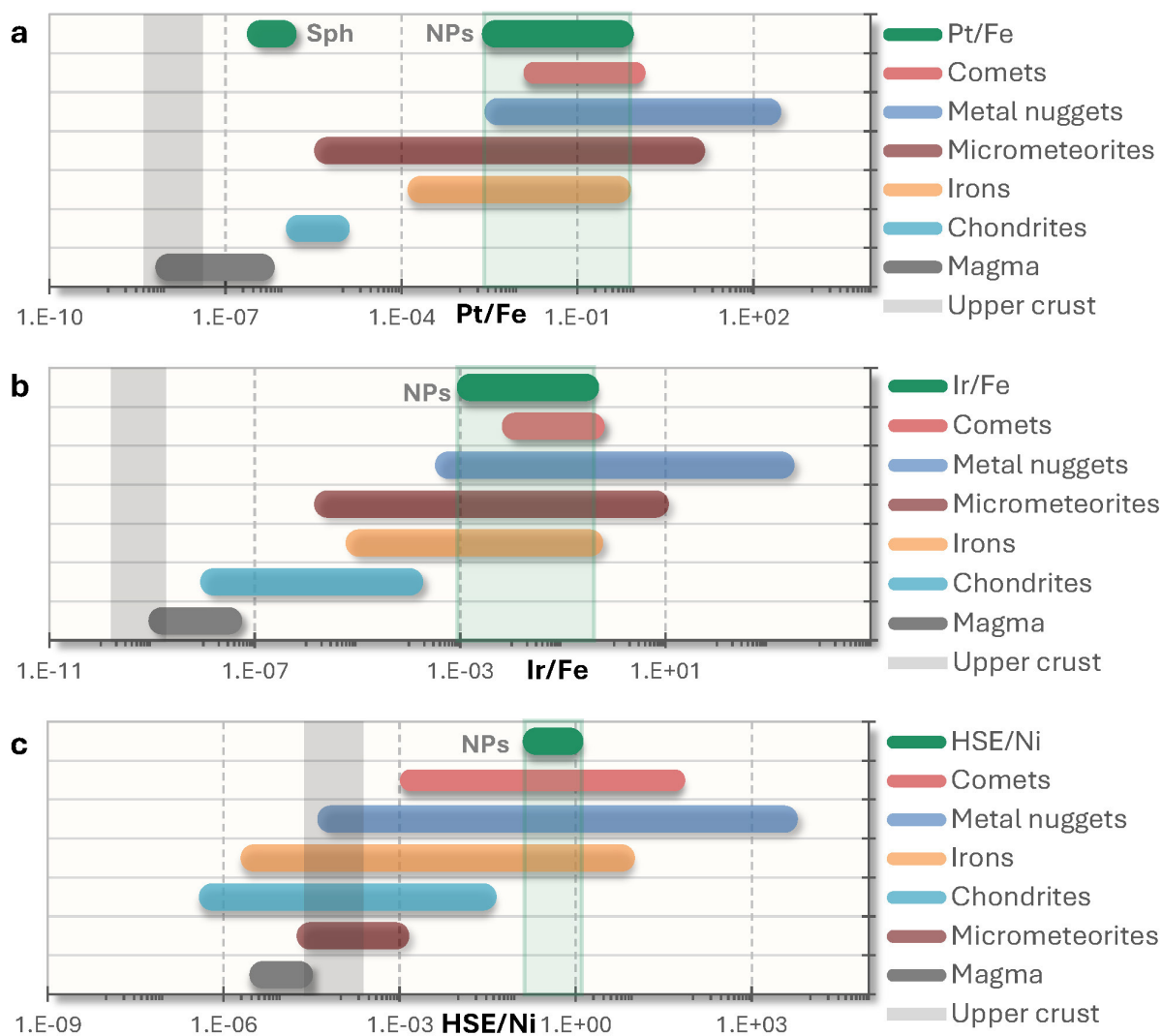


Figure 11: Elemental ratios measured at White Pond for two particle populations, nanoparticles (NPs; SP-ICP-TOF-MS) and microspherules (Sph; LA-ICP-MS), and compared with representative terrestrial and extraterrestrial compositional fields. Panels show (a) Pt/Fe, (b) Ir/Fe, and (c) HSE/Ni values on a logarithmic y-axis. HSE represents the sum of highly siderophile elements (Au, Ir, Os, Pd, and Pt) measured in the nanoparticle population. Green symbols labeled “Sph” indicate Fe-normalized ratios measured by LA-ICP-MS in individual YDB spherules. Comparative fields include comets, refractory metal nuggets, micrometeorites, iron meteorites, chondrites, magmatic rocks, and upper continental crust (gray band). Nanoparticle ratios overlap fields defined by metal-rich and refractory extraterrestrial materials, including cometary materials and refractory metal nuggets, and show no overlap with magmatic or upper-crustal compositions. In contrast, LA-ICP-MS spherule ratios plot near terrestrial compositional fields, despite elevated absolute platinum concentrations. The contrast between spherule and nanoparticle ratios indicates chemically distinct particle populations within the YDB layer. For the Pt/Fe and Ir/Fe graphs, the plotted values represent only single particles that contain both elements. HSE/Ni represents only single particles that contain Ni and at least one HSE (Au, Ir, Os, Pd, or Pt). Dataset sources and analytical caveats are summarized in Supplementary Information (Figure S24; Text S1; <https://zenodo.org/records/18684761>).

Nickel, cobalt, chromium, vanadium, and iron all exhibit concurrent mass and number concentration peaks within the YDB interval (Figure 9), indicating delivery of a compositionally coherent nanoparticle assemblage within the same stratigraphic interval. Similar increases in nanoparticle abundance, coincident with YDB proxies, have been reported at other YDB sites, where microspherule-rich horizons occur

near the base of the event bed and PGE-rich nanoparticle flux peaks slightly above [18]. This pattern is consistent with aerodynamic sorting and delayed settling of fine vapor-condensate particles, as documented for other impact events [61] and from the YDB layer in the Greenland ice sheet [17].

Critics have argued that the Greenland Pt enrichment in GISP2 post-dates the Younger Dryas onset because the two

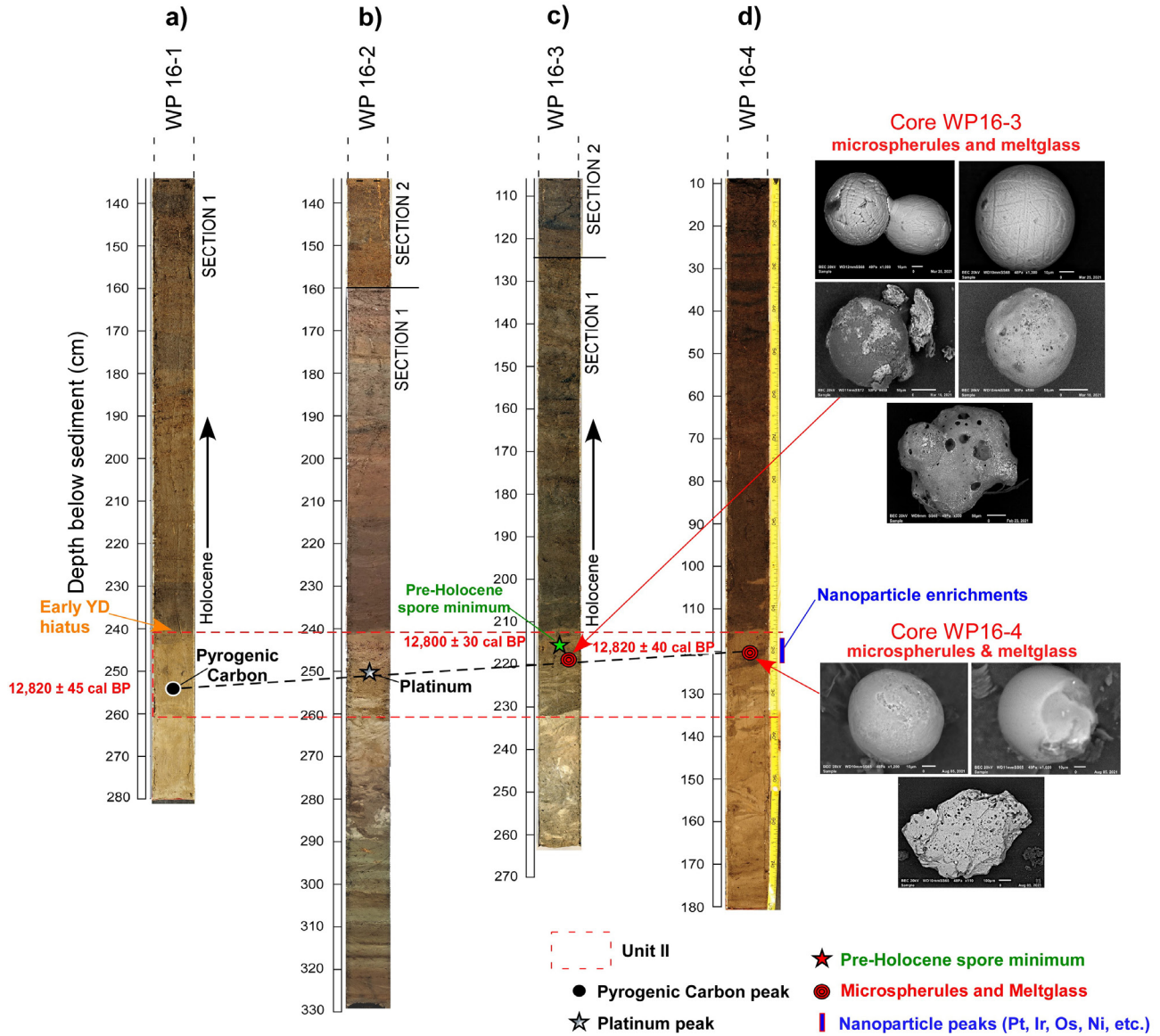


Figure 12: Stratigraphic profiles and impact-related proxy materials from White Pond, South Carolina (a–d). Photomosaics of the lower sections of four vibracores (WP-16-1 through WP-16-4) show sediment depth (cm below top of core) and the stratigraphic context of the Younger Dryas Boundary (YDB) layer corresponding to the modeled YD onset (~12,875–12,775 cal BP; IntCal20) [19, 45, 46]. Several calibrated and unmodelled radiocarbon ages (INTCAL20) for cores WP-16-1, WP-16-3, and WP-16-4 are shown in red text (see Supplementary Table S1 <https://zenodo.org/records/18684761>) for all dates used in the Bayesian model by Moore et al. 2019 [19]. Proxy locations identified in the previous study [19] are indicated as follows: black circle = pyrogenic carbon peak (WP-16-1); silver star = platinum enrichment (WP-16-2); green star = pre-Holocene spore minimum (WP-16-3); and for this study red circles = microspherules and meltglass (WP-16-3 and WP-16-4); blue vertical bar = nanoparticle peaks measured in WP-16-4 (Figures 8–10). The dashed red rectangle indicates lithologic Unit II, which is present in all cores. Inset SEM images from WP-16-3 and WP-16-4 show meltglass and microspherules found in stratigraphic association with the YD onset within Unit II. Variation in the depth of the Holocene peat and Unit II between cores indicates a dip from right (WP-16-4) to left (WP-16-1) that may indicate a filled relict stream channel. Thus, Unit II with impact proxies occur slightly deeper as cores deepen (black dashed line). Cores were collected ~1 meter apart at identical starting elevations.

Pt-rich samples reported by Petaev et al. [17] occur above the formally transferred NGRIP GS-1 boundary on the GICC05 timescale [62]. This comparison, however, treats the GS-1 boundary as a single stratigraphic level, whereas the onset is

expressed in Greenland records as a short transition interval in $\delta^{18}\text{O}$ accompanied by increases in dust and major ions. Although volcanic tie points tightly synchronize the relative alignment of Greenland ice cores, the GICC05 chronology

retains a maximum counting error near the GS-1 onset of $\sim\pm 140$ years (2σ) that reflects uncertainty in the absolute layer-count timescale rather than inter-core misalignment. When evaluated within the broader onset interval expressed in GISP2, the Pt-enriched interval overlaps the $\delta^{18}\text{O}$ transition and associated increases in dust and ionic concentrations that characterize the onset of GS-1. Accordingly, the Greenland Pt enrichment is best interpreted as broadly coeval with Younger Dryas onset conditions within the chronological resolution of the GISP2 ice-core record rather than as evidence for a multi-decadal delay.

The slight stratigraphic offset between the microspherule-rich horizon and the peak in PGE-bearing nanoparticles is therefore interpreted as a depositional sorting effect rather than a temporal mismatch. Dense melt products formed and settled rapidly, whereas fine metal-rich vapor condensates remained suspended longer in the atmosphere or plume and were deposited with a short delay, a pattern documented in impact ejecta, airburst fallout, and ice-core records. Although post-depositional processes can influence metal mobility in organic-rich lacustrine sediments, the tight stratigraphic confinement of the nanoparticle peaks and their internal coherence across elements with differing geochemical behavior are inconsistent with diagenetic redistribution. Instead, the data support an externally driven, short-lived enrichment in metal-bearing nanoparticles at the YDB.

Nanoparticle mass–number relationships and implications for particle flux

Combined nanoparticle mass, number, and mass-per-particle profiles (Figure 10) provide further constraints on the YDB signal. Total nanoparticle mass and number increase sharply and synchronously within the YDB interval, whereas average mass per particle decreases. This relationship indicates dominance of numerous low-mass nanoparticles and confirms that the enrichment reflects increased nanoparticle flux rather than accumulation of a small number of anomalously large particles. Such behavior is consistent with rapid deposition of fine metal-bearing particles during a short-lived event rather than gradual sedimentary accumulation.

Elemental ratios and nanoparticle carrier phases

Elemental ratios further constrain nanoparticle composition and source. YDB nanoparticle Pt/Fe, Ir/Fe, and HSE/Ni (with HSE representing total highly siderophile elements, Au, Ir, Os, Pd, and Pt) values show minimal overlap with terrestrial magmatic compositions and overlap most strongly with metal-rich extraterrestrial materials (Figures 11 and S24). Elevated Pt/Fe, Ir/Fe, and HSE/Ni values indicate selective enrichment of highly siderophile elements within a metal-rich nanoparticle subset rather than bulk meteoritic dilution.

These patterns are consistent with refractory metal-bearing alloy particles, such as refractory metal nuggets, documented in carbonaceous chondrites, micrometeorites,

interplanetary dust particles, and cometary material [63, 64]. Such particles are interpreted as high-temperature condensates that preferentially concentrate Os, Ir, Pt, and related elements and may be delivered directly or produced through high-temperature atmospheric entry, airburst, or impact-plume processes.

Laser ablation geochemistry of spherules in context with nanoparticle ratios

The LA-ICP-MS results provide an important complement to the nanoparticle dataset. Although individual YDB spherules contain elevated absolute platinum concentrations and Pt/Fe values relative to average crustal compositions, their Ni/Fe ratios remain within or near terrestrial compositional fields. In contrast, Pt/Fe ratios derived from LA-ICP-MS analyses of spherules closely match those obtained from SP-ICP-TOF-MS nanoparticle measurements (Figure 11), and although this overlap is numerical, it is not diagnostic of bulk extraterrestrial incorporation, where Pt/Fe overlaps strongly with metal-rich extraterrestrial materials and shows little to no overlap with magmatic or upper-crustal compositions. This divergence demonstrates the presence of two chemically distinct populations within the YDB layer. The microspherules analyzed by LA-ICP-MS are dominantly terrestrial in bulk composition and are consistent with derivation from melted local sediment subjected to extreme heating and rapid quenching. Their compositions support high-temperature processing but do not indicate bulk incorporation of meteoritic metal.

In contrast, the SP-ICP-TOF-MS nanoparticle population exhibits markedly elevated Pt/Fe, Ir/Fe, and HSE/Ni values that overlap refractory metal nuggets, cometary materials, and metal-rich meteoritic alloys. These ratios indicate the concentration of siderophile elements within a discrete subset of metal-rich nanoparticles.

The coexistence of terrestrial-dominated melt spherules and a compositionally distinct metal-rich nanoparticle population is consistent with high-temperature plume processes in which target sediments melt to form aluminosilicate and Fe-rich spherules. At the same time, vaporized metal phases condense separately as fine Fe–Ni–PGE-bearing particles. Under such conditions, physical and chemical segregation of phases is expected, and bulk meteoritic mixing is not required to generate ET-like nanoparticle ratios.

Accordingly, the LA-ICP-MS data do not weaken the interpretation of an exogenic component; rather, they clarify its carrier phase. The spherules record thermal processing of terrestrial material, whereas the nanoparticle population records a minor but geochemically distinct metal-rich component consistent with extraterrestrial dust or condensate input. This two-population framework is internally consistent with the REE stability of the bulk sediment, the absence of wholesale meteoritic mixing, and the stratigraphically confined nanoparticle enrichment at the YDB.

Implications for the nature of the YDB event

This and previous work [19, 37] interpret the White Pond depression as a natural lacustrine basin formed by erosional scour and dune damming. At present, no diagnostic shock metamorphic features or impact breccias have been documented at White Pond, and sediment cores indicate basin infilling extending to at least ~30–32 ka [37], implying formation well before the YDB. The high-temperature proxies reported here occur within a discrete stratigraphic horizon inside the basin and do not depend on the origin of the depression itself.

A definitive assessment of whether the White Pond depression could represent a much older impact structure would require integrated geomorphic, subsurface, and petrographic investigations, including high-resolution topographic analyses, targeted geophysical surveys, deep coring across the basin and margins, and systematic searches for diagnostic shock metamorphism in quartz grains.

Independent of basin origin, the stratigraphically confined YDB proxy assemblage provides direct evidence for the nature of the depositional event. Together, the spherules, meltglass, and nanoparticle data indicate a brief, externally driven depositional pulse involving metal-rich nanoparticles at the YDB. The inferred carrier-phase assemblage, Fe–Ni metal nanoparticles with a PGE-enriched subset, is consistent with primitive extraterrestrial material and high-temperature processes capable of generating or dispersing fine refractory particles. Although nanoparticle ratios alone do not uniquely discriminate between cometary and asteroidal sources, they are consistent with a dust-producing, metal-bearing primitive body, including comets or rubble-pile asteroids.

It is important to clarify that our interpretation does not rely on bulk comet composition. Although cometary nuclei are volatile-rich and contain abundant silicates, their refractory dust fraction includes Fe–Ni metal, sulfides, and PGE-bearing condensates derived from primitive solar nebular material, as demonstrated by analyses of Stardust samples from comet 81P/Wild 2 and studies of carbonaceous chondrites and interplanetary dust particles [65, 66]. Platinum enrichment alone is not diagnostic of a cometary source; rather, the observed co-enrichment of highly siderophile elements and elevated HSE/Ni and Pt/Fe nanoparticle ratios are consistent with delivery or atmospheric condensation of metal-rich refractory phases characteristic of primitive extraterrestrial materials. Our interpretation therefore concerns the metal-bearing dust component of primitive bodies, not their bulk volatile-rich composition.

When integrated with the broader White Pond proxy suite, including microspherules, meltglass, platinum anomalies, soot, and stratigraphic context, the nanoparticle evidence supports interpretation of an abrupt, high-energy event at the onset of the Younger Dryas. The nanoparticle record thus provides particle-scale evidence that complements bulk geochemical anomalies and macroscopic impact proxies,

strengthening the interpretation that the YDB at White Pond records a sudden, transient, and energetic phenomenon consistent with processes proposed under the Younger Dryas Impact Hypothesis.

Comparative evidence from documented airbursts and near-surface fragmentation

Modern and historical airburst events demonstrate that atmospheric explosions commonly deliver solid fragments to Earth's surface and can generate localized shock and thermal effects comparable to small impact events. During the 1947 Sikhote-Alin event in Siberia, thousands of iron fragments totaling >23,000 kg were dispersed over ~1.6 km [67], producing more than 100 small craters up to 26 m in diameter [68]. Similarly, the Campo del Cielo meteorite field in Argentina contains numerous shallow crater-like impact structures formed by fragmented meteoritic masses up to 26.5 m wide and 6 m deep formed by fragmented meteoritic masses. The 2013 Chelyabinsk airburst, although substantially smaller (~500 kt at ~29.7 km altitude [67, 69–71]), also produced surviving fragments, including masses of 64.7 and 540 kg [72]. The largest fragment penetrated the frozen surface of a lake, producing a 9-m-diameter hole. These events confirm that even disrupted bolides can retain sufficient kinetic energy to generate multiple shallow impact structures in unconsolidated sediments and melt surficial sediment into spherules and meltglass.

In addition, multiple proposed Holocene near-surface airbursts across Western Europe have been associated with shallow crater-like impact structures and high-temperature proxies, including spherules, meltglass, shocked quartz, and microbrecciated quartz [73]. Investigations in the Czech Republic [74, 75], Germany [76–89], and Finland [90] suggest that such events may have occurred repeatedly during the Holocene, indicating that airburst-related ground effects are not anomalous in geologic time.

Although no single, unequivocally dated impact crater has yet been confirmed for the Younger Dryas Boundary (YDB), several candidate end-Pleistocene structures have been proposed whose ages overlap the YDB interval. These include Corosol [91], Charity Shoal [6, 92], Bloody Creek [93], Brushy Creek [94], and Perkins [95]. While the ages and origins of these features remain debated, their existence demonstrates that near-surface impacts or airburst-related ground effects during the terminal Pleistocene are plausible. Moreover, the absence of a confirmed source crater does not preclude an impact origin, as demonstrated by well-accepted impact-related deposits such as the Australasian tektite field and Libyan Desert Glass, for which no definitive crater has been identified despite extensive investigation [96, 97]. In this context, White Pond is interpreted as a distal sedimentary archive recording atmospheric fallout from a short-lived high-energy event, rather than as a proximal impact site.

Collectively, these examples show that airbursts and fragmented meteoroid impacts can generate meltglass and

spherules, along with localized shock metamorphism and small, shallow impact or penetration craters, without requiring formation of a large primary crater. Such processes provide a physically plausible mechanism for generating the high-temperature proxies observed at White Pond, including microspherules, meltglass, and metal-rich nanoparticles, within a short-lived depositional pulse.

Conclusions

Multiproxy evidence from White Pond documents a stratigraphically discrete depositional pulse coincident with the onset of the Younger Dryas (~12,875–12,775 cal BP [45]; IntCal20 [46]). This boundary layer, previously shown to contain a pronounced platinum anomaly, elevated Pt/Pd ratios, a peak in pyrogenic carbon, and a decline in coprophilous spores, is further characterized here by high-temperature microspherules, vesicular meltglass, and compositionally distinct metal-bearing nanoparticles.

Scanning electron microscopy confirms the presence of Fe-rich and aluminosilicate microspherules exhibiting dendritic crystallization, quench textures, vesiculation, and collisional deformation features consistent with melting and rapid cooling. Laser ablation ICP-MS analyses demonstrate that, although individual spherules contain strongly elevated absolute platinum concentrations, their Fe-normalized Ni/Fe and Pt/Fe values remain within or near terrestrial compositional fields. These data indicate that the spherules are dominantly derived from melted local sediment and do not represent bulk meteoritic metal.

In contrast, SP-ICP-TOF-MS analyses reveal sharply defined, stratigraphically coherent enrichments in platinum-group element (PGE)-bearing nanoparticles (Ir, Pt, Pd, Os, Ru) and associated transition metals (Ni, Co, Cr, V, Fe). The YDB interval is characterized by synchronous increases in total nanoparticle mass and total particle number, coupled with a reduction in average mass per particle, indicating that deposition is dominated by numerous fine nanoparticles rather than by rare coarse grains. Normalized nanoparticle ratios (Pt/Fe, Ir/Fe, HSE/Ni) overlap metal-rich extraterrestrial materials and show minimal overlap with terrestrial magmatic fields; selected nanoparticles exceed ~4 wt% Ni relative to Fe, values rarely achieved in near-surface terrestrial systems.

Chondrite-normalized multi-element, rare-earth-element (REE), and PGE patterns demonstrate that the YDB horizon does not record bulk meteoritic mixing or large-scale melt–residue differentiation. REE trends above and below the boundary are parallel and lack significant Eu anomalies, indicating that any high-temperature processing was localized and limited in mass. The bulk sediment geochemistry, therefore, reflects a subtle overprint superimposed on an otherwise uniform depositional system.

Together, the data defines two chemically distinct particle populations within the YDB layer: (1) terrestrial melt-derived

microspherules and meltglass, and (2) a metal-rich nanoparticle population enriched in highly siderophile elements. This two-population framework is consistent with high-temperature plume processes in which the target sediment was melted. At the same time, a minor metal-bearing component, either delivered directly or produced through vaporization and condensation, was concentrated into fine nanoparticles.

The absence of cryptotephra argues against a volcanic origin for the boundary layer. When integrated with previously documented platinum anomalies, soot peaks, and ecological disruption signals, the White Pond record supports deposition during a brief, high-energy event at the onset of the Younger Dryas. While elemental ratios alone cannot uniquely distinguish between cometary and asteroidal sources, the combined mineralogical, nanoparticle, and stratigraphic evidence is compatible with processes proposed under the Younger Dryas Impact Hypothesis, including low-altitude atmospheric airbursts or fragmented impacts by metal-bearing primitive bodies, such as a comet or rubble-pile asteroid.

While the evidence presented here supports interpretation of a short-lived, high-energy event at the onset of the Younger Dryas, it does not preclude the possibility that multiple forcings, including internal climate dynamics and meltwater-driven ocean circulation changes, operated concurrently or sequentially during this transition.

Finally, these results highlight an important methodological implication. The White Pond record demonstrates that high-energy depositional events may leave their most diagnostic signatures preserved at the scale of individual particles rather than as bulk geochemical anomalies. In this case, the extraterrestrial signal is carried primarily by rare, metal-rich nanoparticles and not by wholesale modification of the host sediment. Such grain-scale preservation implies that some impact- or airburst-related events, particularly those involving limited mass input or extensive atmospheric processing, may be difficult to detect using conventional bulk-sediment analyses alone but can be resolved using particle-specific techniques such as SP-ICP-TOF-MS. This does not imply frequent impacts but rather underscores the importance of analytical scale in recognizing short-lived, high-energy depositional events in the geologic record.

Methods

Microspherule extraction and analysis

Sediment samples were collected at 2-cm intervals and weighed before processing. To disaggregate the sediments, samples underwent ultrasonication for 30 minutes in a sodium metaphosphate dispersant solution. The suspensions were then wet-sieved through a 20- μ m mesh and dried under a heat lamp. Following drying, the samples were size-fractionated into ≥ 63 – <125 μ m and ≥ 20 – <63 μ m classes. Each fraction was spread thinly on paper, and a neodymium magnet enclosed in a plastic sleeve was passed over the

material in three successive passes to extract magnetic grains. Recovered grains were examined under a stereo binocular microscope to identify candidate microspherules. Selected grains were mounted on carbon SEM tape for subsequent analysis via scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) using a JEOL 6000 Plus LV system. Confirmation of glassy or Fe-rich microspherules was based solely on SEM-EDS criteria [9].

Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS)

Standardized protocols were followed for SEM analysis. At the University of Oregon, particles were imaged and analyzed using both a JEOL-6000 SEM operating in low-vacuum mode and a ThermoFisher Apreo 2 SEM for high-resolution surface imaging and elemental characterization. Complementary SEM work at Elizabeth City State University employed a JEOL-6000 SEM system under identical vacuum conditions. SEM-EDS analyses were performed to determine the elemental composition of particles, with major elements identified within a typical uncertainty of $\pm 10\%$.

Single particle inductively coupled plasma time-of-flight mass spectrometry (SP-ICP-TOF-MS)

Particle extraction

For SP-ICP-TOF-MS analysis, 100 mg aliquots of sediment were suspended in 10 mL of ultrapure water (Millipore Advantage System, Merck Millipore) in acid-washed 15 mL centrifuge tubes. The suspensions were vortexed (Scientific Industries G560) and ultrasonicated (Branson 2800, 40 kHz) for 15 minutes to ensure dispersion. After settling for 24 hours, the upper 5 mL of the supernatant was transferred to clean centrifuge tubes and stored at 4 °C. Before analysis, samples were diluted 5000-fold with ultrapure water and sonicated before and after dilution.

Elemental analysis

Elemental composition of individual particles was determined using a TOFWERK SP-ICP-TOF-MS system, following established protocols [98–100]. Samples were introduced via a 2DX autosampler (Element Scientific) with a MicroMist U-series nebulizer and a quartz cyclonic spray chamber. Instrument settings and monitored isotopes are provided in Supplementary **Tables S3** and **S4**. Calibration standards included multi-element ICP reference solutions (0, 1, 2, 5, and 10 $\mu\text{g L}^{-1}$ in 1% HNO_3) and certified nanoparticle standards (NIST RM 8013 Au) for determining transport efficiency using the known-size method [101]. A 4.5% H_2/He gas mixture served as a collision gas optimized for $^{56}\text{Fe}^+$ and $^{28}\text{Si}^+$ signals. Data processing, including signal thresholding using the Poisson algorithm [102]

and event correction, was conducted using TOFPilot v2.11.3 (TOFWERK). Samples and blanks were analyzed in triplicate, and data were collected for 200 seconds per replicate. Replicates were combined for final interpretation.

Nanoparticle mass concentration refers to the summed elemental mass of all nanoparticles containing a given element detected by SP-ICP-TOF-MS, normalized to the mass of sediment analyzed and reported in ng g^{-1} . This metric represents the total elemental mass hosted within nanoparticles and does not reflect the physical mass or size distribution of individual particles.

Nanoparticle number concentration refers to the total count of nanoparticles containing a given element detected as discrete single-particle events, normalized to sediment mass and reported as $\# \text{g}^{-1}$. Number concentration therefore reflects changes in the abundance of element-bearing nanoparticles, independent of particle mass.

Laser ablation inductively coupled mass spectrometry

Laser ablation on microspherules was conducted at the Center for Elemental Mass Spectrometry (CEMS), University of South Carolina. Element concentrations were determined using a Photon Machines UV-Eximer 193 nm laser ablation system with a HELIX 2 sample cell in a He atmosphere, coupled to a Thermo ELEMENT 2 High-Resolution ICP-MS. Concentrations were determined by spot ablation with a 40–50 μm spot at 8 Hz and $\sim 11 \text{ J cm}^{-2}$ fluence. Relevant laser and ICPMS parameters can be found in Frisby et al. [103]. Microspherules were handpicked and mounted on glass slides with tape. Each spot was ablated for ~ 20 seconds. Tests were conducted to determine the potential overlap of the beam with the tape and the signals generated by ablating tape or glass slide. Each ablation spot data was manually screened for the potential of the beam to obliterate the specimen and hit the underlying tape. In those cases, only the portion of the signal from the unknown spot was used for reduction. We monitored masses ^{23}Na , ^{27}Al , ^{25}Mg , ^{29}Si , ^{43}Ca , ^{47}Ti , ^{51}V , ^{53}Cr , ^{55}Mn , ^{57}Fe , ^{59}Co , ^{60}Ni , ^{63}Cu , ^{66}Zn , ^{85}Rb , ^{88}Sr , ^{89}Y , ^{90}Zr , ^{93}Nb , ^{98}Mo , ^{99}Ru , ^{101}Ru , ^{103}Rh , ^{105}Pd , ^{106}Pd , ^{137}Ba , ^{139}La , ^{140}Ce , ^{146}Nd , ^{149}Sm , ^{157}Gd , ^{163}Dy , ^{167}Er , ^{172}Yb , ^{178}Hf , ^{185}Re , ^{192}Os , ^{193}Ir , ^{195}Pt , ^{208}Pb , ^{232}Th , ^{238}U . Data reduction was performed manually following Frisby et al. [103] and Humayun et al. [104]. As the microspherules were similar in size to the laser beam, they were obliterated during measurement. Each spot data scan was manually inspected, and only the parts of the scan that ablated the microspherules and not the substrate was used for reduction. As we did not know *a priori* if the microspherules were homogenous in terms of metals, we used the total beam signal for each element and for each microspherule to calculate concentrations. Gas blank was subtracted from each analysis. We used a combination of laser ablation standards and

reference materials (NIST SRM612; BCR-2G and BIR-1G reference material from the United States Geological Survey) to quantify the Relative Sensitivity Factors (RSF) and metal content in MSp and the platinum group elements (see also Humayun et al. [104]). For the metal microspherules, we assumed Fe is 99% by weight of each spot, and the rest of the elements are calculated by ratioing the intensities to ^{57}Fe . This assumption is validated *posteriori* by looking at the sum of all element concentrations. The sum of metals in the microspherules analyzed (SI, Table S5) is 99.4 to 100.7%, confirming our assumption to be within 2% total. The uncertainties of the microspherule concentrations cannot be estimated as we used the total ablation signal per analysis, therefore, any “spikes” in the laser data are taken as part of the analyzed microspherule and were not excluded as outliers. Moreover, as the microspherules were obliterated during ablation, there was no opportunity for duplicates.

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Supplementary information

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Data availability

All data generated or analyzed during this study are included in this published article and the Supplementary Information.

Sample availability

Samples from White Pond are mostly depleted, but limited amounts may be available from the Corresponding Author.

Author contributions

All authors reviewed and approved the manuscript. Authors C.R.M., M.A.L., and A.W. designed the study and wrote most of the paper; M.B., M.Bi., D.J.M., M.J.B., A.C.G., T.A.F., S.M., C.S.L., T.R.T., S.P.O., W.S.W., V.A., M.S.H., M.A., G.K., M.J.D., S.G.T., P.A.S., D.A.H., and T.W. contributed data, technical analysis, and editing for the paper.

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 the Comet Research Group (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.

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