



Research Article

A 12,800-year-old layer with cometary dust, microspherules, and platinum anomaly recorded in multiple cores from Baffin Bay (expanded)

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ABSTRACT

The Younger Dryas Boundary (YDB), dated to ~12.8 ka, marks the onset of an abrupt return to near-glacial conditions across much of the Northern Hemisphere. Numerous terrestrial sites contain unusual assemblages of high-temperature materials and geochemical anomalies near this boundary, but marine records remain comparatively sparse. Here we report a multiproxy investigation of four sediment cores (52, 64, 67, and 77) from Baffin Bay, a climatically sensitive region adjacent to the Laurentide Ice Sheet and downstream of major North Atlantic circulation pathways. Within glaciogenic marine sediments dated to the YD onset, we identify distinct layers enriched in inferred impact-related proxies, including meltglass, spherules, carbonaceous particles, metallic dust particles, cometary dust particles, and platinum-group element (PGE) anomalies. Nanoparticles (<1 µm) extracted from bulk sediments were analyzed

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using single-particle inductively coupled plasma time-of-flight mass spectrometry (SP-ICP-TOF-MS), allowing determination of elemental masses and ratios within individual particles. Concentrations of Pt, Ir, Ni, and Co show pronounced peaks associated with the YDB interval across all cores. Elemental mass ratios within nanoparticles, including Ir/Pt, Pt/Pd, Pt/Fe, Co/Ni, and Ni/Fe, also increase sharply within the same stratigraphic interval, with maxima typically occurring slightly above peaks in microspherules and carbonaceous particles. The diagnostic ratio of Pt/Fe is most similar to that of metal-rich extraterrestrial compositions, including comets, and is also strongly enriched relative to average crustal material. The stratigraphic coherence of these enrichments across cores spanning shelf to deep-basin environments indicates a basin-wide depositional signal rather than localized sedimentary processes. The slight offset between peaks in larger melted spherules and submicron nanoparticles is consistent with delayed atmospheric fallout of fine material and subsequent settling through the water column, potentially enhanced by aggregation into marine snow. Background nanoparticle abundances outside the YDB interval are comparatively low, suggesting that the observed enrichments represent a short-lived pulse of metal-rich particulate input. Taken together, the multiproxy evidence from Baffin Bay supports the presence of an unusual depositional layer at the onset of the Younger Dryas marked by high-temperature materials and PGE-enriched nanoparticles. While these anomalies and individual proxies may have alternative explanations, their co-occurrence, stratigraphic confinement, and replication across multiple, widely separated marine cores argue for a common origin. The data are consistent with the addition of extraterrestrial material from a high-energy event capable of injecting large quantities of fine particulate matter into the atmosphere and ocean. Such an event could have contributed to rapid environmental perturbations at the Younger Dryas onset, including atmospheric dust loading and disruption of regional climate. These findings extend the geographic range of YDB proxies into the marine realm of Baffin Bay and provide independent evidence for a sudden, basin-wide depositional episode at ~12.8 ka.

KEYWORDS

Younger Dryas Boundary, Baffin Bay, Ice-rafted debris (IRD), nanoparticles, single-particle ICP-TOF-MS, biomass burning, airbursts and impacts, platinum group elements (PGEs), Younger Dryas impact hypothesis (YDIH)

Editor's Note: An earlier version of this article was retracted by PLOS ONE [1] on the basis of alleged deficiencies in citation handling, reporting clarity, and methodological description. Importantly, the retraction did not cite data fabrication, falsification, plagiarism, analytical error, or invalidation of the study's results, nor did it identify any unreliability in the underlying data or conclusions.

The issues cited by the journal consist of (a) incorrect or incomplete reference metadata (primarily DOI-related production errors), (b) matters of clarity in describing radiocarbon calibration, Bayesian age-depth modeling, and sampling resolution, and (c) inadvertent inclusion of a small number of non-impact-related images in a large supplementary figure set. Each of these issues was readily correctable through standard post-publication correction and, in the authors' view, would typically fall within the scope of corrigenda rather than retraction under Committee on Publication Ethics (COPE) guidance.

The authors maintain that the retraction decision was therefore disproportionate to the issues identified, particularly given that the authors provided detailed explanations and corrective actions to the journal. Retraction in this case removes valid data and interpretations from the scientific record without demonstrating that the findings are unreliable.

This note is included to clarify the nature of the retraction for readers and to ensure transparency regarding the authors' position that the appropriate remedy under COPE standards

would have been formal correction rather than removal of the article from the literature. The present version of the article has been updated to address the issues cited in the retraction notice, including corrected reference metadata. In addition, the authors provide expanded nanoparticle data, additional clarification of radiocarbon calibration, more details on age-depth modeling, and revised supplementary materials.

Introduction

The Younger Dryas impact hypothesis (YDIH)

The YDIH posits that ~12,800 years ago, Earth entered the debris stream of a large disintegrating comet [2]. This impactor is hypothesized to have undergone multiple disintegrations during the last 35 to 20 ky, resulting in the formation of the Taurid Complex, including Comet Encke and dozens of candidate Taurid-complex NEOs [3–8]. During this encounter, comet fragments collided with Earth, transporting an assemblage of impact materials to the Earth's atmosphere, land, and ocean and possibly forming multiple small, shallow, temporary craters [9–13].

Scope of this study

If such an event occurred at the Younger Dryas Boundary (YDB), there should be evidence of a widespread YDB peak in cometary dust, also known as “cosmic dust,” “cometary dust particles (CDPs),” and “interplanetary dust particles.”

Additionally, if there were low-altitude airbursts and surface impacts during such an encounter, there should also be impact-related microspherules (also known as microtektites and microkrystites) [14, 15], mainly produced from terrestrial material with a small extraterrestrial (ET) component (<2 wt%) [16–19]. This layer should also have elevated platinum group elements (PGEs) and other elements, such as cobalt, chromium, and nickel, commonly found in comets and asteroids.

To test the hypothesis of such a cosmic impact event at the Younger Dryas onset, we examined YDB sequences in four marine sediment cores from Baffin Bay, which were identified in earlier studies to include the YD interval [20, 21]. Sediment samples from within, above, and below the YDB layer were analyzed in search of Fe- and Si-rich microspherules containing minerals formed at high temperatures, elevated PGE and REE concentrations, and potential cometary dust particles (CDPs). The sediments were also geochemically analyzed for elemental nanoparticles using a novel application of single-particle inductively coupled plasma time-of-flight mass spectrometry (SP-ICP-TOF-MS). Additionally, microspherule candidates were examined using scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS), as well as laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS).

Geologic setting

Baffin Bay is a narrow ocean strait between Greenland and Baffin Island that provides a restricted connection between the Arctic and North Atlantic Oceans. It extends ~1000 km from Jones Sound in northern Baffin Bay to Home Bay to the south [20, 21]. Water depths in Baffin Bay are up to ~2400 m. The western continental margin of Baffin Bay features a narrow and gently sloping continental shelf, which transitions to a steep continental slope [21].

Cometary dust particles (CDPs)

Metallic micro-particles of various shapes have been found in peaty deposits [22–24], Antarctic ice [25], oceanic sediments [26], terrestrial sedimentary rocks [27, 28], and during research missions into Earth's stratosphere [29]. Most of these particles are attributed to a constant influx of interplanetary dust that falls to Earth at an estimated but variable rate of $\sim 5.2 \times 10^3$ metric tons/year [30].

Tselmovich et al. [24] note that “*the origin of cosmic dust can be quite diverse, including the remains of disintegrated comets, asteroids, and particles of matter ejected by the Sun.*” Flynn et al. [31] also concluded that dust associated with active comets and non-cometary objects in the asteroid belt are both likely sources of cosmic dust. According to Nesvorný et al. [32], up to 85% of this dust is cometary in origin, and most unmelted cosmic dust originates from Jupiter-family comets, with a smaller portion coming from the asteroid belt [30]. Other studies estimate that comets supply a significant percentage of dust particles that reach

Earth, with various studies suggesting a range of 30–90% [33–35], with the rest coming from asteroids. Schmidt [36] also observed that “*meteoric dust is probably related to ablation of cometary meteors in the Earth's atmosphere.*” He suggested that high-velocity entry of this dust into Earth's atmosphere would evaporate ice and release metallic particles with amorphous coatings. This hypothesis is supported by Parkin and Hunter [37], who found that metallic flake abundances seemed to be related to “meteor showers.” However, it is widely accepted today that “meteor showers” result not only from meteors but also from the influx of material from cometary trails.

Recent studies by Tselmovich et al. [22–24, 38] and Sungatullin et al. [27, 28, 39, 40] have documented a variety of melted and unmelted metallic dust particles (MDPs) commonly present in Holocene peats, interpreted as indicators of the flux of cometary dust. Large peaks in these MDPs are also observed within sedimentary layers associated with potential cometary airburst or impact events. Electron microscope and microprobe analyses of these MDPs show that they typically consist of native iron (Fe), low-oxygen Fe (wüstite), and native nickel (Ni), along with metal alloys such as FeNi, FeCr, and FeCrNi. These particles exhibit a range of distinctive morphologies, including flaky or platy forms, needle- or string-like shapes, and spirals with twisted, folded, laminated, and deformed surface textures characterized by trenches or furrows.

These morphologies are interpreted to originate during atmospheric entry, when cometary dust undergoes differential melting and separation of components (e.g., Fe, Ni, Cr, and Si). Such processes lead to the formation of flat metallic “flakes,” including elongated Fe or FeNi particles that are prone to curving or twisting during passage through the atmosphere [28, 41]. In addition, some particles display partially melted and folded edges that are inconsistent with formation by terrestrial volcanic or authigenic processes and are instead consistent with extraterrestrial material that entered the atmosphere at high velocity and experienced partial melting [42]. Many native Fe and native Ni cosmic dust particles (CDPs) are proposed to have formed through differentiation of Fe and Ni from silicate during complete or partial melting in atmospheric transit and/or during explosive detonations associated with cometary airbursts or impacts [28]. Tselmovich [24] further notes that magnetite microspherules and flake-like particles of oxygen-depleted iron, nickel, and intermetallic compounds found in sedimentary rocks are often of cometary origin.

Microspherules

Unlike cometary microspherules, those related to impact are produced when rock vaporized by meteoritic impacts or airbursts condense into glassy or crystalline spherical particles and then deposited as proximal and distal ejecta [14]. Glassy microspherules lacking crystals are known as microtektites, while other microspherules form through vapor condensation.

The surfaces of these microspherules often exhibit a dendritic or segmented soccer ball pattern due to Fe crystallization of melted magnetite and are called microkrystites [14, 15]. Both silica-rich microtektites and Fe-rich microkrystites containing high-temperature melted minerals have been reported in the YDB layer at numerous sites from various depositional environments and depths on six continents [2, 9, 10, 43, 44]. Collectively, we refer to both types as impact microspherules, shortened to “microspherules” in this contribution.

Study sites

Sediment samples were collected from four piston cores curated at the National Marine Geoscience Collection at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia (SI, Figure S1). These marine cores were selected based on their previously published radiocarbon dates and/or stratigraphic changes suggesting the presence of the YD

onset [20, 21]. These are the first marine sedimentary cores to be studied in search of the YDB cosmic impact layer. We studied four piston cores sequences (Cores 83023-052, 2013029-064, 2013029-077, and 2008029-67) spanning a distance of ~1000 km from a cross-shelf trough off the mouth of Jones Sound, along the northeast Baffin Slope, in the Baffin Bay Basin, and to offshore of Home Bay, just north of Davis Strait (Figure 1 and Table 1). Cores were collected in water depths ranging from ~500 to nearly 2,400 meters. All of the metadata for these cores are available via the Expedition Database (ED) https://ed.marine-geo.canada.ca/cruises_e.php.

Sampling of individual cores targeted stratigraphic intervals considered to bracket the Younger Dryas boundary and thus sampling resolution was optimized for search of a discrete peak in impact-related particles (Table 2). Intervals above and below the YDB were sampled at a lower resolution needed to assess background variability.



Figure 1: (a) Map of northeast Canada and Greenland showing the location of Baffin Bay and core 83023-052 (small red box in panel a), and (b) locations of cores 2013029-064, 2013029-77, and 2008029-67 sampled for this study (small red boxes). The map was created using the NCEI Bathymetric Data Viewer and is in the public domain. (<https://www.ncei.noaa.gov/maps/bathymetry/>). See higher resolution Bathymetry Data for Core 83023-52 in SI, Figure S2 (<https://zenodo.org/records/18877755>).

Table 1: Sediment cores used in this study.

Expedition number	Core number	Core type	Latitude (N)	Longitude (W)	Water depth (m)	Centimeters (cm)
2013029	64	Piston-ACG Large	72.426113	−72.769305	875	713
2008029	67	Piston-ACG Large	72.434431	−67.877178	2357	519
83023	52	Piston-Benthos	75.58667	−78.69167	512	875
2013029	77	Piston-ACG Large	68.308682	−63.794663	1153	649.5

Table 2: Core samples and depth (cm) below the top of the core.

Core 52	Depth (cm)	Core 64	Depth (cm)	Core 67	Depth (cm)	Core 77	Depth (cm)
83023-052	587-589	2013029-064	272-274	2008029-067	24-25	2013029-077	90-91
83023-052	615-620	2013029-064	286-290	2008029-067	25-26	2013029-077	159-160
83023-052	625-630	2013029-064	290-293	2008029-067	26-28	2013029-077	160-161
83023-052	630-635	2013029-064	293-297	2008029-067	28-30	2013029-077	161-162
83023-052	635-640	2013029-064	302-308	2008029-067	30-32	2013029-077	167-168
83023-052	640-645	2013029-064	312-318	2008029-067	32-35	2013029-077	286-290
83023-052	770-775	2013029-064	323-325	2008029-067	35-36		
83023-052	785-790						

Radiocarbon dating and Bayesian modeling

Core sections for radiocarbon dating were chosen based on previous chronometric dating that suggested the sampled interval included the YD boundary. Radiocarbon dating was performed on assemblages of hyaline calcite foraminiferal tests composed primarily of benthic taxa and, where present or dominant, planktic taxa. Porcelaneous benthic foraminifera (high-Mg calcite) were excluded from all radiocarbon samples to minimize potential diagenetic or reservoir-related effects (see SI, “Foraminifera: Radiocarbon Dating and Environmental Setting”). These age estimates and previously published radiocarbon ages of foraminifera and a molluscan shell were used to develop a Bayesian geochronology for sampled sections of each of the four cores (Figure 2; SI, Figures S3-S6 and SI, Tables S1-S5). For radiocarbon calibration, we applied regionally specific marine reservoir corrections (ΔR) in OxCal using Baffin Bay values from Pearce et al. [46]: Zone 4 for Core 52 ($\Delta R = +71$ y); Zone 3 for Cores 64 and 67 ($\Delta R = +218$ y); and the Zone 3/2 boundary for Core 77 ($\Delta R = +103$ y, the mean of $+218$ and -12). For Core 77, we adopted a simple mean of Zone 2 and Zone 3 values to reflect its position near the zone boundary; although a pooled mean weighted by sample counts would be statistically preferable, the resulting difference would be small relative to the intrinsic ΔR uncertainty and does not affect the stratigraphic placement of the Younger Dryas interval.

Given the strong spatial variability in freshwater input, circulation, and sea-ice conditions across the basin, these region-specific corrections are more appropriate than the application of a single global marine offset. McNeely et al. [47] also provided reservoir corrections for Baffin Bay, but

they were based on a previous IntCal calibration curve. Although the corrections were similar, with a range of $\Delta R = +220$ to $+50$, we used the more recent values from Pearce et al. [46]. Bayesian age-depth modeling of foraminiferal dates indicates that all four cores contain sediments deposited at the onset of the Younger Dryas episode established by Kennett et al. [45] as an age range of 12,875–12,775 cal. BP (IntCal20) based on analysis of 354 dates from 23 sedimentary sequences over four continents.

Throughout this manuscript and Supporting Information, calibrated ages are sometimes shown, and Bayesian modeled ages are shown at other times. Calibrated ages refer to the direct outputs of the radiocarbon calibration procedure, whereas modeled ages denote Bayesian age-depth estimates derived using OxCal. These values are not always identical, commonly due to radiocarbon reversals associated with redeposition and/or bioturbation. In cases of discrepancy, the Bayesian modeled ages were preferred. Each radiocarbon determination was assigned to the midpoint of the sampled depth interval, and Bayesian age-depth modeling incorporated both analytical radiocarbon uncertainty and the vertical uncertainty associated with sample thickness. All chronological interpretations presented here rely on the modeled age ranges, which explicitly account for both sources of variance.

Results

The Baffin Bay cores exhibit distinct, anomalous abundance peaks in unusual materials in the Bayesian-modeled YDB layer (Figures 3 and 4). These include peaks in Fe-rich and silica-rich microspherules (~ 4 to 163 μm in diameter) with high-temperature minerals, MDPs, meltglass, and platinum

OxCal v4.4.4 Bronk Ramsey (2021); r:5

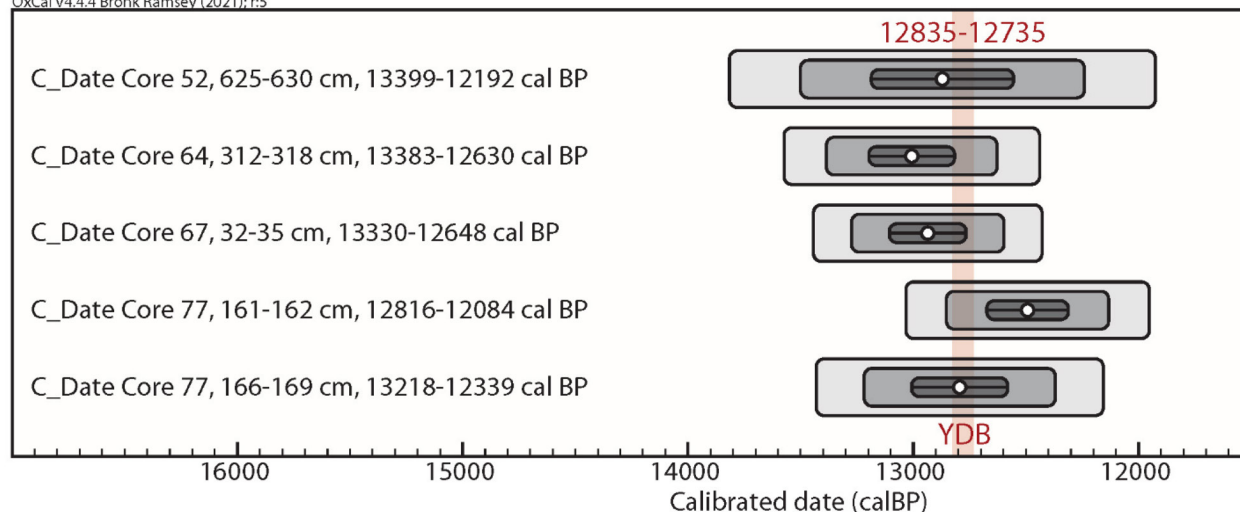


Figure 2: Bayesian radiocarbon analyses of cores. Bayesian analyses were generated to produce age-depth models for the four cores (see SI, Figures S3–S6, and SI, Tables S2–S5) <https://zenodo.org/records/18877755>). We also generated calibrated ages for each core's YDB layer, which contains abundance peaks in microspherules, MDPs, and PGE-enriched nanoparticles. The results here list the core, depth interval of the YDB in each core, and calibrated ages (cal BP) at 95.4% Confidence Intervals (CI). The Bayesian interpolated mean age is displayed as a white dot. Confidence Intervals (CI) of 68.3% CI are shown as dark gray horizontal bars, 95.4% CI as medium gray, and 99.7% CI as light gray. The previously published YDB age range of 12,835–12,735 cal BP [45] is shown as a vertical red bar. **(a) Core 52**, for the 625–630-cm interval, the 68.3%, 95.4%, and 99.7% CI bars overlap the YDB age range. **(b) Core 64**, for the 312–318-cm interval, the 68.3%, 95.4%, and 99.7% CI bars overlap the YDB age range. **(c) Core 67**, for the 32–35-cm interval, the 68.3%, 95.4%, and 99.7% CI bars overlap the YDB age range. **(d) Core 77**, for the 161–162-cm interval, the 95.4% and 99.7% CI bars overlap the YDB age range, suggesting that this sample may slightly post-date the YDB, and the proxies have been redeposited upward. Alternatively, for the 171–173-cm sample, which was not analyzed for proxies, the 68.3%, 95.4%, and 99.7% CI bars overlap the YDB age range, suggesting that this may be the YDB layer. OxCal version 4.4.4 was used with the Marine20 calibration curve, and reservoir corrections were applied to all radiocarbon dates.

group elements (PGEs). Microspherule and MDP abundance peaks and examples of meltglass occur in the YDB-dated layers of each core, typically just below the base of an ice-rafted detritus (IRD) layer and falling off rapidly in samples above and below the YDB (Figure 4).

Core 64 contains one elevated data point for MDPs above the main abundance peak within the modeled YDB interval. This younger value is interpreted as background variability, most likely reflecting redeposition, and does not constitute an independent peak. Importantly, this data point lies within the broader 99% modeled age-range envelope for the YDB. The primary YDB peak in Core 64 remains well defined and consistent with the YDB peaks observed in the other cores.

Microspherules

Fe-rich and silica-rich microspherules peak in the YDB-dated core samples and feature evidence for high-temperature minerals, secondary spherule-on-spherule impacts, bubbles/vesicles, dendritic surface textures on Fe-rich microspherules, and aerodynamic shapes indicating high-velocity travel (Figure 5 and SI, Table S6). Fe-rich microspherules exhibit blebs of a low-oxygen metal (e.g., Figure 5d) that is transitional between chromite (FeCr_2O_4 ; melting point = 1,850–2,200°C) and Cr-magnetite ($\text{Fe}^{2+}(\text{Fe}_{1-x}\text{Cr}_x)_2\text{O}_4$; melting point = 1,583–1,587°C), both found in

some chondritic and achondritic meteorites, as well as in impact-related materials; the microspherules also contain iron phosphide (FeP; melting point = 1,370°C) (Figure 5k, m). Some silica-rich microspherules also exhibit numerous blebs of iron-silicide (FeSi; melting point = 1,410°C) and iron-sulfide (FeS; melting point = 1,184°C) (e.g., Figure 5e, h). These inclusions indicate formation at high temperatures in a reducing environment with limited oxygen, consistent with impact events [9–12, 48, 49]. See SI, Figures S10–S53 (Core 52); S112–122 (Core 64); S163–171 (Core 67); S218–S226 (Core 77) for EDS analysis of microspherules and metal inclusions.

Meltglass

Fragments of meltglass and melted grains were identified in Cores 64 and 52. These included various forms, including a melted cluster consisting of aluminosilicate and Fe-rich microspherules; a quartz grain that was either melted ($\geq 1715^\circ\text{C}$) or boiled ($\geq 2200^\circ\text{C}$); Fe- and Cr-rich aluminosilicate meltglass; potassium-enriched aluminosilicate meltglass; and Ti-rich aluminosilicate meltglass (Figure 6).

Metallic dust particles (MDPs)

These particles were analyzed using both SEM/EDS and LA-ICP-MS. MDPs range from ~20 to 150 μm in diameter. Baffin Bay MDPs are typically composed of native iron (Fe),

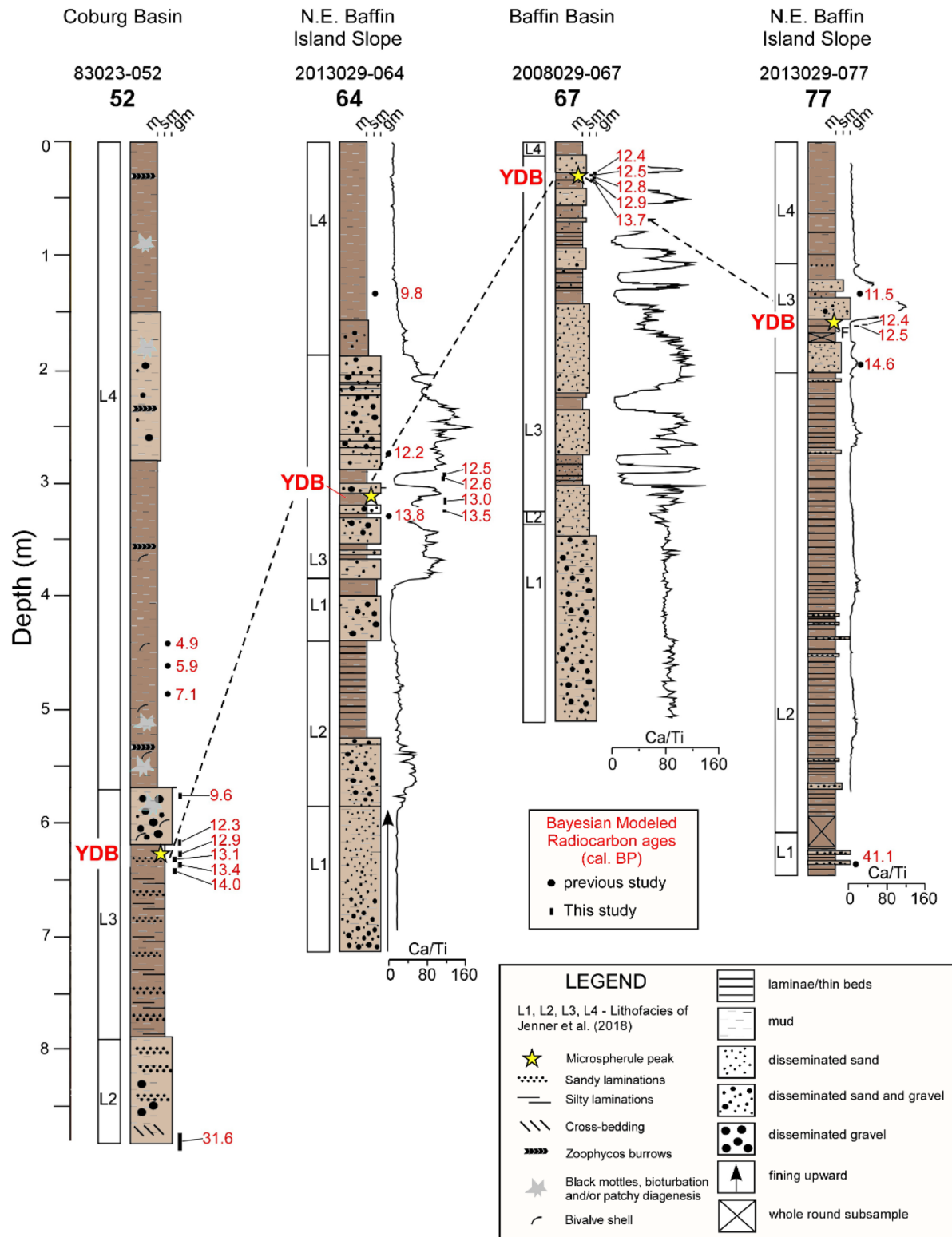


Figure 3: Comparison of Baffin Bay core lithofacies, Bayesian-modeled calibrated radiocarbon ages (SI, Tables S2-S5), and microspherule peaks (SI, Table S6) for Core 83023-052; and lithofacies, pXRF Ca/Ti ratios, and microspherule peaks (SI, Table S6) for Cores 2013029-064, 2008029-067, and 2013029-077 <https://zenodo.org/records/18877755>). The core 52 log is adapted from the Geological Survey of Canada marine core archives. Core logs for Cores 64, 67, and 77 are adapted from Figure 4 in Jenner et al. 2018 (Jenner, 2018 #1248). Notes: ¹Calibrated radiocarbon dates from Jenner et al. [20] and ²calibrated radiocarbon dates (this study) are shown as Bayesian modeled median ages. Red boxes (a-d) are core sections examined for impact proxies, as shown in Figure 4. Figure generated from data in Jenner et al. [20].

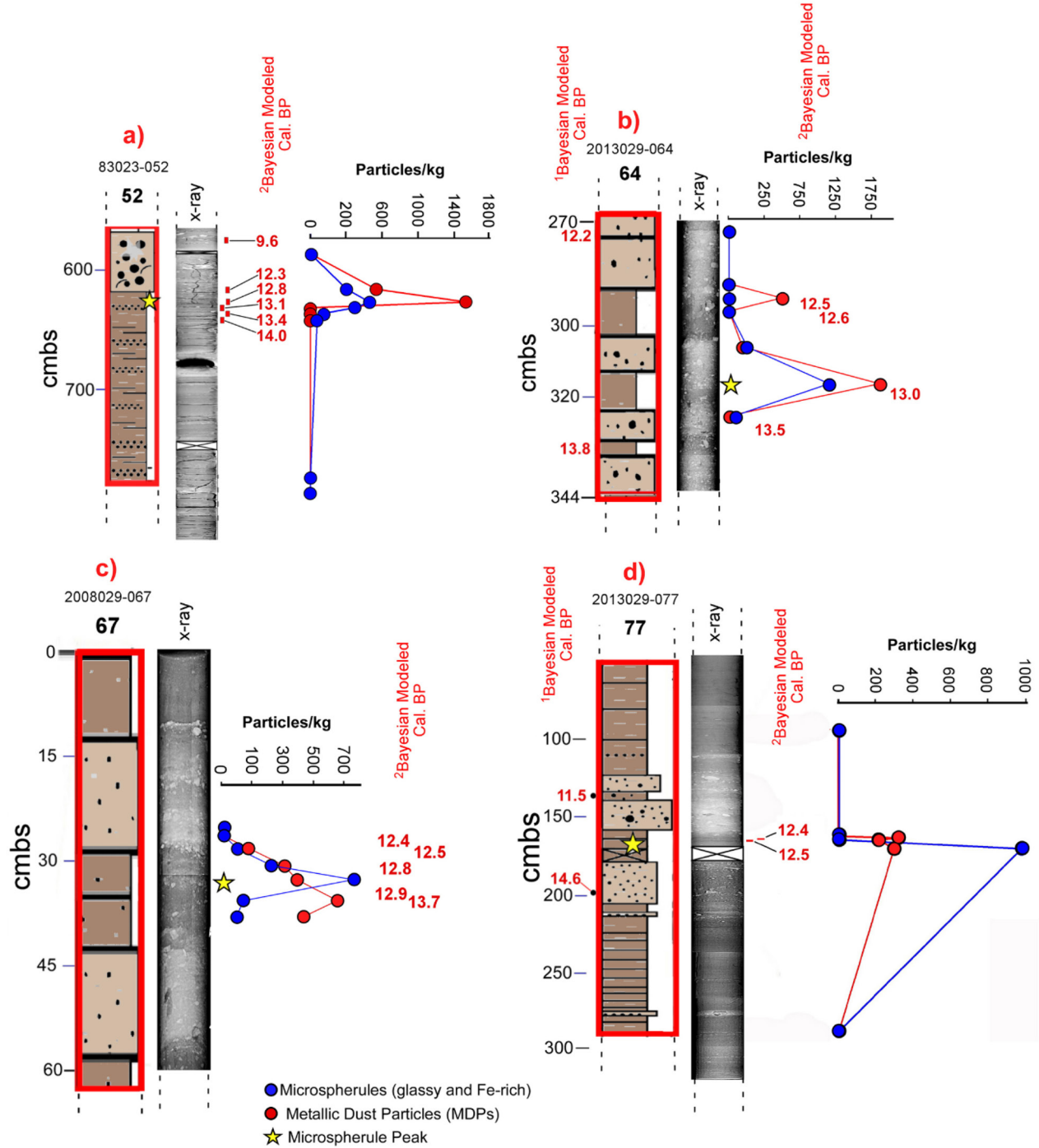


Figure 4: Close-up of areas shown in Figure 3 (red boxes) illustrating core lithology, core x-ray images, microspherule (MSP) and metallic dust particle (MDP) peaks (spherules/kg), and Bayesian-modeled radiocarbon ages. *Notes:* ¹Radiocarbon dates included in this analysis are from Jenner et al. [20] and ²this study (see SI, Table S1 and Bayesian-modeled ages in SI, Tables S2-S5) (<https://zenodo.org/records/18877755>). The X-ray images in panels a) and d) are stretched laterally to improve visibility. A yellow star indicates the YDB microspherule peak. Refer to Figure 3 for lithology keys and optical and X-ray images for cores in SI, Figures S249-252. The figure was generated from data from Jenner et al. [20].

native nickel (Ni), oxygen-depleted iron (low-O₂ Fe), chromite (FeCr₂O₄), and chromite enriched with Ni (FeCrNi). These MDPs include flat, “flake-like,” or elongated forms that often appear stretched, deformed, folded, and melted along the edges (Figure 7).

Melt splatter

Blebs of splattered chromite (FeCr₂O₄), FeCrNi, FeO, and tungsten (W), as labeled on each panel, were observed fused on rounded detrital quartz and magnetite from YDB-dated layers in the Baffin Bay cores [SI, Figures S98-S111 (Core

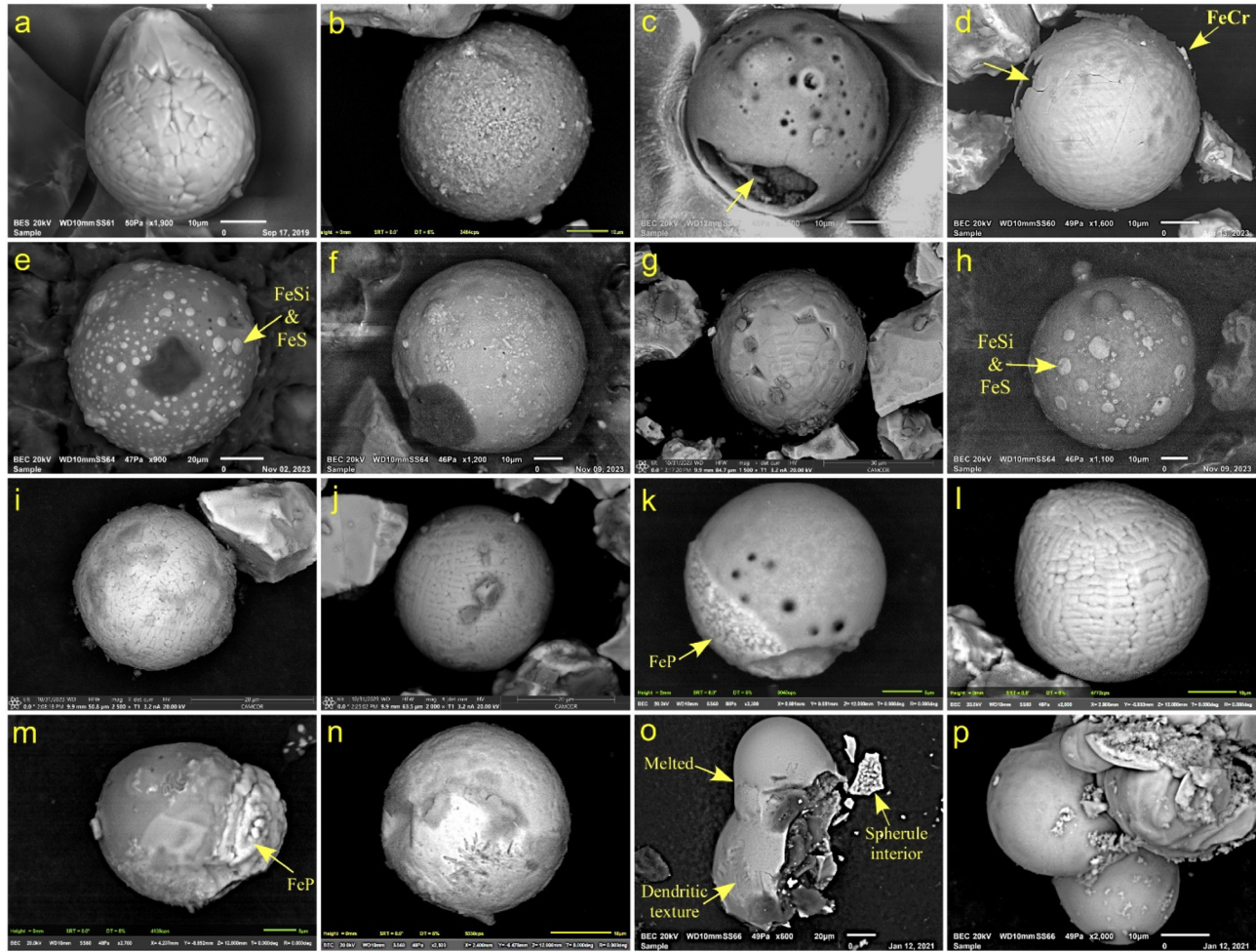


Figure 5: Examples of Fe-rich and silica-rich impact microspherules from Baffin Bay cores: Core 83023-052 (a-d); Core 2013029-064 (e-h); Core 2008029-067 (i-n); and Core 2013029-077 (o-p). Shown are aerodynamically shaped microspherules (panels a and l); a broken microspherule revealing a hollow interior (panel c); and a hollow microspherule containing a bleb of a low-oxygen transitional mineral phase between chromite (FeCr_2O_4) and Cr-rich magnetite (panel d). Microspherules with rounded blebs consisting of mixtures of iron sulfide and iron silicide (FeS and FeSi), indicating formation under reducing conditions, are shown in panels e and h. Multiphase microspherules with possible secondary impacts of molten material containing iron phosphide (FeP), also indicative of reducing conditions, are shown in panels k and m. Microspherules in panels a, d, g, i, j, l, and o exhibit dendritic crystallization textures, and conjoined microspherules showing dendritic textures, localized melting, and preserved interior fragments are shown in panels o and p. Microspherules in panels c, e, f, and h are silica-rich (see SI Figure S9); all others are Fe-rich. Diameters for 73 microspherules range from 4 to 163 μm , with a mean diameter of 64 μm . See SI Figures S10-S53 (Core 52), S112-S122 (Core 64), S163-S171 (Core 67), and S218-S226 (Core 77) for EDS analyses of microspherules and metal inclusions. Data available at <https://zenodo.org/records/18877755>.

52); S154-S162 (Core 64); S205-S217 (Core 67); and S236-248 (Core 77)]. These metallic blebs are primarily composed of native Ni, FeCrNi, and chromite, and they morphologically resemble melted splatter on quartz, ilmenite, and garnet grains from a South Carolina site described as cometary dust particles (CDPs) by Tselmovich et al. [38] (Figure 8).

Nanoparticle geochemistry in Baffin Bay cores

Nanoparticles (<1 μm) extracted from bulk sediment from Baffin Bay cores 52, 64, 67, and 77 were analyzed using SP-ICP-TOF-MS. This technique enables quantification of elemental mass and particle number for individual

submicron particles, allowing identification of population changes in nanoparticle abundance, particle size distribution, and elemental composition. Samples were obtained from the interval dated as YDB as well as from levels above and below (Figures 9-12; SI, Figures S7 and S8; SI, Table S7 [<https://zenodo.org/records/18877755>]). The YDB interval in these cores consists of a spherule-bearing layer overlain by a thin fallout layer enriched in fine particles and metal-rich nanoparticles, followed by an overlying detrital layer representing background sedimentation.

Figure 9 presents depth profiles for each core of nanoparticle mass concentration, number concentration, and

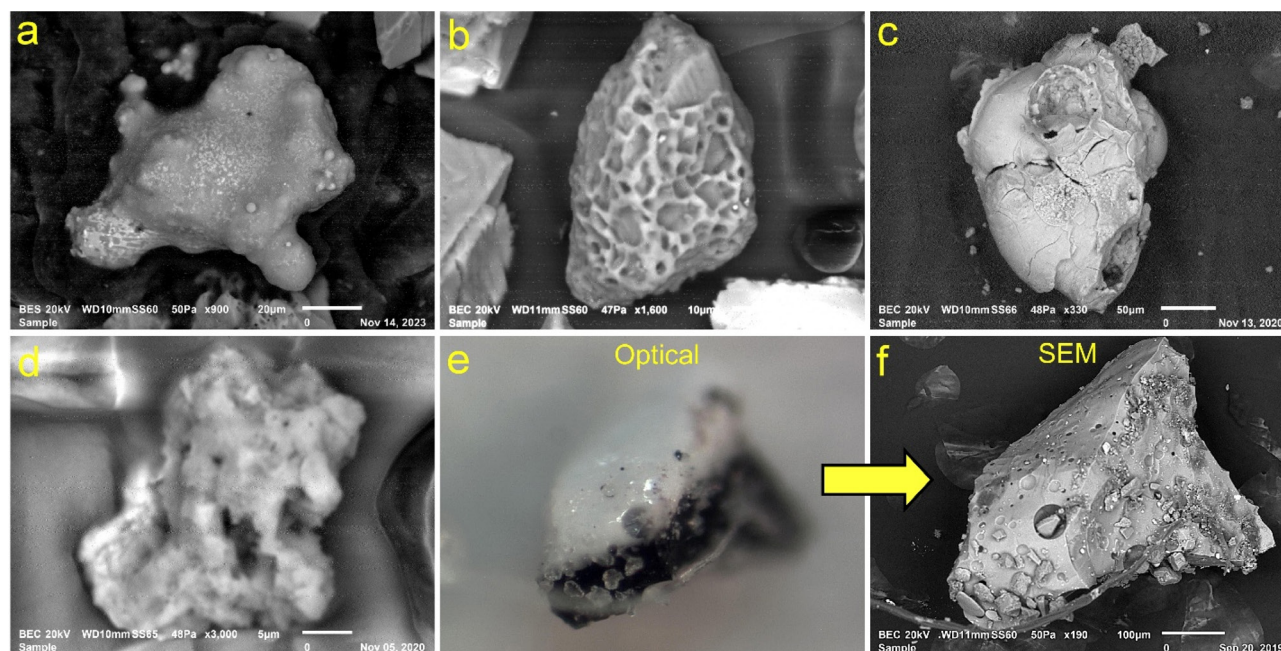


Figure 6: Examples of meltglass from Baffin Bay cores: (a) Agglutinated cluster of aluminosilicate and Fe-rich microspherules (Core 64_312-318 cm); (b) Partially melted quartz grain (Core 52_574-579 cm); (c) Fe and Cr-rich aluminosilicate meltglass (Core 52_625-630 cm); (d) Agglutinated potassium-enriched aluminosilicate meltglass (Core 52_630-635 cm); (e) Optical image; and (f) SEM image of Ti-rich aluminosilicate meltglass particle (Core 52_574-579 cm). See SI, Figures S82-S97 (Core 52) and S152-S153 (Core 64) for EDS data (<https://zenodo.org/records/18877755>).

mass per particle for 45 elements measured from aluminum to uranium. These parameters were examined to determine whether nanoparticle enrichments reflect normal variations in background sediment supply or instead represent a discrete increase in nanoparticle abundance or particle mass consistent with an anomalous input.

Figure 10 shows total PGE nanoparticle mass normalized to lithogenic elements (Fe, Al, Ti, and La). Because these elements represent major detrital components hosted in different mineral phases and exhibiting different mobility in sediments, lithogenic normalization helps account for dilution and grain-size variability associated with changes in background sediment supply. Selected elemental ratios within nanoparticles were examined to assess the presence of any compositional shifts in the metal-bearing particle population. Stratigraphic variations in these four ratios can signal the introduction of material from a source distinct from typical lithogenic inputs.

Figure 11 further evaluates inter-element relationships among siderophile and transition metals within nanoparticles, providing constraints on the composition of the contributing particle population independent of absolute abundance. In particular, a Pt/Pd ratio >1.0 is expected for an exogenic extraterrestrial (ET) contribution because platinum is enriched relative to palladium in many meteoritic materials and is less susceptible to post-depositional mobility. Pd is more prone to redox-driven remobilization

and formation of soluble complexes with ligands in pore waters. Thus, stratigraphically restricted elevations of Pt/Pd above unity, especially when coincident with enrichments in other siderophile elements, provide evidence for an external Pt-rich source rather than *in situ* fractionation or background variability [51].

Figure 12 compares and contrasts the Pt/Fe ratios of YDB nanoparticles with representative terrestrial and extraterrestrial materials. These include comets, refractory metal nuggets, micrometeorites, iron meteorites, chondrites, terrestrial magma, and the Pt/Fe of the upper continental crust.

By integrating elemental abundances, normalized PGE signals, inter-element ratios, and comparisons with peaks in microspherules and cometary dust particles (CDPs), we assess whether the nanoparticle record represents a discrete depositional pulse and whether its geochemical characteristics are consistent with an exogenic input. In interpreting any stratigraphic offsets between microspherule maxima and nanoparticle peaks, we also consider delayed atmospheric fallout of fine particles [52] and the potential role of aggregation into marine snow during descent through the water column [53].

Contrasting REE and PGE nanoparticle behavior across the younger dryas boundary

Paired analyses of nanoparticle data from the YDB horizon and the immediately underlying sample in four cores,

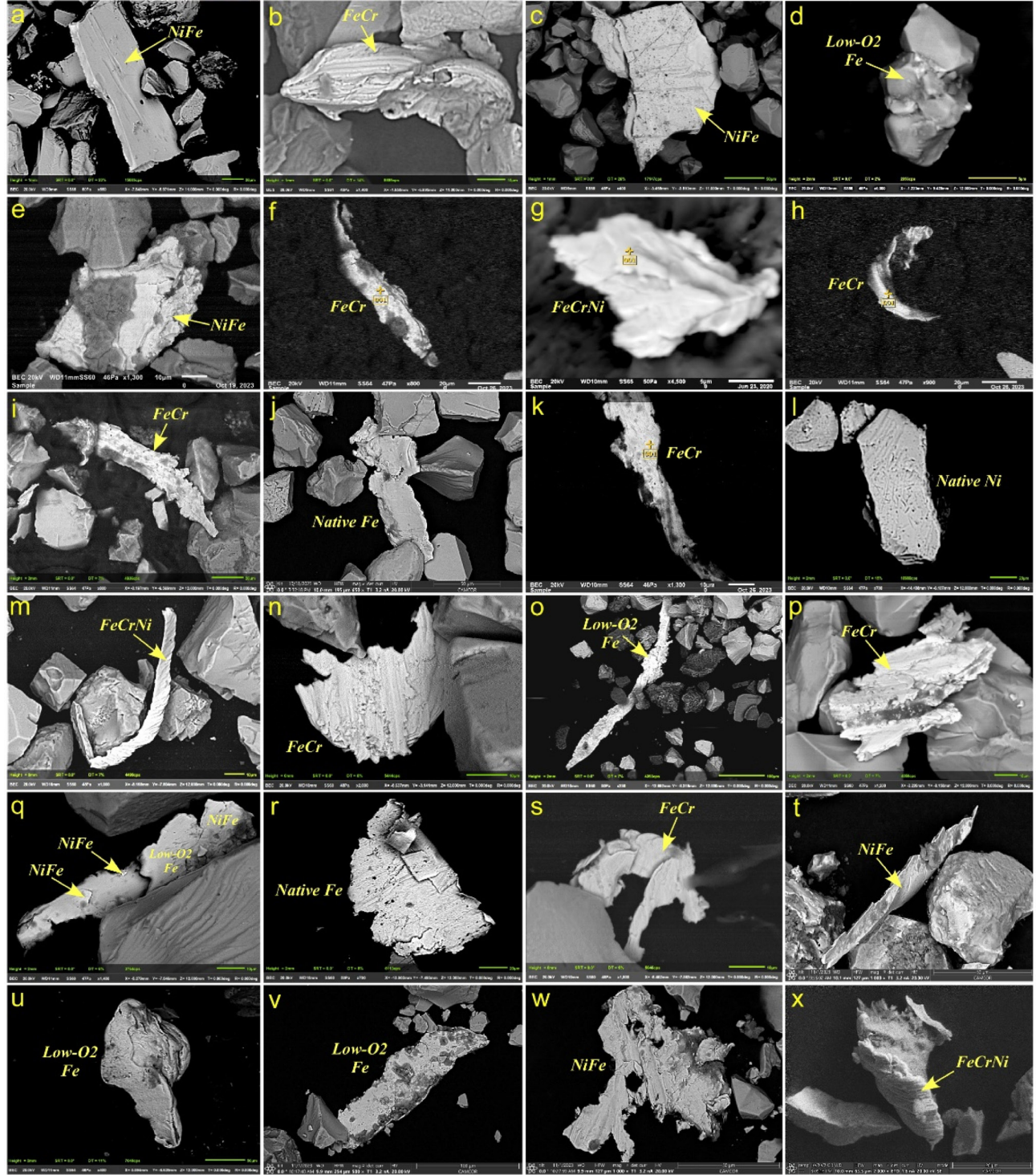


Figure 7: Examples of Baffin Bay metallic dust particles (MDPs). The MDPs range from unmelted to partially melted. They are typically enriched in Fe, Ni, and Cr and are oxygen-deficient (low- O_2 Fe), as labeled on each panel. Core 83023-052 (a-d); Core 2013029-064 (e-l); Core 2008029-067 (m-t); and Core 2013029-077 (u-x). MDPs in this figure range from ~20 to 150 μm in diameter. See SI, Figures S54-S81 (Core 52), S123-151 (Core 64), S172-S204 (Core 67), and S227-S235 (Core 77) for EDS data (<https://zenodo.org/records/18877755>).

expressed as aggregated elemental mass distributions from the SP-ICP-TOF-MS measurements, show a clear contrast between REE behavior and PGE behavior (Figures 13 and 14). Chondrite-normalized REE patterns are broadly

similar in all cores, LREE-enriched and decreasing toward the HREE, with YDB vs. sub-YDB differences expressed mainly as vertical offsets (concentration changes) rather than major changes in pattern shape (Figure 13). This behavior is

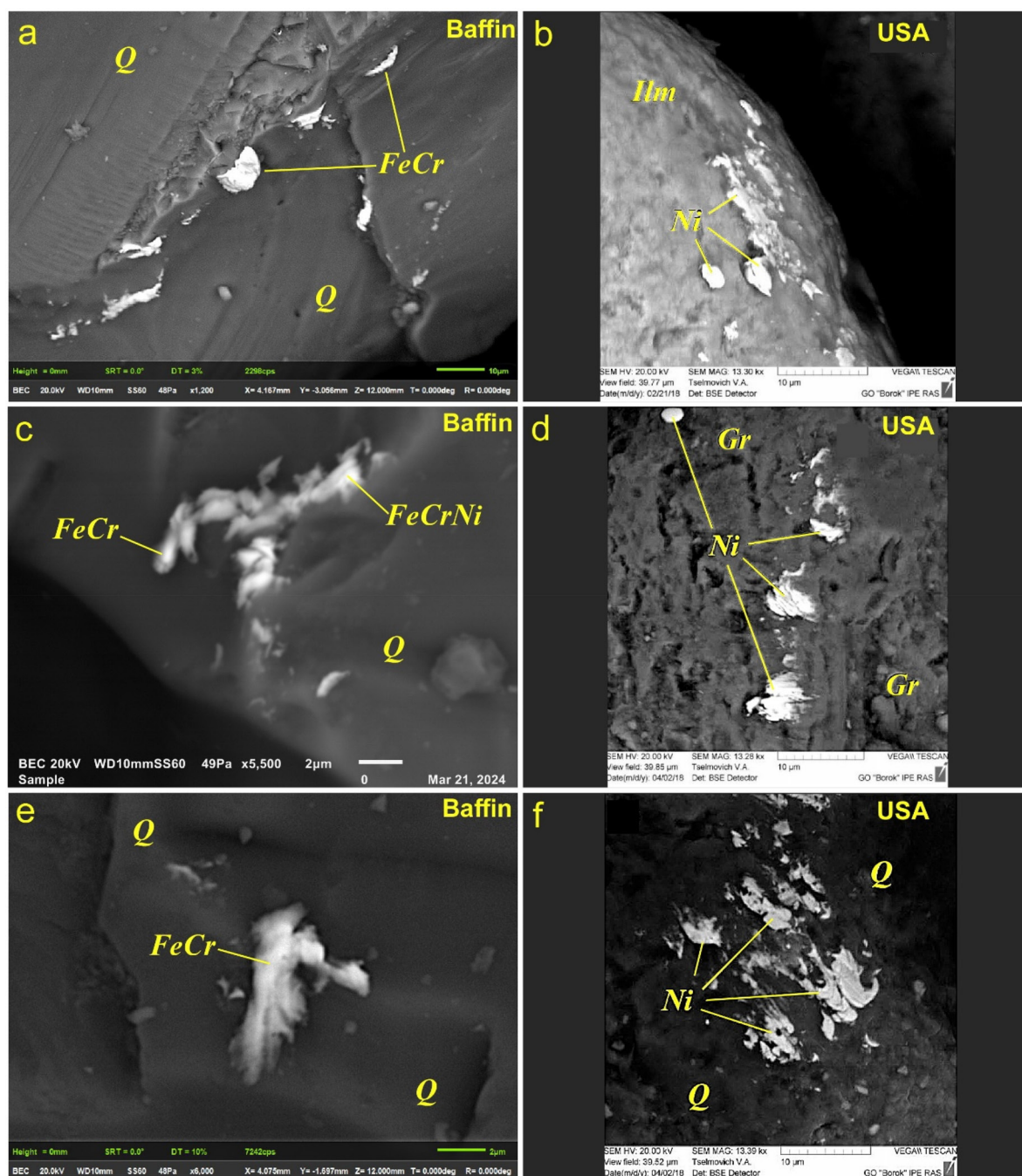


Figure 8: Comparison of metallic melt splatter on quartz grains from Baffin Bay versus similar melt splatter from South Carolina, USA [38]. (a) Baffin Bay quartz grain (Q) splattered with FeCr. (b) South Carolina ilmenite grain (Ilm) splattered with native Ni [38]. (c) Baffin Bay quartz grain splattered with FeCr and FeCrNi. (d) Garnet (Gr) splattered with native Ni [38]. (e) Baffin Bay quartz grain splattered with FeCr. (f) South Carolina quartz grain splattered with native Ni [38]. Baffin Bay melt splatter morphologically and chemically matches many MDPs (i.e., FeCr and FeCrNi) that peak during the YD onset for all cores (see Figure 7). [SI, Figures S98-S111 (Core 52); S154-S162 (Core 64); S205-S217 (Core 67); and S236-248 (Core 77)].

most consistent with lithogenic controls on the REE abundances (e.g., varying detrital/clay contribution and/or dilution by non-silicate phases), rather than a fundamentally different REE source at the boundary.

In contrast, chondrite-normalized PGE patterns (Figure 14) display sharper, element-specific anomalies at the YDB,

producing a stratigraphically discrete enrichment signal not matched by comparably diagnostic REE changes. This is quantified by PGE enrichment factors ($EF = YDB \div \text{underlying sample}$; Table 3). The strongest enrichments occur in Core 52 for Pt ($EF = 3.72$) and in Core 64 for Pd ($EF = 6.74$), with additional notable enrichments in Core 67 (Pd $EF =$

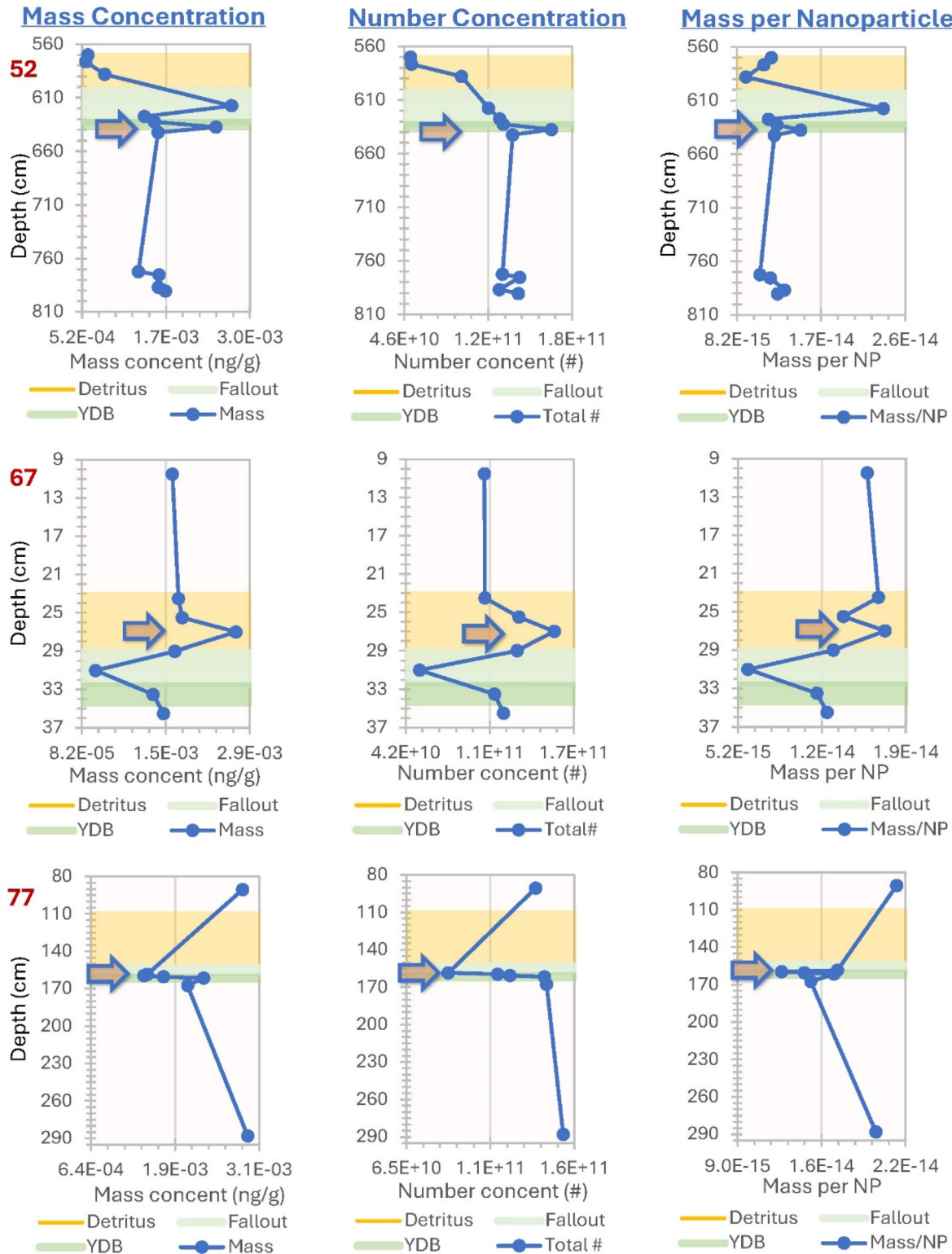


Figure 9: Nanoparticle mass concentration, number concentration, and mass per nanoparticle for all elements across the Younger Dryas Boundary (YDB) interval in Baffin Bay sediment cores 52, 67, and 77. Colored bands denote lithostratigraphic units: the YDB spherule layer (green), the overlying fallout layer (light green), and the overlying detritus layer (gold). Arrows indicate the primary nanoparticle enrichment interval. Despite markedly different depositional environments, all cores exhibit pronounced nanoparticle enrichments within or immediately above the YDB layer. Core 52 was recovered from the mouth of Jones Strait in shallow northern Baffin Bay, a dynamic setting strongly influenced by meltwater discharge and iceberg transport from the Canadian interior. Core 67 was obtained from the deepest part of the basin, where

settling of debris from melting icebergs would dominate sediment delivery. Core 77 was collected from the continental slope near southern Baffin Island, a comparatively distal setting less directly affected by major meltwater outlets. The broadly consistent stratigraphic placement of nanoparticle peaks across these contrasting environments indicates a basin-wide depositional signal rather than localized sedimentary processes. In several cases, nanoparticle peaks occur slightly above the peak in microspherules and metallic dust particles, consistent with delayed atmospheric fallout of submicron material and subsequent settling through the water column. Similar elemental profiles for Core 64 are shown in SI, Figures S7 and S8 (<https://zenodo.org/records/18877755>).

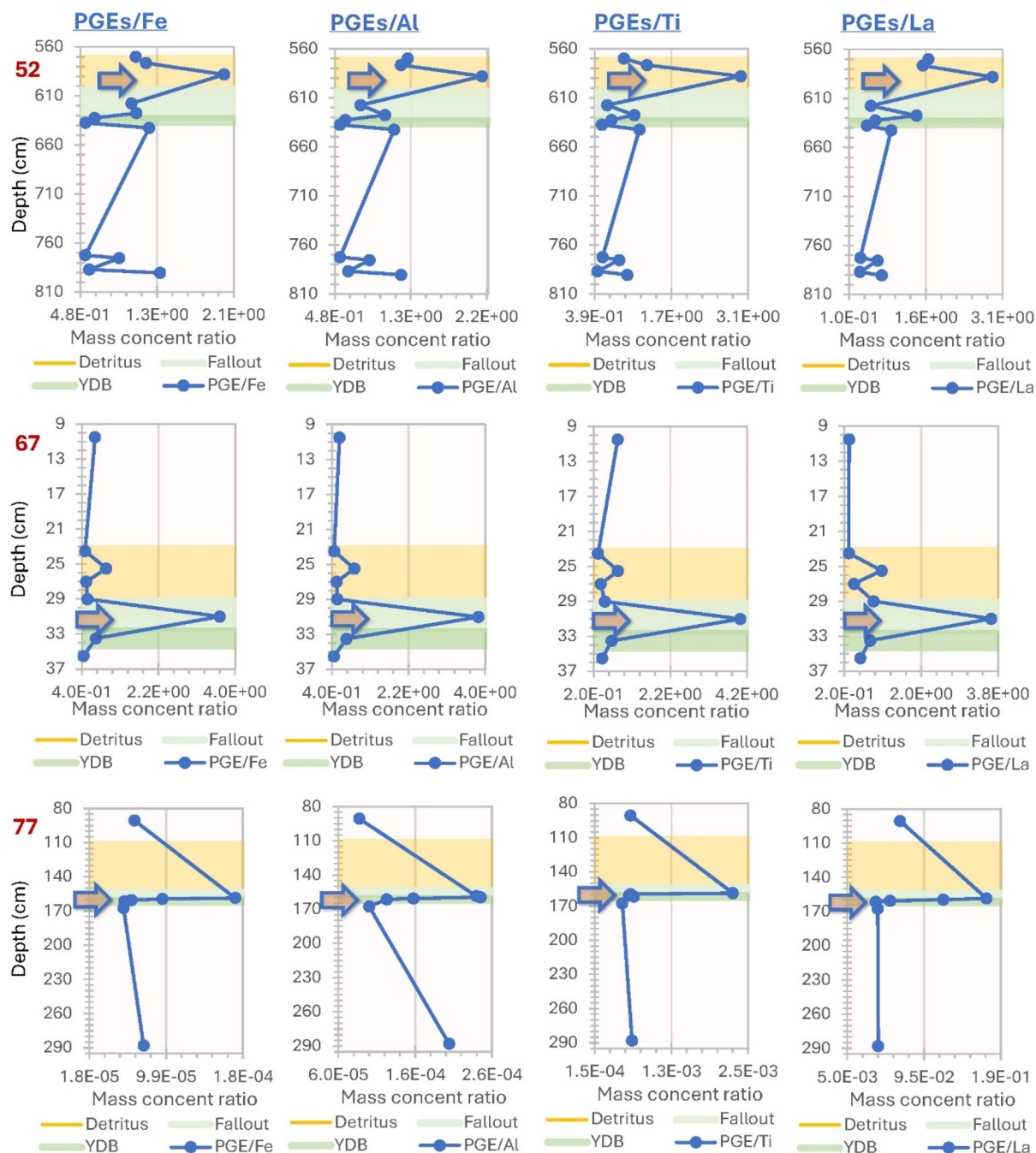


Figure 10: Ratios of total platinum-group element (PGE) nanoparticle mass to selected lithogenic elements (Fe, Al, Ti, La) across the Younger Dryas Boundary (YDB) interval in Baffin Bay sediment cores 52, 67, and 77. Colored bands denote stratigraphic units: the YDB layer (green), the overlying fallout layer (light green), and the overlying detritus layer (gold). Arrows indicate the principal enrichment interval. Normalization of PGE nanoparticle mass to major and trace lithogenic elements reduces the influence of variations in sediment composition, grain size, and depositional processes. Across all three cores, PGE/element ratios show pronounced, stratigraphically restricted increases within

or immediately above the YDB layer, indicating an influx of PGE-rich particles decoupled from the background detrital sediment supply. The consistency of this signal using both major elements (Fe, Al, Ti) and the immobile trace element La suggests that the enrichments do not result from redox remobilization, carbonate dilution, or other post-depositional effects. Peak ratios commonly occur in the fallout layer above the spherule-rich YDB horizon, consistent with delayed atmospheric residence and settling of submicron particles relative to larger ejecta. In some intervals, elevated ratios extend into the overlying detrital unit, likely reflecting continued deposition of fine particles released during iceberg melting or reworking of previously deposited fallout. Similar nanoparticle results for Core 64 are shown in SI, Figures S7 and S8 (<https://zenodo.org/records/18877755>).

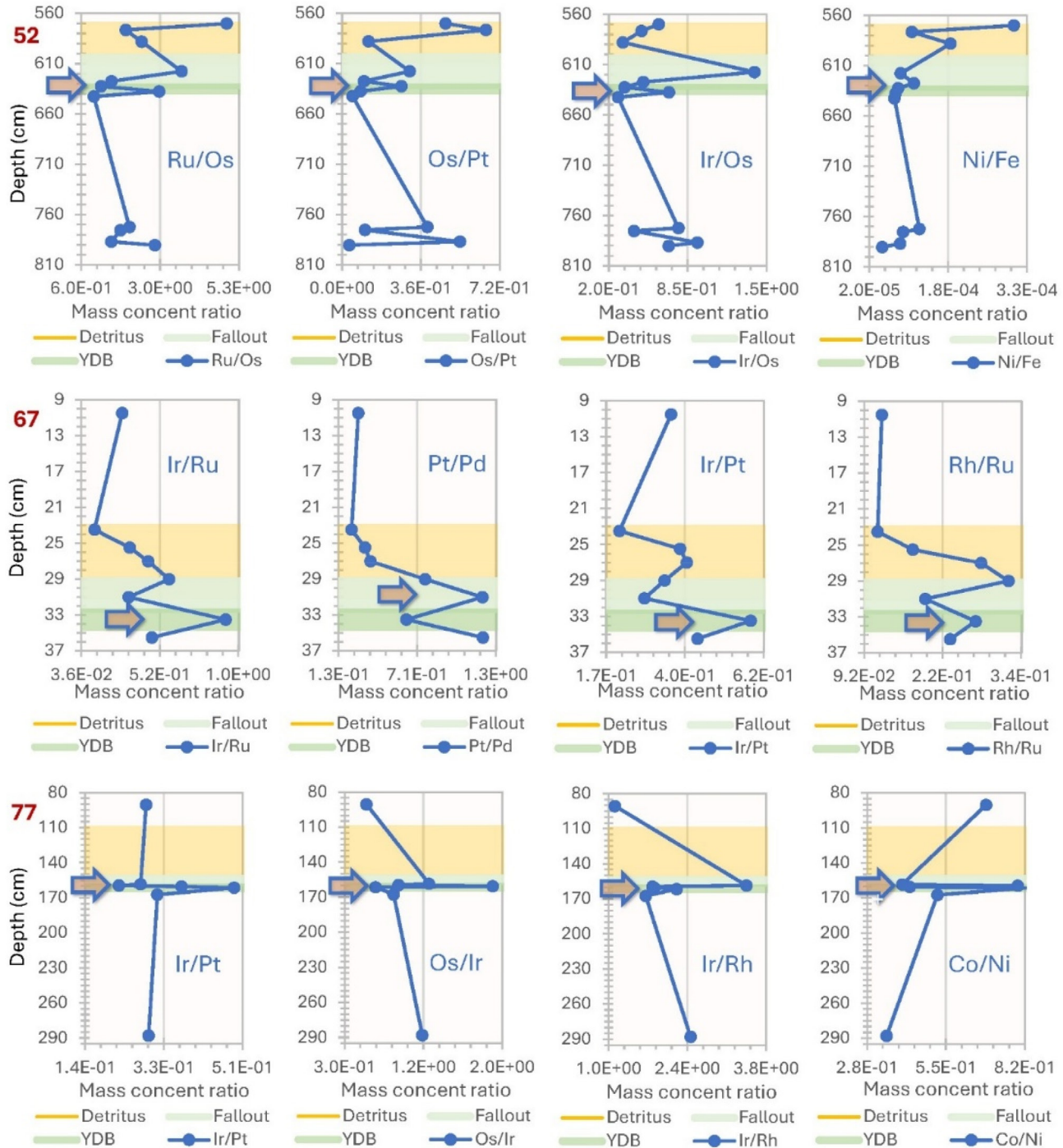


Figure 11: Elemental ratios among siderophile and transition metals within individual nanoparticles (e.g., PGE-Ni-Co systematics) across the Younger Dryas Boundary (YDB) interval in Baffin Bay sediment cores 52, 67, and 77. Colored bands denote stratigraphic units: the YDB layer (green), the overlying fallout layer (light green), and the overlying detritus layer (gold). Arrows indicate the interval of maximum compositional anomaly. These inter-element ratios provide constraints on the composition of the metal-bearing particle population independent of total

abundance. Within each core, ratios shift abruptly in the YDB interval, indicating the introduction of particles with a geochemical signature distinct from background sediment sources. The observed patterns are inconsistent with derivation from typical crustal, volcanic, or mantle materials, which would be expected to produce relatively stable ratios through time. Instead, the data suggest the arrival of a chemically unusual, metal-rich particulate component. Differences in the magnitudes of ratios among cores likely reflect varying degrees of mixing with locally derived sediments and differential settling through water columns of different depths. In several cases, the strongest compositional excursions occur slightly above the spherule-rich horizon, implying continued delivery or redistribution of fine particles after emplacement of the primary ejecta layer. The coherent appearance of these anomalies across geographically separated sites indicates a regionally extensive depositional pulse rather than isolated local inputs.

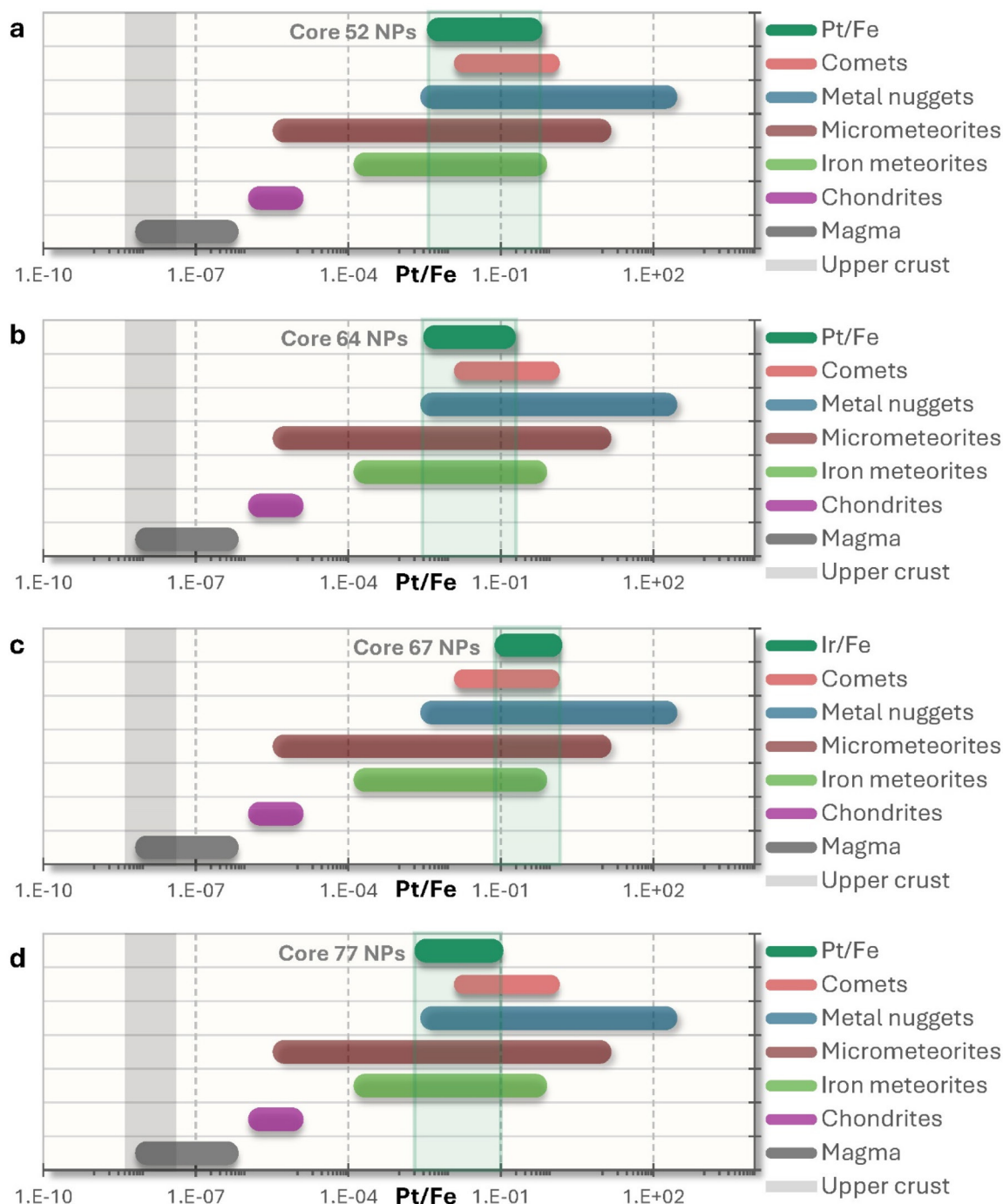


Figure 12: Comparison of nanoparticle Pt/Fe ratios measured across the YDB interval in Baffin Bay cores with representative terrestrial and extraterrestrial compositional fields. (a-d) Pt/Fe ratios are plotted on a logarithmic scale for the four cores (52, 64, 67, and 77). The YDB nanoparticle Pt/Fe values overlap strongly with metal-rich and refractory extraterrestrial materials (comets, refractory metal nuggets,

micrometeorites, and iron meteorites) and show no overlap with chondrites, average continental crust, or typical magmatic compositions. Refractory metal nuggets are highly siderophile-element-rich condensate particles (e.g., enriched in Pt, Ir, and Os) formed under high-temperature conditions in the early solar nebula and are commonly preserved within primitive meteoritic materials [50]. Refractory metal nuggets are morphologically and geochemically similar to the metallic dust particles found in Baffin Bay. Nanoparticles constitute a trace component of the sediment; therefore, the plotted ratios represent discrete metal-rich particle populations rather than bulk sediment chemistry.

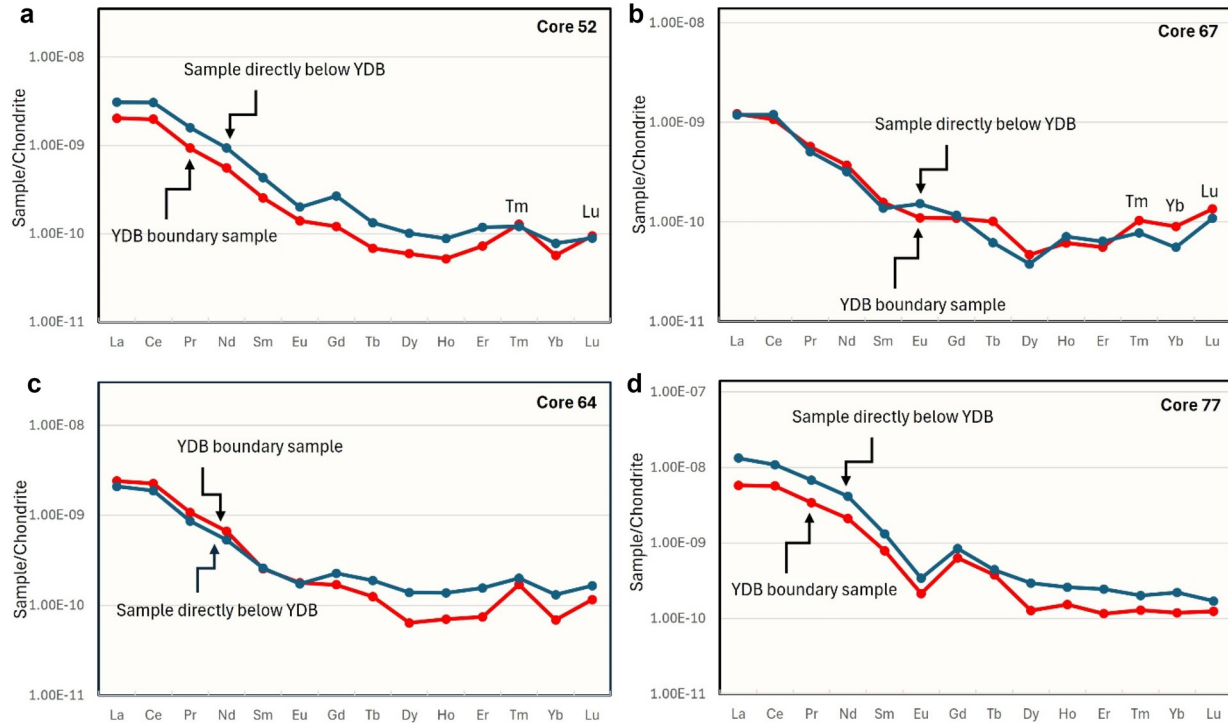


Figure 13: Chondrite-normalized rare earth element (REE) patterns for paired samples from four sediment cores: a) 52, b) 67, c) 64, and d) 77; the Younger Dryas Boundary (YDB) layer (red) and the sample immediately below the YDB (blue). Across all cores, REE patterns show broadly similar shapes (LREE-enriched, declining toward the HREE), with differences expressed mainly as modest vertical offsets rather than large changes in pattern form, consistent with variations in the relative contribution of detrital/clay-rich components and/or dilution by non-silicate phases rather than a fundamentally different REE source. Chondrite normalization: McDonough and Sun [54].

2.55; Au EF = 1.86; Ir EF = 1.82; Re EF = 1.76) and Core 77 (Rh EF = 1.97; Ir EF = 1.34). Moderate enrichments (EF $\approx$ 1.1–1.8) are also present for Os, Re, Ir, Ru, Rh, and Au where values are positive. The element(s) showing the largest EF differ among cores, implying heterogeneous concentration of PGE-bearing phases at the scale sampled and/or variable sedimentary partitioning processes (e.g., grain-size/heavy-mineral effects or scavenging onto Fe–Mn oxyhydroxides, sulfides, or organic matter) [55]. Thus, while REEs appear largely governed by background sediment components, PGEs provide the clearest geochemical expression of the YDB horizon in these paired comparisons.

Bulk oxygen isotope analysis

The sediment recovered from the Baffin Bay cores consists predominantly of terrestrial material containing a small proportion of impact-related components, including microspherules and metallic dust particles (MDPs) interpreted as cometary dust. Trace element data presented in this study

indicate that the microspherules are largely composed of melted terrestrial sediment containing only a minor extraterrestrial component, estimated at approximately 1–2%.

However, in some impact structures a much larger extraterrestrial component has been recovered from drill cores. For example, piston cores obtained from the Late Pliocene deep-sea Eltanin impact structure contain a high concentration of extraterrestrial material. This material was initially interpreted as deriving from a mesosiderite impactor and this interpretation was later confirmed using bulk oxygen isotope analysis. Similarly, fragments of ordinary chondrite recovered from drill cores at the 145-Ma Morokweng impact crater in South Africa have also been identified using bulk oxygen isotope measurements.

To evaluate whether any intervals in the Baffin Bay cores might contain a significant extraterrestrial component at the local scale, we performed bulk oxygen isotope analyses using laser fluorination on selected samples. Oxygen isotope compositions are sensitive indicators of extraterrestrial

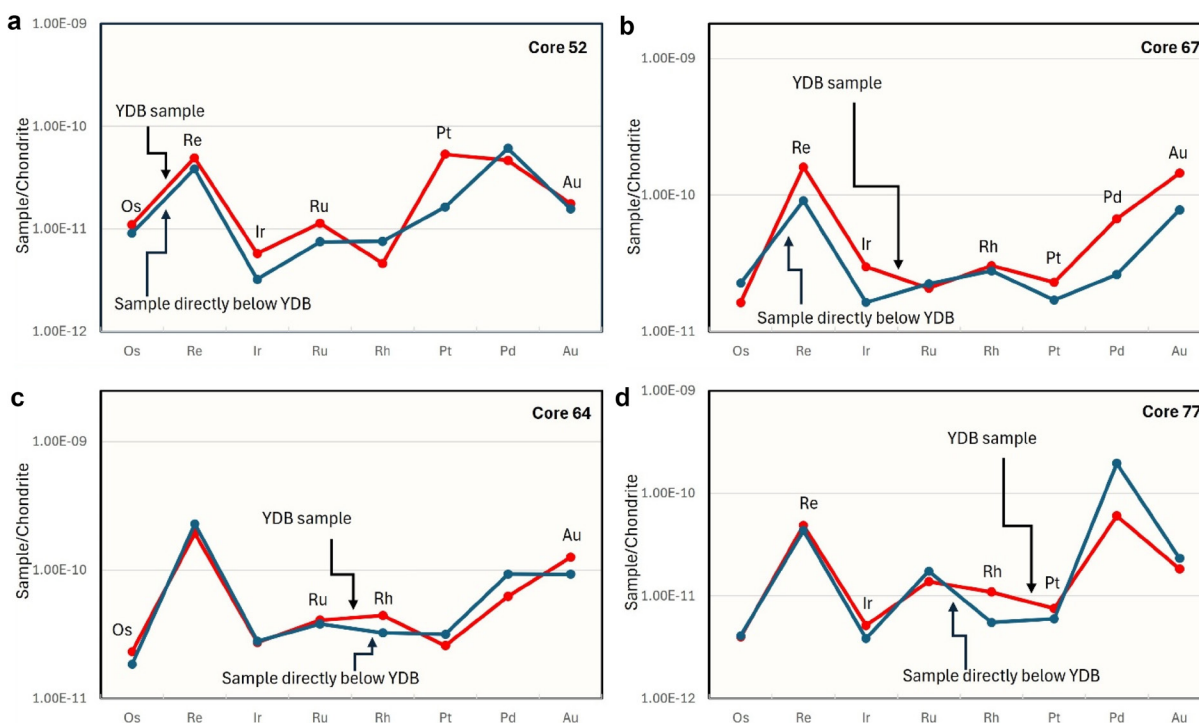


Figure 14: Chondrite-normalized platinum-group elements (PGE; Os–Au) for the same paired samples shown in Figure 13 (a–d). In contrast to the comparatively conservative REE patterns, several PGEs exhibit pronounced, element-specific enrichments in the YDB layer relative to the sample immediately below in multiple cores, producing a visually distinct “event-like” signature at the boundary horizon (the enriched elements are listed on the graph). The magnitude and specific elements enriched vary among cores, consistent with heterogeneous concentration of PGE-bearing phases and/or variable sedimentary partitioning processes at the centimeter scale. Chondrite normalization: McDonough and Sun [54].

Table 3: PGE enrichment factors at the Younger Dryas Boundary (YDB).

	Core 52	Core 64	Core 67	Core 77
Os	1.21	1.25	-	-
Re	1.29	-	1.76	1.13
Ir	1.78	-	1.82	1.34
Ru	1.52	1.07	-	-
Rh	-	1.37	1.09	1.97
Pt	3.72	-	1.35	1.25
Pd	-	6.74	2.55	-
Au	1.13	1.36	1.86	-

The chondrite YDB values are divided by the sample chondrite values directly below the YDB “-” indicates enrichment factor less than 1). Chondrite normalization: McDonough and Sun (1995) [54].

material because many meteorite groups exhibit $\Delta^{17}\text{O}$ values that differ from those of terrestrial rocks.

Analytical results are presented in Appendix Table A1, together with measurements of an internal obsidian standard used to monitor analytical accuracy and precision. Based on 38 repeat analyses, the obsidian standard has the following composition:

- $\Delta^{17}\text{O} = 3.81 \pm 0.05 \text{ ‰}$ (2SD)
- $\delta^{18}\text{O} = 7.27 \pm 0.10 \text{ ‰}$ (2SD)
- $\Delta^{17}\text{O}^* = 0.00 \pm 0.02 \text{ ‰}$ (2SD)

($\Delta^{17}\text{O}^*$ calculated using a linearized slope of 0.5247; Starkey et al., 2016) [56].

The three obsidian analyses conducted during this study closely match these values. The mean $\Delta^{17}\text{O}^*$ value of $-0.01 \pm 0.01 \text{ ‰}$ (2SD; $n = 3$) falls within the analytical uncertainty of the reference value reported by Starkey et al. (2016) [56], confirming the accuracy of the measurements.

Foraminifera

Cross-shelf trough core 52 exhibits foraminiferal biofacies changes near the beginning of the YDB interval consistent with expected YD-related climatic/oceanographic changes. In contrast, mid-slope (cores 64 and 77) and basinal (core 67) foraminiferal assemblages are associated with water depths and related water masses and do not exhibit changes that can be definitively attributed to the Younger Dryas climatic change (see SI, “Foraminifera: Radiocarbon Dating and Environmental Setting” for a detailed description of the foraminiferal assemblages).

Discussion

Baffin Bay glacial evolution

Glaciogenic processes have primarily influenced the late Quaternary development of Baffin Bay [20, 21]. Although

the margins of the Laurentide and Innuitian Ice Sheets did not extend beyond the continental shelf edge of Baffin Bay during the Last Glacial Maximum (LGM) [57, 58], glaciogenic sedimentary input was significant. These included till delta deposits within the Lancaster Sound trough mouth fan [21], sheet-like turbidites [59] in the Baffin Bay basin, and ice-shelf mass transport along the NE Baffin Bay slope [20, 59–61]. Cross-shelf troughs, formed by ice streams during glacial episodes, are common in western Baffin Bay [20] and have multiple sediment source areas, resulting in complex and varied lithostratigraphy within the basin [20]. Cores 52, 64, and 67 of this study (Figure 1) were almost certainly located beneath an ice shelf (Northern Baffin Bay Ice Shelf) during the LGM that likely collapsed between 16.5 and 14.2 ka before the YD onset [62], exposing these areas to relatively ice-free open water. Ice-rafted debris (IRD) dominated Baffin Bay sediments during the last deglaciation, while hemipelagic sediments dominated during the present Holocene interglacial [20, 59, 63]. Depositional events feature tan-colored, carbonate-rich, gravelly, sandy mud layers and sporadic ice-rafted detrital carbonate and gravel [20].

Three potential causes of the Younger Dryas climate event

The abrupt onset of the Younger Dryas cooling event in the Northern Hemisphere is a well-documented phenomenon, marked by a significant and abrupt decrease in temperature of approximately $10^{\circ}\text{C} \pm 4^{\circ}\text{C}$ [64, 65]. This drastic cooling was associated with a shift in atmospheric and oceanic circulation which persisted for ~1200 years from ~12,800 to ~11,600 cal BP [66].

Meltwater flooding and thermohaline circulation

The widely accepted conventional hypothesis attributes the abrupt Younger Dryas cooling (12.8 ka) to the failure of ice dams on proglacial Lake Agassiz and other related lakes. These failures led to a sudden and massive diversion of the overflow water from the Mississippi Basin to the St. Lawrence Basin [67] through newly opened eastern outlets (Lake Superior/St. Lawrence Seaway) and through northwestern outlets into the Arctic Ocean via the Mackenzie River [65, 68–71]. Moreover, modeling experiments suggest that a collapse of the Keewatin Ice Dome of the Laurentide Ice Sheet through Hudson Strait into the North Atlantic also contributed to the freshwater forcing leading to the Younger Dryas cooling [66]. The diversion of continental interior drainage and its intensification in the early Younger Dryas were of sufficient magnitude to freshen the surface waters of the Arctic Ocean and the northernmost Atlantic. This drainage resulted in a cap of low-salinity surface waters, which strongly reduced the production of North Atlantic Deep Water (NADW) and led to the abrupt climatic feedbacks that caused the Younger Dryas cooling to persist for ~1200 years [65, 70, 72, 73].

Volcanic triggering

Baldini et al. [74] offered an alternative hypothesis, invoking sulfur-rich volcanic aerosols from the Laacher See eruption (LSE) as the trigger for the YD. They argued that ice-core stratigraphy links the LSE (~12,880 years ago) as the initial trigger of YD cooling, which was then amplified by shifts in oceanic circulation and sea-ice expansion, sustaining North Atlantic cooling. While direct climatic effects from volcanic aerosols would have lasted only ~1–3 years, Baldini argued that feedback mechanisms prolonged the climate shift. However, Warken et al. [75] countered this interpretation using high-resolution age correlations between German speleothem and Greenland ice core records, which clearly record the LSE. These show that YD cooling occurred synchronously across Europe and Greenland, approximately 150–160 years *after* the LSE, which they dated at $13,008 \pm 8$ years B.P. Arguing against a volcanic connection to the LSE, Kletetschka et al. [76] reported finding a stratigraphically distinct LSE tephra layer that predates the YDB microspherule layer in a lake core in the Czech Republic by ~30 years. The age differences are critical, first challenging the interpretation of a delayed climatic response and refuting an LSE volcanic aerosol trigger for the YD climate change by demonstrating that the LSE eruption occurred well before the onset of the YD, making it unlikely to have been the trigger.

The Younger Dryas impact hypothesis (YDIH)

The Younger Dryas impact hypothesis posits that multiple cosmic airbursts/impacts triggered the abrupt onset of the Younger Dryas cooling episode [2, 77]. This hypothesis suggests that the impact event served as both the triggering mechanism and the energy source that shifted the climate system into a significant cooling mode in the Northern Hemisphere. Major, abrupt shifts in the atmosphere and cryosphere caused the initial cooling. This shift began with reduced solar radiation due to increased atmospheric dust loading and biomass burning, producing an impact winter [78, 79]. This initial cooling was immediately followed by surface water freshening of the Arctic and northernmost Atlantic surface waters, caused by outburst flooding and ice sheet destabilization (iceberg calving), which strongly reduced the thermohaline overturning circulation. This reduction, in turn, reinforced Northern Hemisphere cooling marked by the YD episode, which lasted for ~1200 years, long after its initiation by the cosmic impact event [2, 77, 80].

Since 2007, numerous publications have presented evidence consistent with the YDIH from sites on six continents. This evidence includes anomalously high concentrations of multiple impact-related proxies, including anomalies in platinum [9, 10, 51, 52, 81–85], iridium [2, 10, 82, 86, 87], magnetic & non-magnetic microspherules [2, 9, 10, 43, 44, 76, 83–85, 88], meltglass [9, 10, 76, 48], nanodiamonds [9–11, 82, 89–91], and combustion aerosols and soot [9–11, 78, 79,

81, 82]. These proxies have been reported in a sediment layer dating to the lower Younger Dryas Boundary (YDB) across North America [2], central Mexico [92], South America [93, 94], South Africa [95], Europe [2, 76, 96–98], Greenland [86], the Middle East [9–11, 82] and in lacustrine and ice core records globally [78, 79].

The YDIH has been challenged in several studies questioning the validity of the reported impact proxies, the timing of the purported impact event, and its presumed effects on global climate, ecosystems, and human societies [99–113]. Critics have suggested that reported impact proxies (e.g., microspherules and platinum) from shallow terrestrial sites are instead industrial contaminants rather than serving as evidence for an impact [110]. Identification of the YDB-dated impact layer containing key proxies in Baffin Bay marine sediments refutes this claim, given the layer's remoteness in cores up to 6+ meters beneath the ocean floor, below up to 2400 meters of water, and far from potential industrial contamination.

Baffin Bay microspherules

Microspherules from YDB-dated sediments in the Baffin Bay cores were analyzed using SEM/EDS and LA-ICP-MS to determine platinum, Ni, Co, and Cr relative abundances, which are typically enriched in extraterrestrial (ET) material. The compositions of the Baffin Bay microspherules do not overlap with dust particles from Comet Wild, cosmic dust from the stratosphere, or cosmic dust particles reported from sites in Russia [22–24] and the USA [38], and exhibit only weak overlap with micrometeorites (Figures 15a, c and 16a, c). These findings are consistent with results from microspherules at other YDB sites, indicating compositions dominated by terrestrial target rock.

Estimates that YDB melt products contain on the order of ~0.3–2 wt% impactor material are derived from simple two-component mixing models using highly siderophile elements (e.g., Ir, Pt, Ni), which are strongly enriched in meteoritic material relative to crustal sediments [2, 44]. These estimates assume a chondritic or chondrite-like impactor composition and uniform incorporation of siderophile elements into the melt. Importantly, this range does not imply that YDB microspherules are dominantly meteoritic in composition; rather, it reflects a small extraterrestrial contribution superimposed on melts derived primarily from terrestrial target materials. The exact fraction is model-dependent and varies with assumed impactor type, target composition, and post-impact elemental partitioning.

Baffin Bay microspherules exhibit weak overlap with meteoritic material such as chondrites, achondrites, and iron meteorites, and moderate overlap with Antarctic microspherules (Figure 17) (see SI Tables S8a, b, and S9 for comparison data and sources).

A terrestrial origin for Baffin Bay microspherules is consistent with their Fe/Ni and Fe/Cr ratios, which strongly overlap terrestrial crustal material and only partially overlap

impactites, mantle, and volcanic material (Figure 18). To evaluate the possibility of a minor ET component, we modeled the effect of ~1 wt% extraterrestrial material mixed with 99 wt% terrestrial material. Because ET concentrations of Ni and Cr are substantially higher than crustal abundances (~35× for Cr and ~315× for Ni) [114], we multiplied measured Ni and Cr concentrations by 100 and recalculated the ratios, following approaches used in studies of confirmed impact structures [16–19]. The ET-normalized Baffin Bay ratios substantially overlap with Comet Wild dust and stratospheric cosmic dust (Figure 15b, d), consistent with microspherules containing on the order of 1 wt% ET material.

The same pattern is evident when the ET-normalized Baffin Bay ratios are compared to micrometeorites from Antarctica and cosmic dust samples from Russia and the USA [22–24, 38] (Figure 16b, d). Based on this compositional data, we propose that Baffin Bay microspherules comprise terrestrial target materials melted by touchdown airbursts [115, 116] and impacts (See data sources for proxy comparisons in SI, Table S9) (<https://zenodo.org/records/18877755>).

Origin of Baffin Bay microspherules

Analyses of YDB microspherules from Baffin Bay cores indicate that they are primarily produced from the melting of surficial sediments during touchdown airbursts and deposited as distal ejecta (microtektites and mikrokrystites). This inference is consistent with an earlier study by Wittke et al. [43], who concluded that YDB microspherules were mainly composed of terrestrial target rock and that an estimated ~10 million tonnes of YDB microspherules were deposited over 50 million square kilometers on four continents. In the following, we compare and contrast some possible origins for the Baffin Bay microspherules summarized as follows, and then with specific discussions:

- Meteoritic ablation and cosmic influx (ruled out by low MgO content) [117].
- Mantle material (excluded as mantle processes do not produce microspherules) [43, 82].
- Volcanic activity (eliminated because of the absence of tephra and sulfur, and volcanoes only produce silica-rich microspherules) [43, 78, 79, 48].
- Wildfires (temperatures insufficient for formation) [43, 118].
- Anthropogenic sources (excluded by core depth and location).
- Extraterrestrial impact (most likely based on the evidence).

Specifically:

1. Meteoritic. Differentiating between ablated meteoritic and impact microspherules often hinges on their MgO content. This is because meteoritic microspherules are dominantly silica-rich and originate from the more common stony asteroids, which also typically exhibit high MgO concentrations (Taylor et al. [117]), based on microspherules from

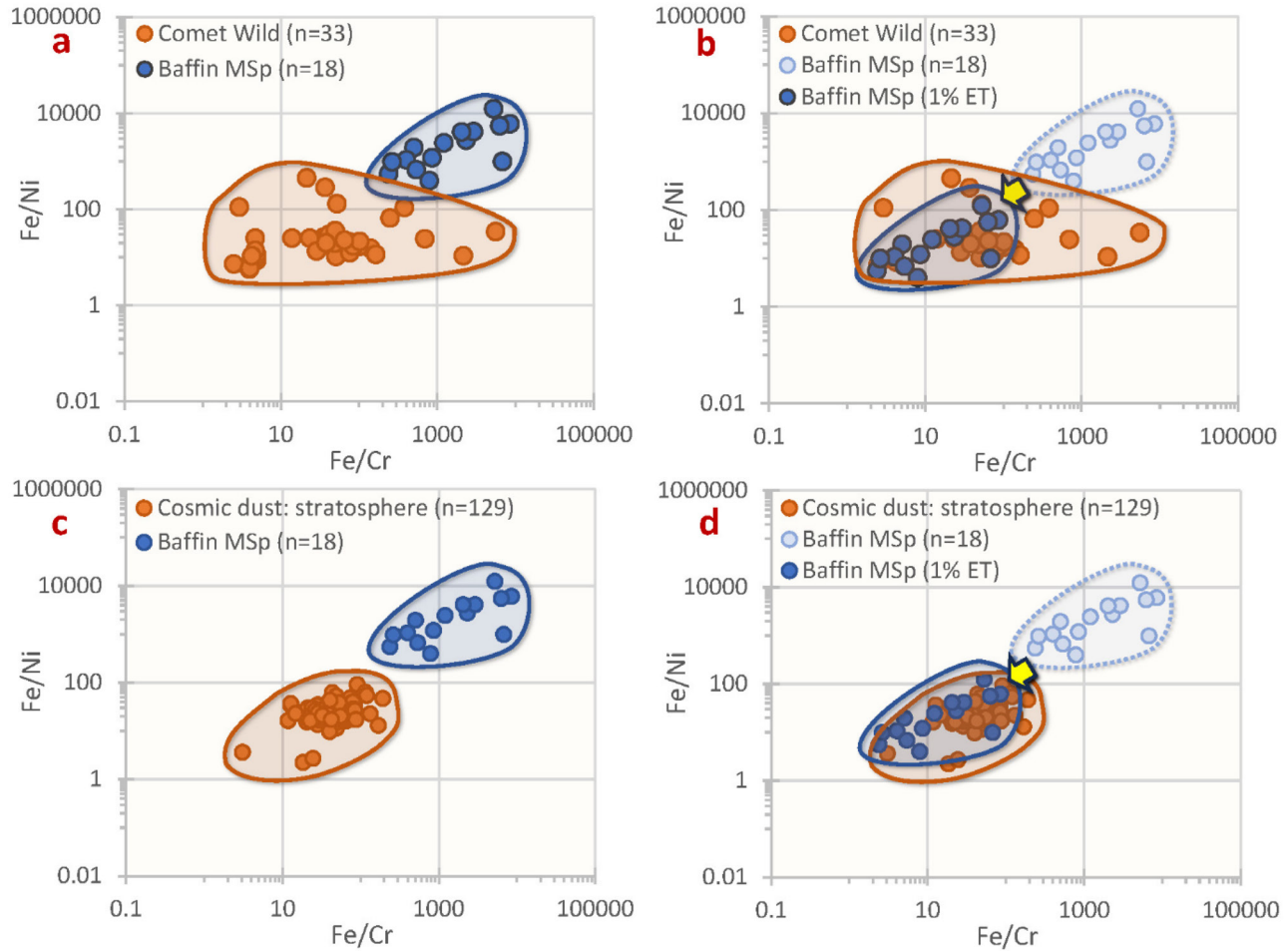


Figure 15: Comparison of Fe/Cr and Fe/Ni ratios between Baffin Bay microspherules (MSP), cometary material, and cosmic dust. (a) Particles retrieved from the debris trail of Comet Wild (orange; $n = 33$) do not overlap with Baffin Bay microspherules (blue; $n = 18$), suggesting that the microspherules are not dominated by ET material. (b) However, if it is inferred that the Cr and Ni were mostly derived from an ET source comprising ~ 1 wt% of the impactor, there is excellent correspondence, e.g., as reported by Koeberl et al. [17] (c) Cosmic dust particles ($n = 129$) collected from the stratosphere also do not overlap. (d) If Cr and Ni are inferred to comprise ~ 1 wt% of the impactor, this results in excellent correspondence. The ratios show that Baffin microspherules typically contain less Cr and Ni than most cometary materials, consistent with a dominance of terrestrial materials. See SI, Tables S8a, b, and S9 for Baffin LA-ICP-MS data and sources of proxy comparisons (<https://zenodo.org/records/18877755>).

Antarctic ice, which largely lacks terrestrial sediments. Of the 277 microspherules analyzed, 99 wt% contained >5 wt% MgO with an average of 29.9 wt% (range 0.0–55.7 wt%). In contrast, 17 Baffin Bay microspherules averaged only 0.65 wt% MgO (range: 0.0–1.54 wt%), suggesting that they did not originate from meteoritic ablation or cosmic influx.

2. Mantle. A mantle origin for the microspherules can be discounted, as materials ascending from Earth’s mantle are not known to produce microspherules [43, 82].

3. Volcanic. Core sediments from Baffin Bay exhibit no tephra or detectable related sulfur content, indicating that YDB impact proxies are unlikely to be of volcanic origin. Supporting this, Wolbach et al. [78, 79] noted that the sulfate record in the Greenland ice sheet [119, 120] indicates no significant volcanic eruptions within 50–100 years of the YDB. Similarly, Tselmovich [24] interpreted microspherule-like particles as cosmic dust in Russian peat deposits, noting an

absence of active volcanism in that area. This observation also applies to Baffin Bay, where Iceland’s nearest volcanic sources are downwind ~ 2000 km away. Furthermore, Baffin Bay microspherules do not align well with magma in biplots (Figure 18c), although they exhibit some overlap with crustal sources, interpreted as being terrestrial material melted during airburst/impacts (Figure 18a, b, d). In addition, Fe dendritic microspherules reported here and for other YDB sites globally are unknown from volcanic eruptions, which only produce silica-rich microspherules [48]. Even then, volcanic microspherules are not widely distributed but are typically confined to the volcano’s slopes during low-energy eruptions [43, 48].

4. Wildfires. High-temperature minerals indicate that YDB microspherules did not form during wildfires, which only reach extreme maximum temperatures of $\sim 1,450^\circ\text{C}$ [118]. These temperatures are sufficient to form

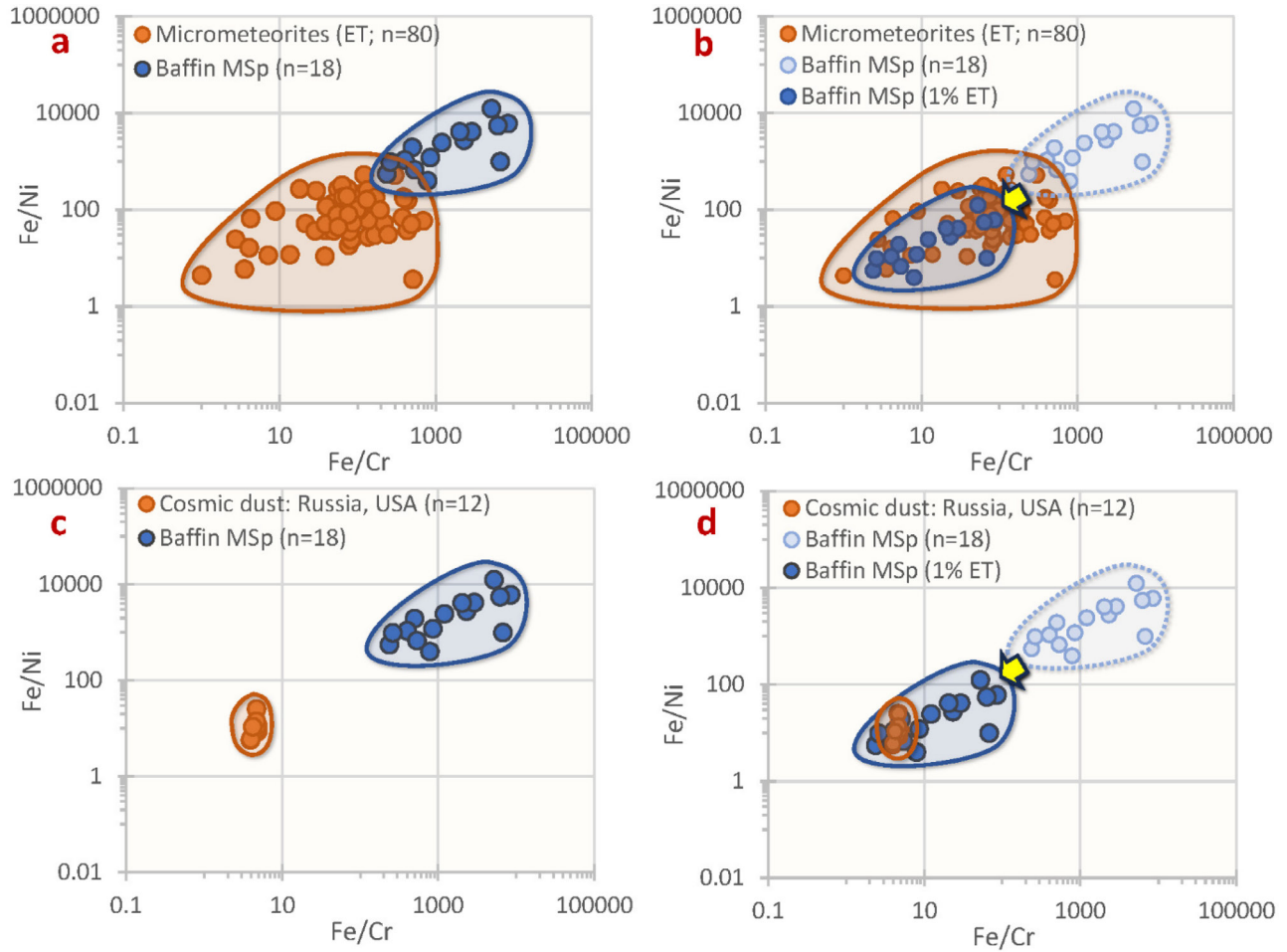


Figure 16: Comparison of Fe/Cr and Fe/Ni ratios between Baffin Bay microspherules (MSP), micrometeorites, and cosmic dust. (a) Antarctic ET micrometeorites ($n = 80$) only weakly overlap with Baffin Bay microspherules (blue; $n = 18$), suggesting that most Baffin microspherules are not dominated by ET material. (b) However, if it is inferred that the Cr and Ni were mostly derived from an ET source comprising ~ 1 wt% of the impactor, there is excellent correspondence. (c) Inferred cosmic dust from peat deposits in Russia ($n = 6$) [22–24] and the USA ($n = 6$) [38] also do not overlap. (d) If Cr and Ni are inferred to comprise ~ 1 wt% of the impactor, this results in excellent correspondence. The ratios show that Baffin microspherules typically contain less Cr and Ni than most cosmic materials, consistent with a dominance of terrestrial materials. See SI, Tables S8a, b and S9 for Baffin LA-ICP-MS data and sources of proxy comparisons (<https://zenodo.org/records/18877755>).

low-temperature carbon microspherules but not silica-rich and dendritic Fe-rich microspherules containing high-temperature, refractory minerals. Only two high-temperature minerals in Baffin microspherules (FeS, FeP) could plausibly have been formed during wildfires at the extreme high end of the recorded temperature range [118]. However, such temperatures are still less than required to melt silica ($>1,700^{\circ}\text{C}$) [43]. Moreover, YDB microspherule peaks occur only in the YDB layer. If formation from frequent wildfires were possible, the peaks would be broadly distributed throughout the sequences, but they are rare instead.

5. Anthropogenic. The remote geographic location of Baffin Bay cores, coupled with the significant water and core burial depths of the YDB layer, precludes any likely

possibility that the microspherules were derived from fly ash or industrial contamination.

6. Extraterrestrial. Our evidence suggests that YDB Baffin Bay microspherules, as with other YDB examples elsewhere, most likely formed from terrestrial material mixed with a small percentage of ET material that melted during low-altitude touchdown airbursts/impacts [115, 116]. Although we found no evidence to confirm a cometary source, this seems more likely based on previously reported fragments of YDB meltglass that are widely disbursed ($\sim 12,000$ km from California to Syria). Although it is possible that numerous airbursts/impacts by fragments of a rubble-pile asteroid could account for such a wide distribution, a cometary debris trail represents one possible explanation consistent with the available evidence [7, 121–124].

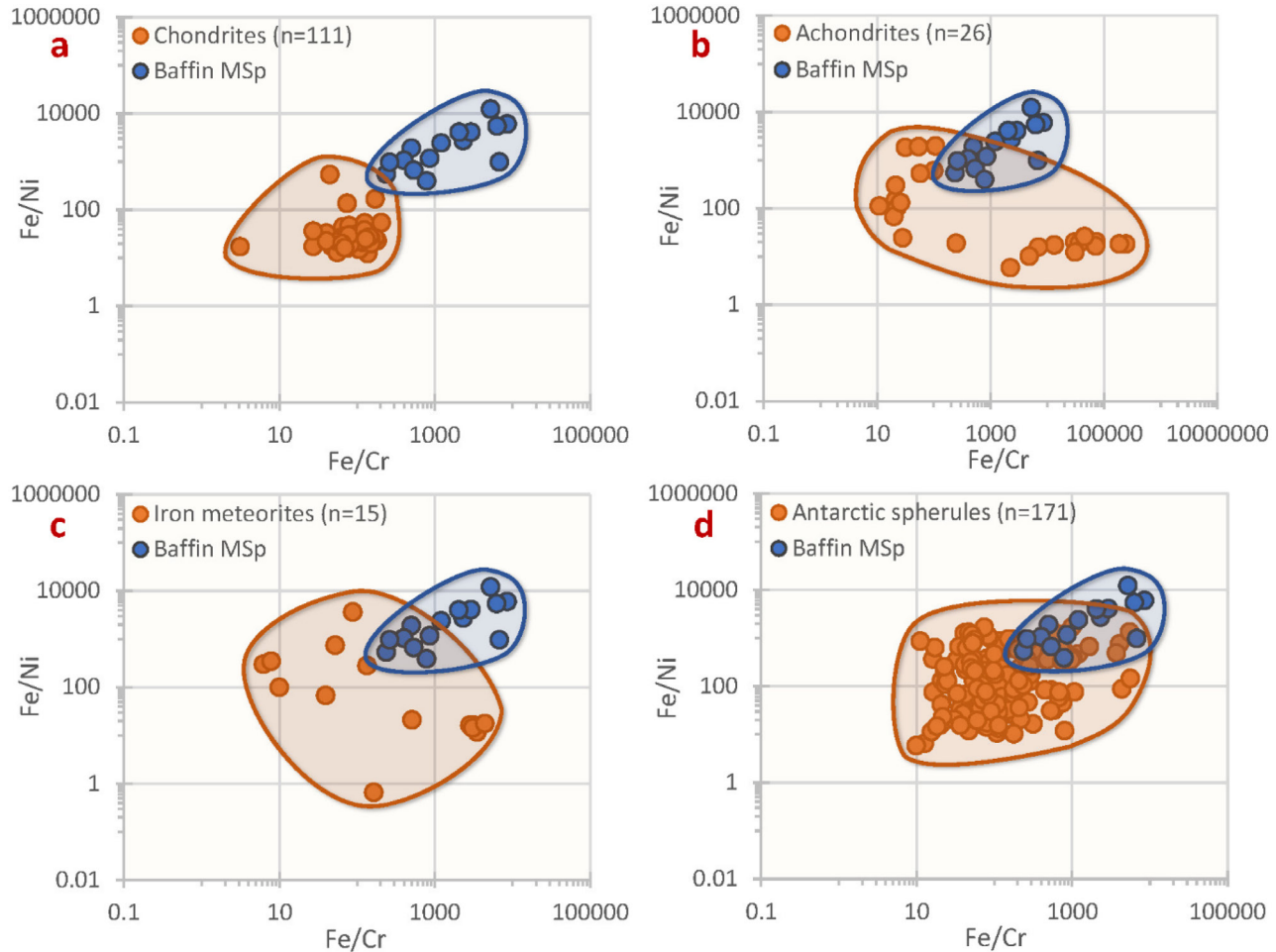


Figure 17: Comparison of Fe/Cr and Fe/Ni ratios between Baffin Bay microspherules (MSP) and various meteoritic materials. (a) Fe/Cr and Fe/Ni ratios of chondrites (orange; $n = 111$) partially overlap with Baffin Bay microspherules (blue; $n = 18$), as do **(b)** achondrites (altered chondrites; $n = 26$); **(c)** iron meteorites ($n = 15$); and **(d)** meteoritic microspherules ($n = 229$), from Antarctic ice and deep-sea deposits. These ratios show that Baffin microspherules typically contain less Cr and Ni than most ET material, consistent with a dominance of terrestrial materials. See SI, Tables S8a, b and S9 for Baffin LA-ICP-MS data and sources of proxy comparisons and references (<https://zenodo.org/records/18877755>).

Metallic dust particles (MDPs)

SEM/EDS with LA-ICP-MS (data; SI, Table S10) revealed that Baffin Bay YDB MDPs exhibit Fe/Ni and Fe/Cr ratios that show a significant overlap with (i) CDPs collected from Comet Wild by the NASA Stardust Spacecraft; (ii) the ratios of cometary dust collected from the stratosphere [125]; (iii) cometary dust from sites in the USA and Russia [22–24, 38–40]; and (iv) with Antarctic micrometeorites [30] (Figure 19). This compositional overlap is consistent with an extraterrestrial origin for the MDP particles and shows particularly strong similarity to reported compositions of cometary dust particles.

Fe/Ni and Fe/Cr ratios in MDPs from the Baffin Bay cores also show some overlap with chondritic and achondritic meteorites, iron meteorites, and Antarctic microspherules (Figure 20). However, they show excellent overlap with cometary material (Figure 19), consistent with a cometary

rather than a meteoritic origin. These observations suggest that some Baffin Bay YDB dust particles might be of meteoritic origin, although most have higher levels of Ni and Cr than previously measured for meteoritic material. The reason for this enrichment is unclear and requires further study.

Baffin Bay MDPs show poor or no overlap with terrestrial impactites, mantle material, volcanic magma sources, and Earth's crust (Figure 21). Most terrestrial materials contain much less Ni and Cr relative to Fe than nearly all Baffin Bay MDPs. This finding strongly suggests that these particles are likely of extraterrestrial (ET) rather than terrestrial origin, an interpretation consistent with CDPs described by other researchers. Baffin MDP data and sources of comparison data are in SI, Tables S10–S12.

CDPs from Baffin Bay are very similar to those reported by Tselmovich et al. [22–24, 38], Sungatullin et al. [27, 28, 39, 40], and Pechersky et al. [126–129] from sites in Russia

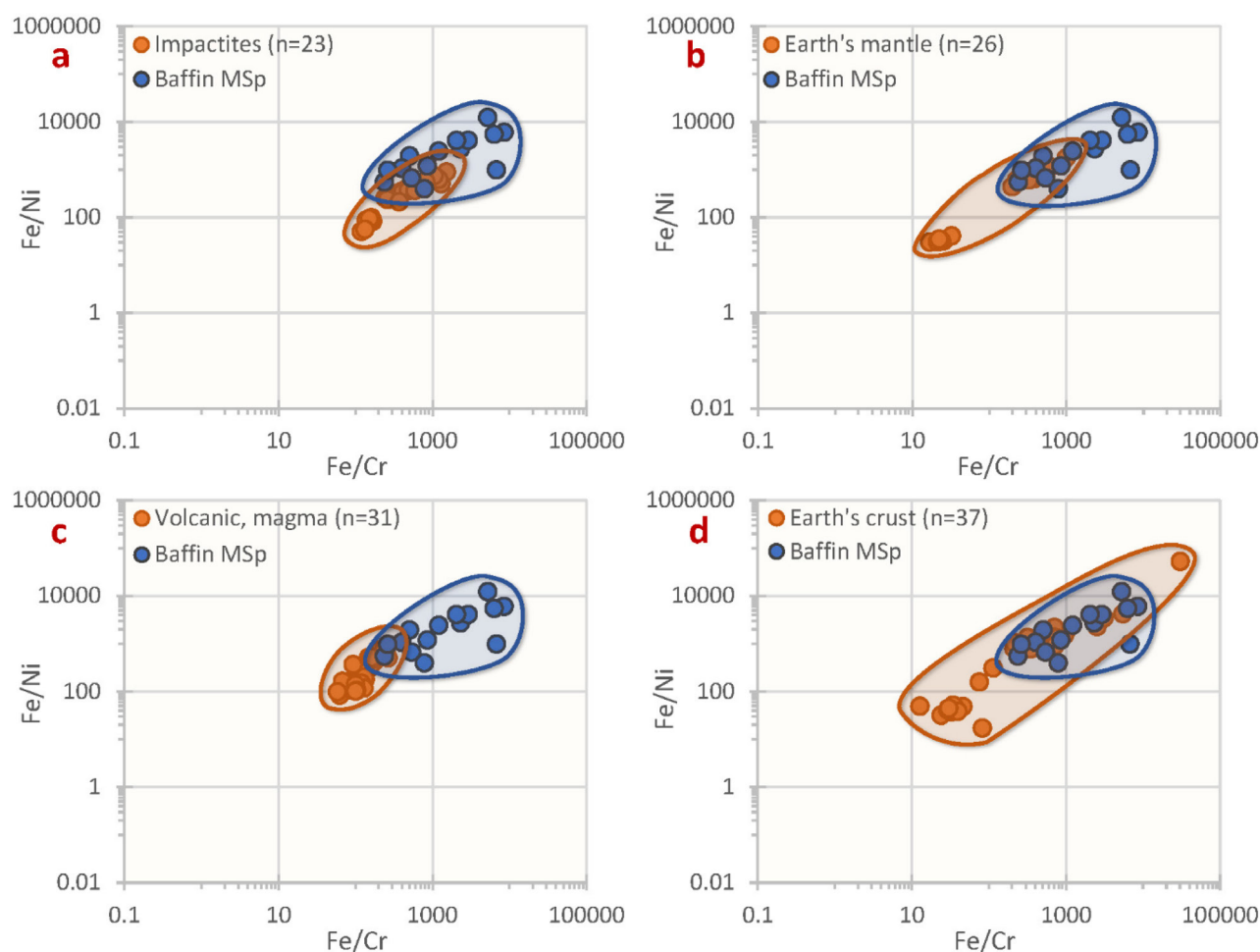


Figure 18: Comparison of Fe/Cr and Fe/Ni ratios between Baffin Bay microspherules (MSp) and various terrestrial materials. (a) Impactites (orange; $n = 23$), typically consisting of >98 wt% terrestrial material, partially overlap with Baffin Bay microspherules (blue; $n = 18$), as well as (b) Ratios of mantle material ($n = 26$); and (c) Ratios of volcanic/magmatic materials ($n = 31$). (d) Ratios of crustal materials ($n = 37$) strongly overlap with Baffin Bay microspherules. The ratios indicate that terrestrial materials typically dominate Baffin microspherules. See SI, Tables S8 and S9 for Baffin LA-ICP-MS data and sources of proxy comparisons (<https://zenodo.org/records/18877755>).

and the USA (see Figures 22 and 23 and Table 4). The Baffin Bay CDPs are typically composed of native Fe, native Ni, NiFe, NiFeCr, and FeCr and show a wide range of morphologies depending on whether they are unmelted, melted, or partially melted. Some CDPs exhibit unusual featherlike or twisted forms, similar to twisted chromite (FeCr_2O_4) particles reported in the YDB layer from Abu Hureyra, Syria [82]. Other CDPs exhibit striated and curved morphologies or appear as thin, striated, flake-like particles with folded edges. Tselmovich et al. [22–24, 38] propose that these morphologies result from partial melting during atmospheric entry or explosive detonations during an airburst (see Figure 23c, d).

Finally, we tested for and rejected possible contamination from coring equipment and metal tools by comparing SEM-EDS of the particles with that of coring hardware used to collect the cores and various types of industrial metal (see

ternary plot in Appendix A and SI, Table S13). Most Baffin MDPs do not overlap with anthropogenic/industrial metallic particles, which typically group near the vertices. Clusters of nearly pure nickel-plated neodymium magnet coatings overlap with some MDPs, but contamination is unlikely because the magnets were shielded from the sample. Alternatively, cometary material can contain blebs of native nickel and native iron [39, 130].

Oxygen-depleted nickel

Nickel was found both in the form of films and as separate flake-like particles. We suggest that these forms result from the deposition of high-temperature nickel, either by high plasticity or by condensation from atomic nickel vapor produced in comet trails [130, 131]. However, this suggestion is preliminary because samples directly from comets are unavailable for analysis and because processes occurring during

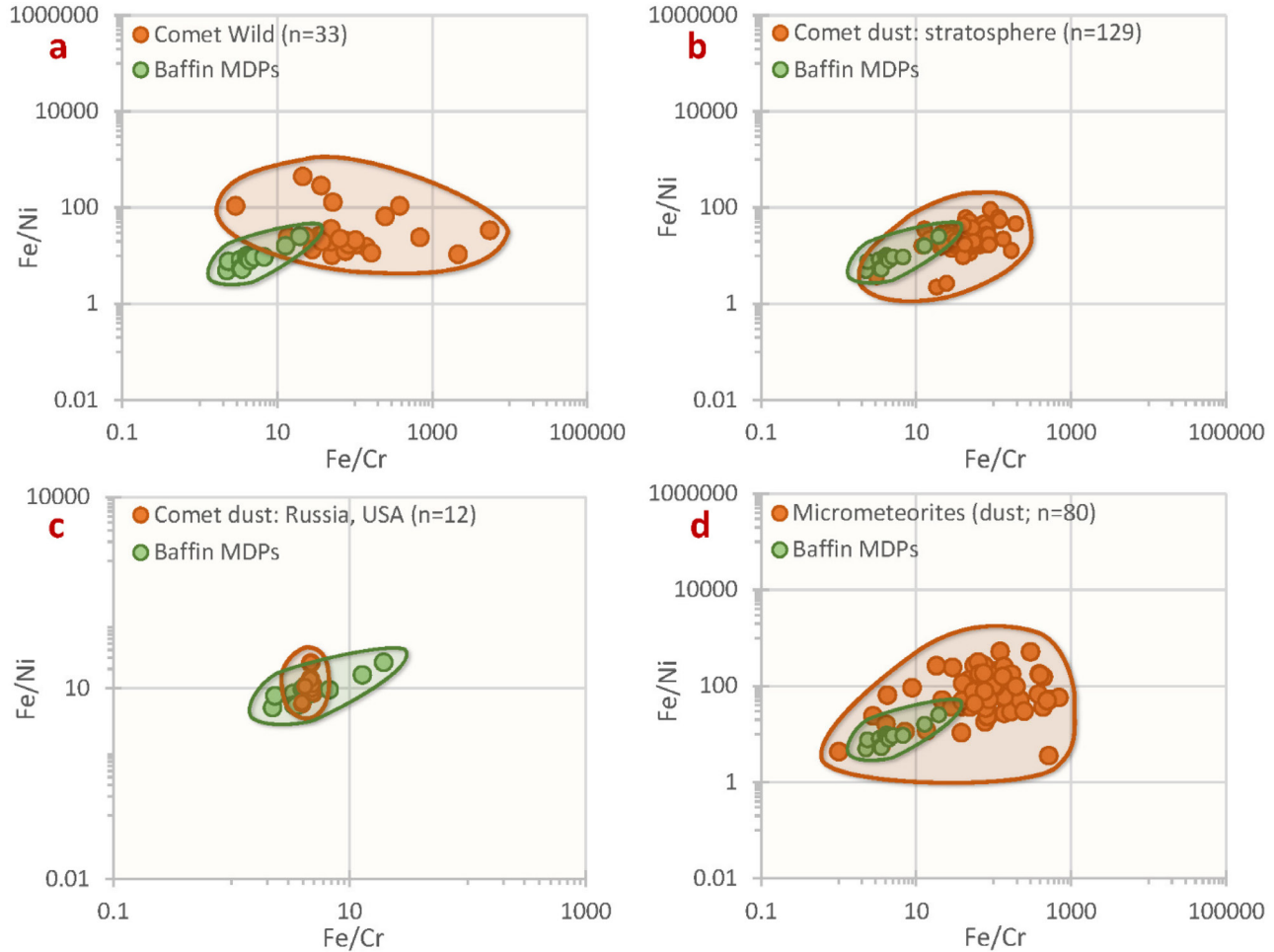


Figure 19: Baffin Bay metallic dust particles (MDPs) compared to cometary material. The Fe/Cr and Fe/Ni ratios of Baffin Bay MDPs overlap those of four types of cometary material: (a) CDPs retrieved from the debris trail of Comet Wild during the Stardust mission (orange; $n = 33$; green; $n = 15$); (b) CDPs collected from the stratosphere ($n = 129$). (c) CDPs found in peat deposits from Selenga, Russia ($n = 7$), and several sites in South Carolina, USA ($n = 6$) [22, 23, 38] (see SI, Tables S9–S12). (d) CDPs of Antarctic micrometeorites ($n = 80$), which are considered primarily to be cometary dust (SI, Table S9) (<https://zenodo.org/records/14681287>). For comparison, upper continental crust ratios are 426 for Fe/Cr and 834 for Fe/Ni [114].

Earth’s atmosphere’s interaction with clouds of cometary metal vapor have been insufficiently studied.

Baffin Bay platinum peaks

The abundance peaks in Pt are inferred to result from the influx of extraterrestrial material. For further discussion of platinum found in the YDB layer in the Baffin Bay cores and elsewhere, see the discussion in the Supplementary Information in Moore et al. [51].

Baffin Bay metallic dust particles (MDPs)

The compositions of the Baffin Bay MDPs overlap with known cometary material retrieved from Comet Wild and with cometary dust particles retrieved from the stratosphere. Of 143 total Baffin Bay MDPs, 14 (10%) dust particles contain Mn without Ni and, therefore, are likely terrestrial, possibly from mantle deposits [22–24, 38–40]. This finding is

based on Agarwal [132], who observed that magnetite and wustite-bearing microspherules hosting Mn without any Ni traces are considered non-cosmic. Of the remainder, 120 MDPs (83%) contain no detectable Mn (limit of 0.01%), and 9 (6%) contain Mn with Ni, suggesting that all 129 MDPs (90%) are not terrestrial but rather cosmic in origin.

YDB spherule formation

Van Ginneken [116] described evidence suggesting the occurrence of a type-2 or touchdown airburst in Antarctica, which involves the impactor’s vaporized material reaching Earth’s surface at hypervelocity [133]. This interaction causes chemical exchanges between the superheated gas from the projectile and the vaporized ground material. In this example from Antarctica, the airburst interacted with ice, and thus, the microspherules produced were characteristic of a stony asteroid impactor with no terrestrial component.

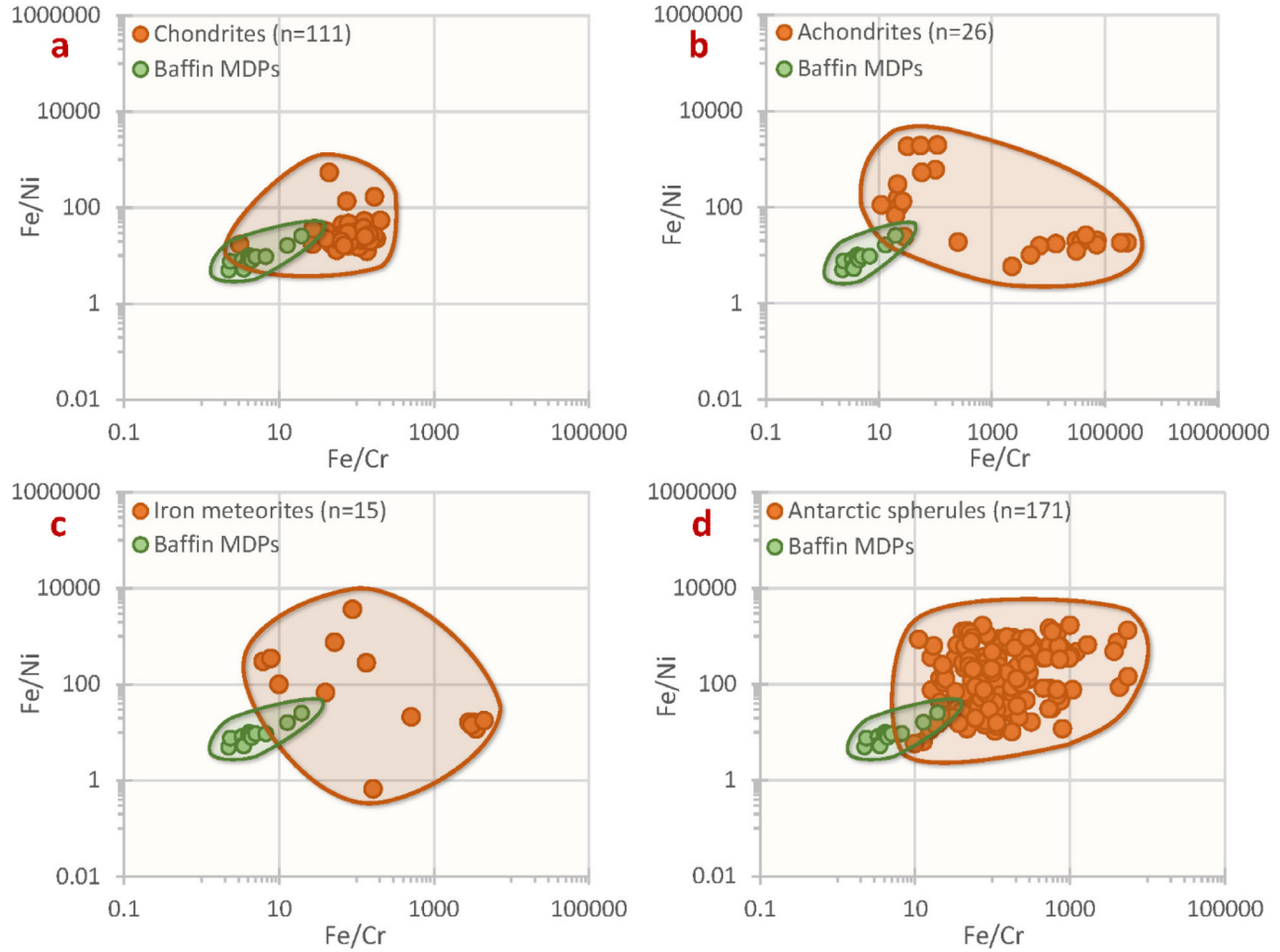


Figure 20: Comparison of Baffin Bay metallic dust particles (MDPs) with meteoritic material. The Fe/Cr and Fe/Ni ratios of about half of Baffin Bay MDPs partially overlap that of various meteoritic materials as follows, although some display greater enrichments in Ni and Cr relative to Fe in meteorites: **(a)** chondritic meteorites (orange; $n = 111$; green; $n = 15$); **(b)** achondrites (altered chondrites; $n = 26$); **(c)** iron meteorites ($n = 15$); and **(d)** meteoritic microspherules ($n = 229$), from Antarctic ice and deep-sea deposits. For comparison, in the upper continental crust, ratios of Fe/Cr = 426 and Fe/Ni = 83498. See Baffin Bay MDP data in SI, Table S10. Data sources other than Baffin Bay can be found in SI, Tables S9, S11, and S12 (<https://zenodo.org/records/14681287>).

Unlike high-altitude airbursts, type-2 or touchdown airbursts occurring over land can generate abundant impact microspherules (microtektites and microkrystites) dominated by target melted material mixed with traces of the impactor [14, 15] material. Microspherules containing a mixture of both target and impactor materials have been reported at terrestrial YDB sites on multiple continents [43, 44, 92, 93, 134].

For Baffin Bay, we detected no microspherules with compositions similar to stony asteroids, consistent with a proposed origin as melted terrestrial target rocks. We thus conclude that Baffin Bay microspherules were produced from terrestrial material mixed with a few percent of the impactor that melted during near-surface airburst plumes (type-2 or touchdown airburst) [116] or crater-forming impacts that reach Earth's surface rather than as a result of meteoritic ablation or cosmic influx. Thus, while microspherule morphologies and surface textures resemble Type I cosmic microspherules [135], the elemental chemistry of

Baffin microspherules is mostly terrestrial and indicates that they are microtektites and/or microkrystites [134, 136]. Microspherules typically contain only 0.3 wt% to 2 wt% of impactor material [16–19]. Schmieder and Kring [137] and Simonson and Glass [134] collectively report >50 ejecta layers and “impact microspherule datum layers” (i.e., microtektites and microkrystites) that are a mix of terrestrial target material and a small percent of ET material. Some are associated with known impact craters (e.g., Chicxulub and Chesapeake Bay), but many have no known crater sources, yet impacts or airbursts have been invoked for their origins.

Identifying possible YDB craters or remnants of craters may require a different set of impact indicators than traditional impact cratering events because low-altitude contact airbursts may only produce shallow craters that are hard to recognize and erode quickly [116]. Impact proxies such as microspherules represent an “impact microspherule datum layer” as proposed by Simonson and Glass [136] for the

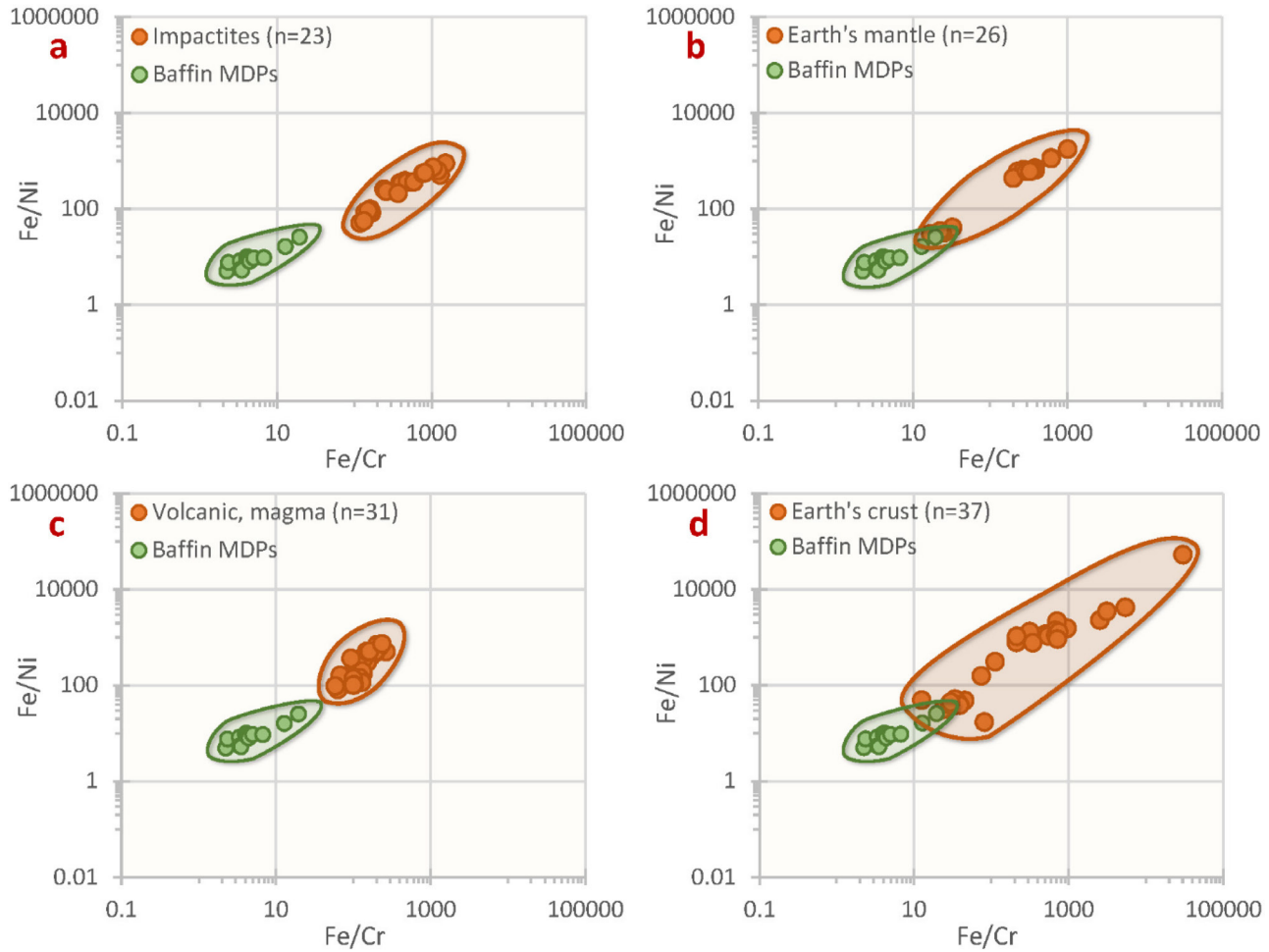


Figure 21: Comparison of Baffin Bay metallic dust particles (MDPs) with terrestrial material. The Fe/Cr and Fe/Ni ratios of Baffin Bay MDPs are compared to those of various terrestrial materials. **(a)** Ratios from impactites (orange; $n = 23$), which contain over 98 wt% terrestrial material, do not overlap with Baffin Bay dust particles (green; $n = 15$). **(b)** Ratios from mantle material ($n = 26$) exhibit only partial overlap with Baffin Bay dust particles. **(c)** Ratios of magma ($n = 31$) do not overlap with Baffin Bay dust particles. **(d)** Ratios of crustal material ($n = 37$) minimally overlap with Baffin Bay MDPs. For the upper continental crust, ratios of Fe/Cr = 426 and Fe/Ni = 834 [114]. See Baffin Bay MDP data in SI, Table S10. Data sources other than Baffin Bay can be found in SI, Tables S9, S11, and S12 (<https://zenodo.org/records/14681287>).

YDB and provide evidence in support of the YDIH, even in the absence of identifiable craters [88].

Oxygen isotope analysis of Baffin Bay microspherules

$\Delta^{17}\text{O}^*$ is a useful parameter in assessing the potential amount of extraterrestrial material in the drill cores. The deviation from the $\Delta^{17}\text{O}^*$ terrestrial value, as defined by the obsidian standard, in all the Baffin Bay microspherules is negative, with an average value of $-0.06 \pm 0.05 \text{ ‰}$ (2SD). If this slight difference with the obsidian standard results from the presence of an extraterrestrial component, then meteoritic material lying above the Terrestrial Fractionation Line (TFL) (positive $\Delta^{17}\text{O}^*$ values), including ordinary chondrites, R chondrites, and Martian samples, can be excluded. The microspherules that might have caused this slight deviation must lie below the TFL and will have originated from the common groups of carbonaceous chondrites,

except for CI chondrites. CO and CM groups are relatively common in the meteoritic record and show significant deviations from the TFL in terms of their $\Delta^{17}\text{O}^*$ values. Using the $\Delta^{17}\text{O}^*$ value of -5.25 ‰ (recalculated to a linear format from the data) [138] for CO fall Kainsaz (grade = 3.2), the potential amount of carbonaceous chondrite input required to account for the -0.08 ‰ deviation of Core 64 (286–290 cm) microspherules from the obsidian standard $\Delta^{17}\text{O}^*$ value of 0.00 ‰ is approximately 1.5%. The maximum deviation of the $\Delta^{17}\text{O}^*$ values from the obsidian standard obtained on the Baffin microspherules is only just outside the 2SD error on these analyses, and consequently, these results must be viewed cautiously. However, the data obtained in this study do not preclude the possibility that at least some of the microspherules contain an extraterrestrial fraction of a few percent. More research is required into oxygen isotopic analyses of Baffin Bay MDPs to test our inferences of their origin as cometary dust.

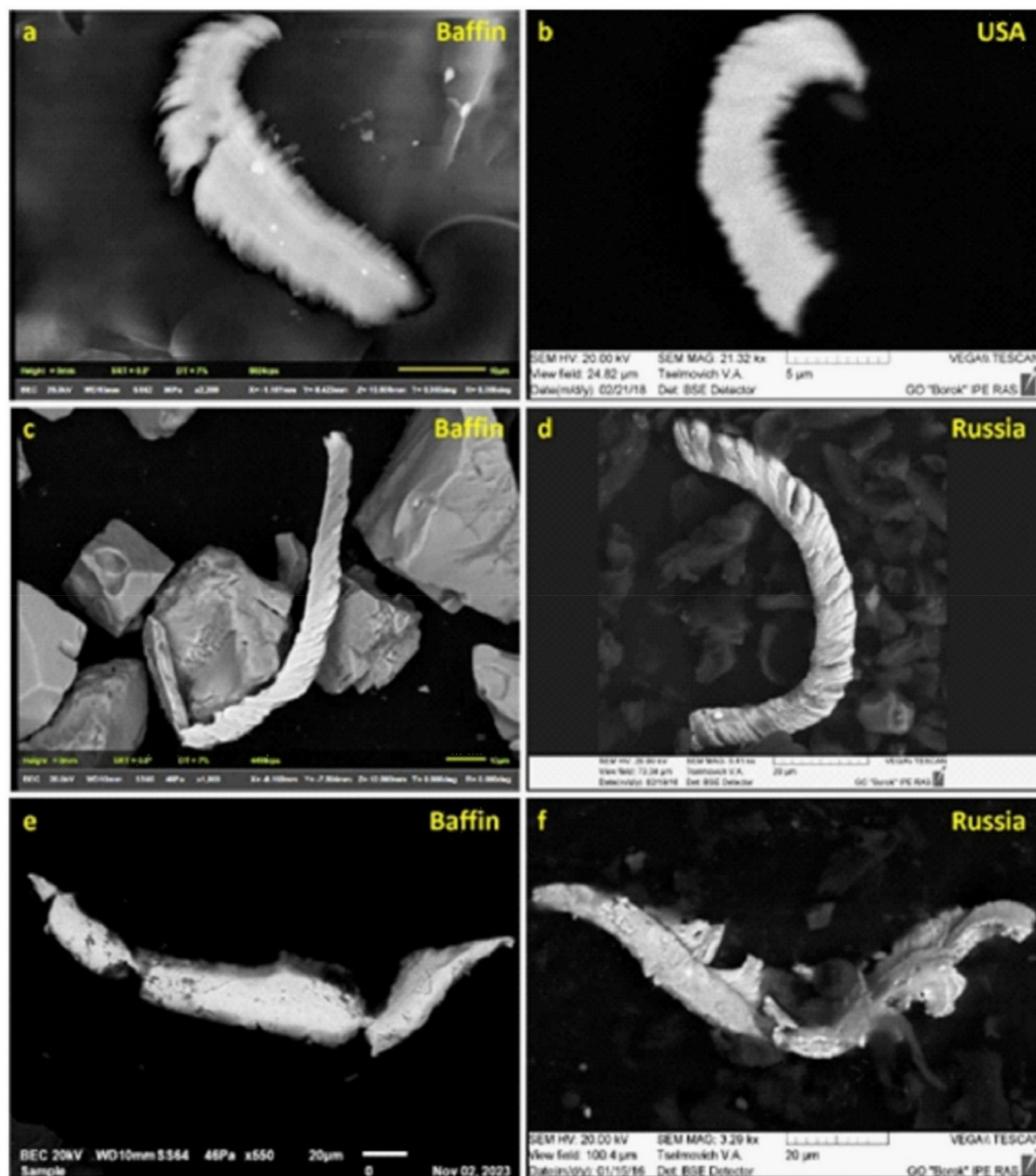


Figure 22: Comparison of flake-like dust particles (MDPs) from Baffin Bay with cometary dust particles (CDPs) from South Carolina, USA [38] (N 33°48'40", W 78°49'00"), and Russia [22–24] (N 52°, W 88°). The compositions of these particles include native Fe, native Ni, NiFe, NiFeCr, and FeCr, and range from melted to unmelted. (a, b) Feather-like particles. Their delicate features suggest that these particles remained *in situ* where deposited and were not reworked. (c, d) Twisted and layered morphologies. These particles resemble a twisted FeCr particle reported in the YDB layer from Abu Hureyra, Syria [82]. (e, f) Thin, linear morphologies. See SI, Tables S11 and S12 for elemental data for CDPs from sites in Russia and South Carolina (<https://zenodo.org/records/14681287>).

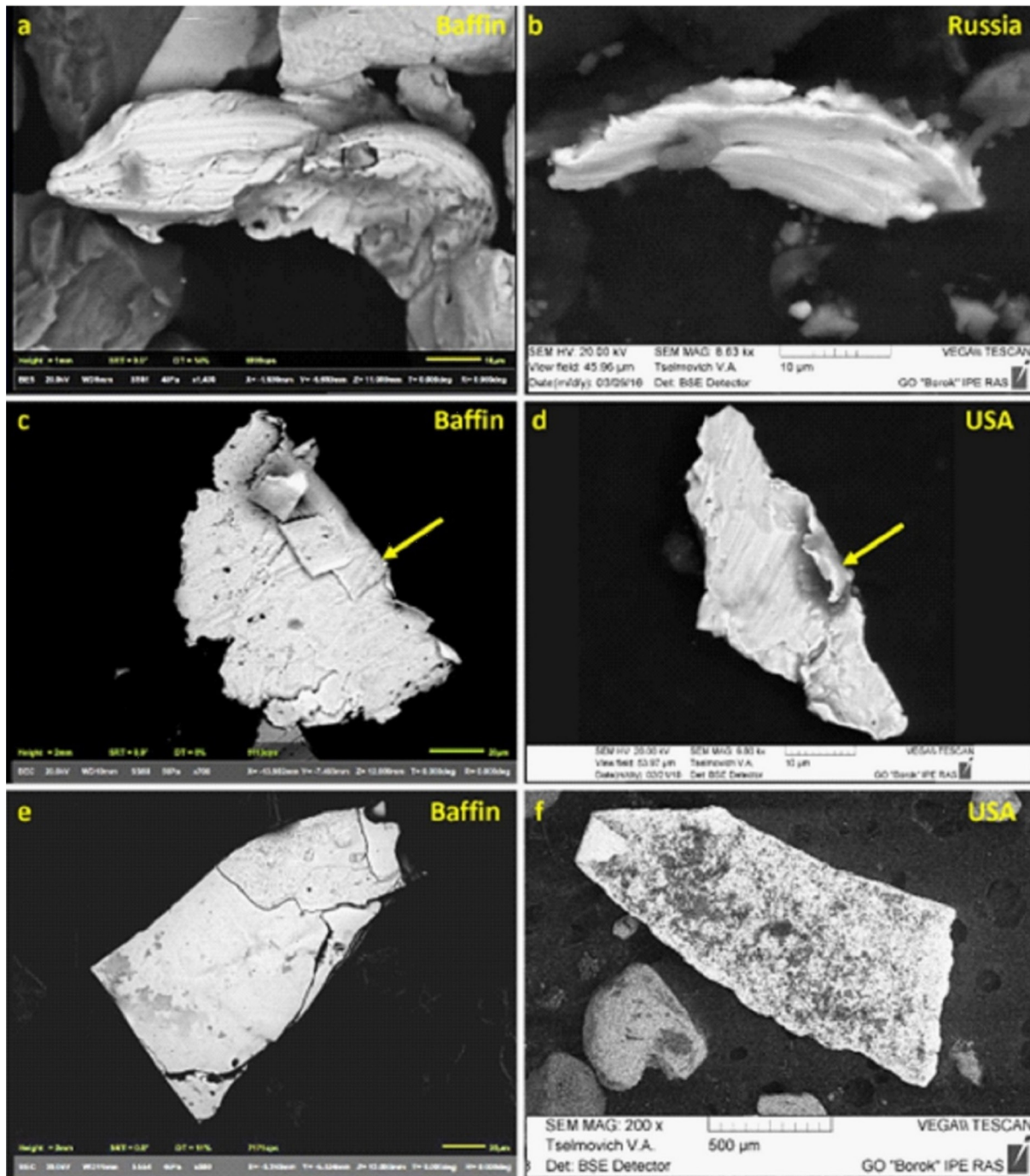


Figure 23: Comparison of flake-like metallic dust particles (MDPs) from Baffin Bay with cometary dust particles (CDPs) from Russia [22–24] and South Carolina, USA [38]. The compositions of these particles include native Fe, native Ni, NiFe, NiFeCr, and FeCr. (a, b) Striated, curved particles. (c, d) Thin, striated, flake-like particles with folded edges (arrows). Some edges appear melted. (e, f) Thin, flake-like particles without striations. See SI, Tables S11 and S12 for elemental data for CDPs from sites in Russia and South Carolina (<https://zenodo.org/records/14681287>).

YDB spherule datum layer

The YDB microspherule layer has been identified at more than 60 stratigraphic sites, covering an area of >100 million km² across five continents [2, 43, 44, 45, 51, 52, 77–79, 83, 85, 48, 89, 90, 92–94, 139–149]. Critics have argued that many purported YDB proxy peaks can be explained by

non-impact processes and/or by time-transgressive deposition, mixing, and chronological uncertainty rather than by a single event [99, 110]. However, as reported by Kennett et al. [12], many known impact craters (notably including the K-Pg's Chicxulub crater) contain peak concentrations of the same YDB proxies, including platinum (e.g., in Chicxulub

Table 4: Comparison of metallic dust particles.

Baffin	#	%	SC	#	%	Russia	#	%	Russia	#	%
NiFe	38	27%	NiFe	11	11%	NiFe	17	5%	Al, low O2	8	2%
FeCr	22	16%	FeCr	5	5%	FeCr	27	7%	FeAg	4	1%
FeCrNi	20	14%	FeCrNi	6	6%	FeCrNi	4	1%	FeC	18	5%
Fe, low O2	20	14%	Fe, low O2	0	0%	Fe, low O2	77	21%	FeCd	2	1%
Fe, native	10	7%	Fe, native	8	8%	Fe, native	12	3%	FeCoW	3	1%
Ni, low O2	8	6%	Ni, low O2	11	11%	Ni, low O2	2	1%	FeCrV	12	3%
FeCrNiCu	8	6%	FeCrNiCu	0	0%	FeCrNiCu	3	1%	FeCrVW	38	10%
NiZn	6	4%	NiZn	0	0%	NiZn	2	1%	FeCrW	13	4%
Ni, native	2	1%	Ni, native	20	20%	Ni, native	0	0%	FeCu	6	2%
FeZn	2	1%	FeZn	0	0%	FeZn	1	0%	FeCuTi	1	0%
FeP	2	1%	FeP	0	0%	FeP	9	2%	FeSi	2	1%
FeO	2	1%	FeO	2	2%	FeO	3	1%	FeTiW	9	2%
FeNiCu	1	1%	FeNiCu	0	0%	FeNiCu	1	0%	FeW	10	3%
NiO	1	1%	NiO	0	0%	NiO	1	0%	NiC	5	1%
CuZn	0	0%	CuZn	7	7%	CuZn	6	2%	NiCu	1	0%
FeNiZn	1	1%	FeNd	2	2%	Ag, low O2	1	0%	NiFe	2	1%
Total: 143			FeNiNd	2	2%	Ag, native	21	6%	NiP	4	1%
			TiFeNi	20	20%	AgCrO	3	1%	Si, native	1	0%
			Zn, native	2	2%	Cr, low O2	3	1%	TiC	2	1%
			ZnO	2	2%	Cu, low O2	5	1%	W, low O2	3	1%
			Total: 98			Cu, native	3	1%	W, native	1	0%
						WC	7	2%	WO	1	0%
						WCCo	7	2%	WTi	1	0%
						Total: 362					

[150] and Clearwater East [151], iridium (e.g., Chicxulub [150, 152] and Clearwater East [151], microspherules (e.g., Chicxulub [153] and Sudbury [153]), meltglass (e.g., Chicxulub [153] and Sudbury [153]), nanodiamonds (e.g., Chicxulub [154] and Ries [155]), carbon microspherules (e.g., Chicxulub [156]), and aciniform carbon/soot (e.g., Chicxulub [157, 158] and Manson [159]). Although each of these proxies potentially can form through non-impact processes (e.g., anthropogenic, volcanism, and tectonism), this comprehensive proxy suite has been reported only in association with known or predicted craters/airbursts and at no other times in the geologic record [86, 92]. Thus, there is broad acceptance that this group of proxies results from cosmic impact events, therefore representing a plausible explanation for the Baffin Bay assemblages.

Nanoparticles in four Baffin Bay cores

Nanoparticle data from SP-ICP-TOF-MS analysis of bulk sediments from Baffin Bay Cores 52, 64, 67, and 77 reveal a stratigraphically discrete enrichment in metal-bearing nanoparticles within the Younger Dryas Boundary (YDB)

interval (Figures 9–12; SI, Figures S7 and S8; SI, Table S7). These particle-scale enrichments show conservative REE behavior but selective PGE enrichment at the YDB (Figures 13 and 14), indicating that the boundary signal is not attributable to a change in sediment provenance but to the addition of a chemically distinct PGE-bearing component. Peaks in the masses of Pt, Ir, Ni, Co, and other PGEs occur within or slightly above the horizons containing the highest abundances of inferred impact microspherules and CDPs (Figure 9). The recurrence of these enrichments across multiple cores, together with their confinement to the YDB layer or immediately overlying strata, indicates that the signal reflects a basin-wide depositional pulse rather than localized sedimentary processes or analytical artifacts.

Influence of contrasting depositional environments

The four cores were recovered from markedly different depositional settings, which would be expected to influence both the magnitude and stratigraphic expression of nanoparticle deposition. Core 52 was obtained from the mouth of Jones Strait in ~512 m of water, where meltwater discharge

and iceberg outflow from the Canadian Arctic Archipelago would have produced a highly energetic and variable environment. Such conditions favor rapid sedimentation, reworking, and incorporation of material released during iceberg calving and melting. Consequently, nanoparticles delivered represent delayed fallout across a broader stratigraphic interval or mixed with locally derived sediments, producing a more diffuse or irregular signal.

Core 67, by contrast, was recovered from the deepest part of Baffin Bay (~2357 m), where sedimentation is dominated by delayed vertical settling of nanoparticles through a thick water column and by debris released from melting icebergs. In addition, impact particles deposited on glacier surfaces or sea ice prior to calving could be transported long distances before release to the water column, contributing to delayed nanoparticle deposition relative to the initial atmospheric event.

Core 77, located at ~1153 m depth near the continental slope off southern Baffin Island, represents a more distal setting with reduced direct influence from major meltwater outlets. Sedimentation here is likely governed primarily by hemipelagic settling and episodic ice-rafted inputs.

Core 64, recovered from ~875 m depth near the northern Baffin Island shelf southeast of Lancaster Sound, was likely affected by meltwater flooding through that gateway. Although nanoparticle sampling was limited, the data indicate delayed nanoparticle fallout following deposition of impact microspherules in the YDB layer, indicating that impact-related material was deposited broadly across Baffin Bay (see SI, Figs. S7 and S8).

Despite these contrasting environments, all cores exhibit a similar stratigraphic pattern: enrichment in metal-bearing nanoparticles within or immediately above the YDB layer. This consistency across settings ranging from energetic outflow zones to deep basinal environments argues strongly for a regionally extensive depositional event rather than site-specific sedimentary processes.

Stratigraphic relationships among YDB, fallout, and detrital layers

In each core, the YDB layer is defined by peaks in microspherules and metallic dust particles. Nanoparticle maxima sometimes coincide with this horizon, suggesting rapid deposition of fine condensates generated during the same high-energy processes that produced the larger particles. However, nanoparticle peaks more commonly occur in the overlying fallout layer. Because submicron particles have extremely low settling velocities, they can remain suspended in the atmosphere and water column for extended periods before final deposition. Evidence from the Greenland GISP2 ice core indicates that Pt deposition associated with the YDB event persisted for approximately two decades [52], consistent with prolonged atmospheric residence of fine material.

Although nanoparticles may remain suspended for extended periods in deep marine settings, their eventual settling is facilitated by incorporation into organic aggregates

(“marine snow”) [53]. The systematic offset between microspherule peaks and nanoparticle maxima observed in several cores therefore likely reflects the longer residence time of nanoparticles in the water column prior to aggregation and settling.

In some cases, nanoparticle enrichments extend higher into the overlying detrital layer above the YDB and are characterized by increased sand and carbonate content indicative of enhanced terrestrial runoff or iceberg rafting during deglaciation. This pattern may reflect continued release of particles trapped within melting ice, resuspension and redeposition of previously deposited fallout, or secondary transport associated with increased sediment flux. Thus, the vertical distribution of nanoparticles records not only the initial atmospheric input but also subsequent redistribution processes within glacial-marine environments.

Evidence for an extraterrestrial source

Normalization of total PGE nanoparticle mass to lithogenic elements (Fe, Al, Ti, and La) (Figure 10) demonstrates that the enrichments are not simply a consequence of changing sediment composition. The persistence of pronounced peaks after normalization indicates that PGEs were introduced independently of the background detrital supply. Because these lithogenic elements occur in different mineral phases and exhibit different susceptibilities to post-depositional reworking, their consistent response argues against redox remobilization, carbonate dilution, or grain-size variability as primary controls.

Elemental mass ratios within nanoparticles also shift abruptly within the YDB interval (Figure 11), indicating the introduction of particles with a composition distinct from typical crustal or mantle materials. Ratios such as Pt/Pd exceeding unity are consistent with an exogenic ET contribution, as Pt is commonly enriched relative to Pd in meteoritic materials and is less prone to post-depositional redistribution [51]. In contrast, volcanic or mantle-derived inputs would be expected to produce more gradual variations and to correlate with other indicators of magmatic activity, which are absent in these cores.

Anthropogenic contamination can likewise be excluded because the studied intervals lie several meters below the seafloor beneath up to ~2400 m of water in remote Arctic to sub-Arctic settings. Continuous background influx of interplanetary dust would not produce the observed sharp, stratigraphically confined anomalies. Together, these observations support an episodic influx of externally derived metal-rich particles.

Implications for impactor type

A diagnostic ratio of Pt/Fe (Figure 12) places the nanoparticle compositions within compositional fields occupied by metal-rich extraterrestrial materials, including comets, refractory metal nuggets, micrometeorites, and iron meteorites, while showing no overlap with chondrites, typical magmatic rocks,

or upper continental crust. Because nanoparticles constitute only a trace fraction of the sediment, these ratios reflect discrete particle populations rather than bulk mixing.

The diversity of compositional signatures suggests that the source was not a single homogeneous meteoritic body, such as an iron meteorite or chondritic body. Instead, the coexistence of characteristics associated with multiple extraterrestrial components is consistent with a heterogeneous, loosely aggregated parent body, such as a fragmented dust-rich comet or rubble-pile asteroid. Disruption of such an object during or before atmospheric entry or low-altitude airbursts would release a spectrum of particle types, including metal-rich condensates, refractory inclusions, and silicate debris, producing the mixed signatures observed here.

Relationship to other impact proxies and regional significance

Nanoparticle enrichments coincide stratigraphically with independent impact proxies documented in the same cores, including microspherules, meltglass, metallic dust particles, and PGE anomalies. The integrated evidence indicates that these materials were deposited during a common high-energy event. Because nanoparticles can be transported globally in the atmosphere, they provide a sensitive indicator of widespread dispersal of impact-generated or impact-delivered material.

Background nanoparticle abundances outside the YDB interval are comparatively low, consistent with steady-state deposition of interplanetary dust and terrestrial aerosols. The abrupt, order-of-magnitude increases observed at the YDB therefore represent a short-lived high-flux episode rather than long-term variability. Replication of this pattern across cores spanning ~1000 km further supports a basin-wide depositional signal.

Climatic implications

A sudden injection of fine metal-rich particles into the atmosphere at ~12.8 ka would be expected to increase atmospheric dust loading and reduce solar insolation, mechanisms proposed to contribute to the rapid onset of Younger Dryas cooling [78, 79]. Delayed settling of nanoparticles, combined with redistribution by oceanic and glacial processes, could produce the stratigraphic patterns observed in Baffin Bay sediments.

Taken together, the nanoparticle evidence indicates a discrete regional influx of PGE-enriched particles coincident with the YDB. When integrated with co-occurring microspherules, meltglass, MDPs, and other proxies, the data are most consistent with deposition of extraterrestrial material during a high-energy event at the onset of the Younger Dryas. Although nanoparticle geochemistry alone cannot uniquely identify the exact nature of the impactor, the compositional signatures strongly favor a heterogeneous, dust-rich source such as a comet fragment or rubble-pile asteroid rather than volcanism, mantle processes, or other terrestrial mechanisms.

YDIH: environmental consequences of an impact event

The evidence observed at Baffin Bay, including anomalous abundances of microspherules, meltglass, platinum (Pt), and iridium (Ir), is also found at over 60 locations spanning more than 100 million km² across North and South America, Europe, Asia, and Africa [2, 9–11, 4351, 52, 77–79, 81–83, 85, 87, 48, 89, 90, 92–94, 140–148, 49, 160–164]. Moore et al. [11] proposed an astronomical model that these YDB deposits were produced when Earth entered a debris stream originating from the disintegration of a large comet, the possible progenitor of Comet Encke and the Taurid Complex. This debris trail was likely wider than Earth's diameter and thousands of times longer. Earth's passage through the trail, which, depending on many variables, likely occurred over a few hours to a few days, resulted in a “meteor hurricane or hailstorm” that loaded the upper atmosphere with millions of tonnes of terrestrial dust, cometary dust particles, soot, smoke, high-altitude ice crystals, and water vapor [2, 11, 122].

We propose that Earth's passage through the impactor debris trail produced tens of thousands of airbursts and ground impacts. Some fragments exploded at high altitudes with little surface effects, while others exploded very close to the ground and are known as type-2 or touchdown airbursts [116, 133, 165, 166]. These low-altitude airbursts generated high-velocity, high-temperature jets of vapor and fragments that reached Earth's surface, causing significant damage and producing microspherules and meltglass randomly and discontinuously across at least one hemisphere. Meltglass is found at only about 10% of YDB sites, presumably because the airbursts were widely spaced, and the larger meltglass fragments did not travel far from ground zero. On the other hand, the smaller microspherules and nanoparticles traveled farther and have been observed at every site across five continents that were tested with sufficiently high stratigraphic/chronological resolution. See Figure 24 for the global distribution of YDB proxies.

Baffin Bay benthic foraminifera and paleoclimate across the YD

In core 52 (~500 m water depth) recovered from the Coburg Basin cross-shelf trough near Jones Sound, benthic foraminiferal assemblages change across the Bølling–Allerød/Younger Dryas (BA/YD) transition (see SI, “Foraminifera: Radiocarbon Dating and Environmental Setting”). The two lowermost samples in the studied interval (biofacies 3A) are dominated by *Cassidulina neoteretis* with lesser abundances of *Stetsonia arctica* (SI Table S18). Five overlying samples are characterized by *Elphidium excavatum* (clavatum form), *Cassidulina reniforme*, and *Buliminella hensoni* (biofacies 2). Samples above the Younger Dryas interval are dominated by *C. neoteretis*, *Cibicides lobatulus*, and *Nonionellina labradorica* (biofacies 3B).

Transitions between these assemblages are not sharp, likely reflecting physical reworking and bioturbation (SI Table S18). Biofacies 2, which spans the BA/YD boundary interval and the immediately overlying sediments, contains abundant allochthonous material including carbonate clasts, transported sediments, and benthic foraminifera. These materials were likely introduced by shallow meltwater plumes (see X-ray images in Figures 3 and 4; SI, “Foraminifera: Radiocarbon Dating and Environmental Setting”; Culver et al., unpublished data).

In the other cores (64, 67, and 77), changes in foraminiferal assemblages across the Younger Dryas interval cannot be evaluated because nearly all dated samples were collected from within the Younger Dryas interval itself (SI, “Foraminifera: Radiocarbon Dating and Environmental Setting”).

Climate-related sedimentary changes in the region are instead recorded by regionally extensive ice-rafted debris (IRD) deposits, which occur both above and below the Younger Dryas interval in cores 64, 67, and 77 (Figures 3 and 4). These IRD-rich units were deposited during the late Bølling–Allerød warm interval (ca. 14.1–13 ka) and during the immediately post-Younger Dryas warming of the early

Holocene (ca. 12.0–10.9 ka) [20, 63, 167]. Comparable IRD deposits do not occur in core 52 because this site lies north of the region of major IRD accumulation. The IRD unit immediately above the Younger Dryas sediments in core 52 is considerably younger (SI Table S18).

The X-ray images of all four cores (Figures 3, 4) reveal distinct increases in carbonate-rich sediment with limestone clasts above the YDB peaks in microspherules and metallic dust particles, consistent with meltwater flooding following the YDB impact event. In addition, the YD climate interval in core 64 lacks foraminifera, consistent with rapid deposition of meltwater-transported sediments and IRD.

Impact-related Younger Dryas climate changes

Consistent with the YDIH, we infer the following sequence of events, based on the sedimentary record in the four cores, including X-ray images (Figures 3 and 4): i) At ~12,800 cal BP, Earth encountered a large comet’s debris stream that loaded the atmosphere with inferred cometary material, including dust particles, high-altitude ice crystals, and water vapor. ii) The encounter resulted in numerous air-bursts/impacts over land, ice sheets, and the oceans, injecting terrestrial dust, soot, and combustion aerosols into the

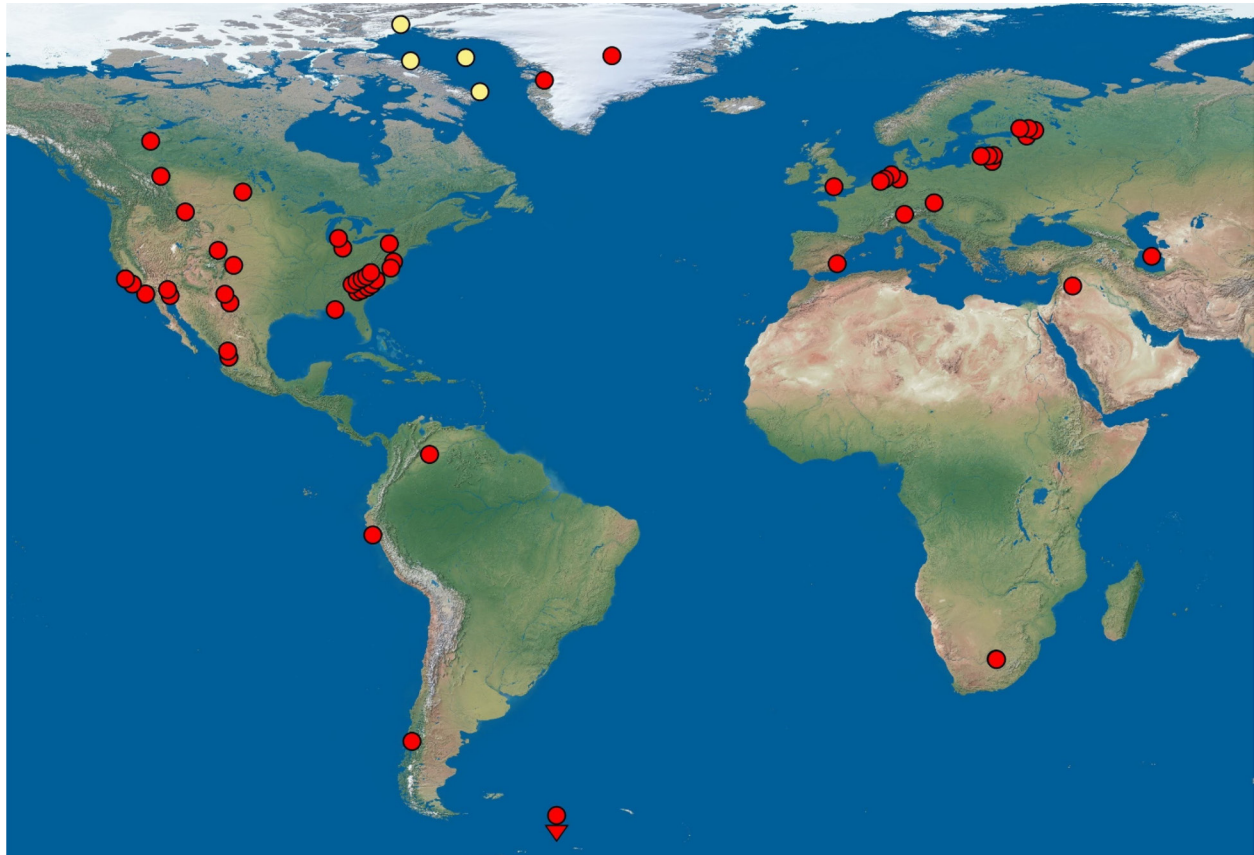


Figure 24: YDB sites. Various YDB proxies have been found at 60 sites on six continents, including Antarctica. Baffin Bay cores are in yellow, and other YDB sites are in red. The base map was provided by Tom Patterson (www.shadedrelief.com).

atmosphere. iii) In Baffin Bay, these processes deposited YDB peaks in microspherules, metallic dust particles, and impact-related nanoparticles into laminated sediments containing minimal carbonate-rich material. iv) The airburst shockwaves and ice impacts destabilized ice sheet margins and collapsed ice dams on proglacial lakes, triggering meltwater flooding and iceberg calving into the Arctic and northern Atlantic Oceans [67–69, 71, 167]. Immediately above the YDB layer, the four cores display significant increases in meltwater-transported sediment and IRD, consisting of quartz grains, carbonate-rich sediment, limestone clasts, and lithic fragments pulverized by the glaciers. v) Atmospheric loading of dust, soot, and aerosols triggered a short-term impact winter. vi) Freshwater flooding into the Arctic and Atlantic led to decreased surface water salinity, disrupting oceanic thermohaline circulation and triggering the long-term YD cooling episode. vii) Feedback mechanisms and hysteresis extended the duration of YD cooling for ~1200 years until the onset of the Holocene when thermohaline circulation resumed its previous interglacial state.

The YDIH also proposes that soot generated by widespread biomass burning across approximately 10% of the planet, caused by airbursts and minor impacts, was an additional mechanism for YD cooling [78, 79]. This effect, combined with the cooling impact of cometary dust, created a potent mechanism for rapid climate change [168].

Turco et al. [169] investigated the effects of dust and soot loading from nuclear warfare, estimating that fires from such events could produce 10^5 to 290^6 tons of atmospheric soot, triggering a prolonged nuclear winter lasting 1 to 3 years. Their modeled decline in temperatures parallels those observed at the onset of Younger Dryas. However, the amount of soot produced by nuclear warfare is several orders of magnitude smaller than the range of cometary dust particles modeled in this study, suggesting far more severe consequences at the YDB onset. Such quantities of cometary dust are capable of causing an “impact winter [170, 171]” akin to the K-Pg impact event, where dust and soot injected into the atmosphere triggered abrupt global cooling.

Extrapolating from the influx of CDPs into four ocean cores from Baffin Bay, the global influx during ~6 months is estimated to be 8.8 million tons, most of which fell as micro- to nano-sized cosmic dust particles. The influx of MSp is estimated to be ~4.8 million tons, most of which is assumed to have been produced from surficial sediments during airbursts. The latter value is reasonably close (~2× less) to the 10 million tons of YDB MSp estimated by Wittke et al. [43] (See Appendix B, “*Microspherule, CDP, and Nanoparticle Global Influx*”).

Future work

Additional oceanic and lacustrine cores from different locations around the globe need to be analyzed to test further the connection between YD cooling and the impact event.

These potentially include further investigations in search of YDB impact proxies along the drainage route from proglacial Lake Agassiz into the Beaufort Sea and along meltwater drainages through Hudson Strait and Nares Strait into Baffin Bay. Our plans include sampling and analyzing deep sea cores with well-dated paleoclimatic records including the independently identified YD onset layer to further test the hypothesis that the YD began soon after the impact event.

Conclusions

The Younger Dryas impact hypothesis (YDIH) proposes that ~12,800 years ago Earth encountered debris from the disintegration of a large comet, producing widespread airbursts and/or impacts. This study evaluates that possibility using four marine piston cores from Baffin Bay spanning continental shelf to deep-basin environments (500–2,400 m water depth) across the Younger Dryas Boundary (YDB).

Within glaciogenic marine sediments dated to the onset of the Younger Dryas, we identify distinct abundance peaks in iron-rich and silica-rich microspherules (microtektites and microkrystites) together with high-temperature minerals, meltglass, cometary dust particles (CDPs), metallic dust particles, and PGE-rich nanoparticles (e.g., Pt and Ir). These proxies occur at different depths in each core but are consistently dated to the YD onset based on Bayesian age-depth modeling of calibrated radiocarbon ages. The host sediments consist primarily of carbonate-rich, gravelly, sandy mud indicative of episodic ice-rafted input [20]. In all cores, the YDB proxy peaks are bracketed between stratigraphically intact IRD layers, supporting deposition during a discrete interval rather than prolonged reworking, and precluding anthropogenic contamination.

Age-depth models (SI, Figures S3–S6) indicate increased sedimentation rates at the YD onset in some cores (none in Cores 52 and 77; ~3.7× in Core 64 and ~5.2× in Core 67). This increase may reflect destabilization of regional ice margins immediately prior to cooling and enhanced deposition of carbonate-rich sediment and IRD thereafter. The combination of increased sedimentation and delayed settling of fine particles likely accounts for the slight stratigraphic separation between heavier impact-related microspherules and much lighter nanoparticles (Figures 9 and 10; SI, Figures S7 and S8).

Geochemical analyses indicate that the Baffin Bay microspherules are microtektites and/or microkrystites composed predominantly of melted terrestrial material with minor extraterrestrial contributions (<~2 wt%) [16–19, 133, 136]. Such materials are widely interpreted as products of impacts or low-altitude airbursts [14, 15, 115, 116].

Nanoparticle geochemistry provides further evidence for anomalous particulate input over the YDB interval. Ratios such as Pt/Fe are strongly elevated relative to crustal compositions and overlap most closely with metal-rich

extraterrestrial materials while showing no overlap with average continental crust or typical magmatic sources. The nanoparticle population, therefore, appears to include a PGE-enriched component superimposed on a lithogenic background. Its stratigraphic coincidence with microspherules, CDPs, and other high-temperature proxies suggests deposition during a short-lived, high-energy event.

The diversity of nanoparticle compositions further implies a heterogeneous source. Overlap with multiple extraterrestrial components, including iron meteorites, micrometeorites, refractory metal-bearing materials, and cometary dust, indicates that the incoming material was unlikely to derive from a single homogeneous meteoritic body. Instead, the assemblage is consistent with debris from a compositionally diverse object such as a dust-rich comet or rubble-pile asteroid containing mixtures of primitive material, differentiated metal, and refractory inclusions. Disruption of such a body during atmospheric entry or airbursts would be expected to generate the broad spectrum of impact materials observed.

Immediately above the YDB layer, the cores show pronounced increases in meltwater-transported sediment and IRD, indicating enhanced glacial discharge. Atmospheric loading of dust, soot, and aerosols could have produced short-term cooling, while freshwater influx into the Arctic and North Atlantic would have weakened thermohaline circulation, contributing to the well-known shifts in North Atlantic Deep Water (NADW) circulation and climate at the YDB. Biomass burning triggered by airbursts or impacts may have further increased atmospheric opacity through the injection of soot and dust into the atmosphere [78, 79]. Together with perturbations to NADW circulation, these processes provide a plausible mechanism for rapid climate change at the YDB [168].

Scaling from CDP concentrations suggests a global influx of ~8.8 million tons of cosmic dust over roughly six months, accompanied by ~4.8 million tons of microspherules generated from terrestrial sediments during airbursts. These estimates are broadly consistent with previous YDB calculations [43] and fall within ranges capable of producing an “impact winter” comparable to that associated with large impacts [170, 171].

In summary, the multiproxy evidence from Baffin Bay, including microspherules, meltglass, metallic dust particles, PGE-rich nanoparticles, and stratigraphic context, indicates a basin-wide depositional episode at the onset of the Younger Dryas. The co-occurrence, stratigraphic confinement, and replication of these proxies across multiple marine environments support the interpretation of a substantial influx of extraterrestrial material from a heterogeneous debris stream. While individual indicators are not uniquely diagnostic, the integrated dataset is consistent with a major high-energy event coincident with the onset of Younger Dryas cooling, thus supporting the Younger Dryas Impact Hypothesis.

Methods

Sample collection

Literature and data already available for each Baffin Bay core, including dating, magnetic susceptibility, elemental composition, and IRD load, were examined to determine the likely depth of the Younger Dryas Boundary [20, 21]. Sections of the core were then sampled in approximately 1 to 5 cm thick quarter core sections with mass amounting to approximately 18 to 53 grams each. Differences in the sedimentary composition, IRD load, and the amount of each core remaining after prior sampling limited the finding of a commonality in the depth and mass of each sample. Each sample taken was placed in a container about the size of a 35 mm film canister. Each sample mass was first homogenized and then cut into equal portions for different teams to process and examine based on their specialized analysis capability. The included foraminifera dating, microspherule and melt glass, nanoparticle and single particle ICP-TOF-MS, and laser ablation IC-MS.

Microspherules, CDP, and meltglass analysis

To analyze sediment samples for microspherule, CDP, and meltglass candidates, we first weighed the core samples and then subjected them to 30 minutes of ultrasonication using a dispersant, sodium metaphosphate, to disaggregate the sediments. After ultrasonication, the samples were wet-sieved over a 20-micron sieve and dried under a heat lamp. The processed samples were then size sorted, and sediment fractions between ≥ 63 and < 125 microns and between ≥ 20 and < 63 microns were spread thinly on a large sheet of paper. A neodymium magnet, placed inside a plastic bag, was slowly moved over the size-sorted sediment fractions to extract the magnetic grains. This process is repeated three times to ensure the extraction of most magnetic grains. The extracted grains were then examined under a stereo binocular microscope to identify potential microspherules, CDP, and meltglass candidates. The non-magnetic fraction was also examined under an optical microscope for the presence of meltglass and silica-rich microspherules not attracted to the magnet. When such candidates were present, they were placed on carbon SEM tape for further analysis using SEM and EDS (JEOL 6010 Plus LV). Only SEM and EDS analysis could confirm the identification of silica-rich or Fe-rich microspherules [44]. The microspherule counts and total sediment sample weights were used to estimate the number of microspherules per kilogram for each sample.

After extracting the magnetic fraction to investigate iron-enriched microspherules and candidate CDPs, the remaining sand fraction was examined for meltglass candidates. This aliquot primarily included larger sand size fractions (> 63 microns), which were examined using optical microscopy to identify meltglass. When meltglass candidates were found, they were placed on carbon SEM tape for SEM and EDS analysis. Per kg abundance values of microspherules and meltglass generally depend on the total mass

of the sample tested. The smaller the mass and the fewer the proxies, the more difficult it becomes to find and accurately estimate the normalized proxy abundance.

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. [172]. 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. [172] and Humayun et al. [173]. 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 were 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. [173]). 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.

Bulk sediment oxygen isotopes

High-precision oxygen isotopic measurements were undertaken at the Open University (Milton Keynes, UK) using an infrared laser-assisted fluorination system [174, 175]. For each core sample, whole-rock powders were prepared from chips of drill core material with a minimum mass of 100 mg. Approximately 2 mg aliquots of these powders were then loaded into a nickel sample block, along with similar-sized aliquots of our internal obsidian standard [56]. The loaded sample block was then placed in a two-part chamber, made vacuum-tight using a compression seal with a copper gasket and quick-release KFX clamp [174]. A 3 mm thick BaF_2 window at the top of the chamber allows simultaneous viewing and laser heating of samples. Prior to analysis, the sample chamber was heated overnight under vacuum to a temperature of about 70°C to remove the majority of the adsorbed moisture. After overnight heating, the chamber was allowed to cool to room temperature. A static leak check was then undertaken to verify that the system was vacuum-tight. The system blank was then reduced further by introducing aliquots of BrF_5 . These were held in the sample chamber for 20 minutes and had the effect of removing any remaining adsorbed moisture. The system was then left to pump for another day and oxygen isotopic analysis only undertaken once the blank level reached <60 nanomoles of O_2 . Sample heating in the presence of BrF_5 was undertaken using an integrated 50W infrared CO_2 laser ($10.6 \mu\text{m}$) and video system mounted on an X-Y-Z gantry supplied by Photon Machines Inc. After fluorination, the released O_2 was purified by passing it through two cryogenic nitrogen traps and over a bed of heated KBr to remove any excess fluorine. The isotopic composition of the purified oxygen gas was analyzed using a Thermo Fisher MAT 253 dual inlet mass spectrometer with a mass resolving power of approximately 200.

Overall system precision, as defined by replicate analyses of our internal obsidian standard is: $\pm 0.053\text{‰}$ for $\delta^{17}\text{O}$; $\pm 0.095\text{‰}$ for $\delta^{18}\text{O}$; $\pm 0.018\text{‰}$ for $\Delta^{17}\text{O}$ (2σ) [56]. Oxygen isotopic analyses are reported in standard δ notation, where $\delta^{18}\text{O}$ has been calculated as: $\delta^{18}\text{O} = [({}^{18}\text{O}/{}^{16}\text{O})_{\text{sample}} / ({}^{18}\text{O}/{}^{16}\text{O})_{\text{VSMOW}} - 1] \times 1000 \text{ (‰)}$ and similarly for $\delta^{17}\text{O}$ using the ${}^{17}\text{O}/{}^{16}\text{O}$ ratio. $\Delta^{17}\text{O}$, which represents the deviation from the terrestrial fractionation line, has been calculated using the linearized format of Miller [176]:

$$\Delta^{17}\text{O} = 1000 \ln(1 + (\delta^{17}\text{O}/1000)) - \lambda 1000 \ln(1 + (\delta^{18}\text{O}/1000)) \text{ where } \lambda = 0.5247$$

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

For particle extraction, 100 mg of bulk sediment samples were suspended in 10 mL of ultrapure water (UPW, Millipore Advantage System, Merck Millipore, Darmstadt, Germany) in 15 mL acid-washed centrifuge tubes. The sediment suspensions were vortexed using a vortex mixer

(Scientific Industries, G560, USA), followed by 15 minutes of batch sonication (Branson 2800, 40 kHz, Danbury, CT, USA) to disperse the particles. After sonication, the samples were left undisturbed for 24 hours to allow larger particles to settle. The top 5 mL supernatant was then transferred into acid-washed 15 mL centrifuge tubes and stored in a refrigerator at 4°C before single particle-inductively coupled plasma-time of flight-mass spectroscopy (SP-ICP-TOF-MS) analysis. Just before SP-ICP-TOF-MS analysis, the samples were diluted 5000-fold in UPW, and the suspensions were sonicated both before and after dilution to enhance particle dispersion and minimize settling during analysis.

Particle composition on a single-particle basis

The elemental composition of individual particles was determined by SP-ICP-TOF-MS (TOFWERK, Thun, Switzerland), following methods described in our previous studies [177–179]. Samples were introduced into the ICP using a 2DX autosampler (Element Scientific, Omaha, United States) and a MicroMist U-series Nebulizer (Thermo Scientific, USA) connected to a Quartz Cyclonic Spray Chamber (Meinhard, USA) and then into the ICP torch. Instrument operating parameters and monitored isotopes are detailed in SI, Tables S14 and S15, respectively. Element-specific instrument sensitivities were measured with multi-element solutions prepared from a mixed multi-element ICP certified reference standard (0, 1, 2, 5, and 10 µg/L multi-element standard, diluted in 1% HNO₃, BDH Chemicals, Radnor, PA, USA). Transport efficiency was calculated using the known size method with certified 60-nm Au ENMs (NIST RM 8013 Au, Gaithersburg, MD, USA) and a series of ionic Au standards (BDH Chemicals, West Chester, PA, USA) [180].

A 4.5% H₂/He gas mixture was used as collision gas to eliminate or minimize interferences, optimized specifically for ⁵⁶Fe⁺ and ²⁸Si⁺ signals. Data processing, including signal thresholding (using the Poisson algorithm [181]) and split-event correction, was conducted using TOFpilot (Version 2.11.3, TOFWERK, Thun, Switzerland). The mass and size detection limits, assuming pure metal and metal oxide phases, are provided in SI, Table S14. All samples and UPW blanks were analyzed in triplicate, and data were acquired for 200 seconds per replicate. After confirming the reproducibility of single particle elemental composition and number concentrations among replicates, the data from the three replicates were combined to achieve comprehensive analysis due to limited detection events of certain elements.

Ethical considerations, permits, and authorship

The curator/collections manager at the National Marine Geoscience Collection at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia, approved this study.

Supporting information

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

SI text: <https://zenodo.org/records/18877755>

Tables on Zenodo: <https://zenodo.org/records/14681287>

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Data availability

Data are provided within the manuscript and supporting information files (<https://zenodo.org/records/18877755>) and in an online public repository.

Sample availability

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

Author contributions

All authors reviewed and approved the manuscript. C.R.M., V.A.T., M.A.L., and A.W. conceived and directed the project. C.R.M., V.A.T., M.A.L., A.W., S.J.C., D.J.M., G.K., J.P.K., R.C.G., and M.J.D. wrote the manuscript. S.J.C., D.J.M., M.B., W.M.N., V.A., S.R.S., G.K., K.A.L., J.P.P., T.W., M.D.Y., M.A., V.T., J.J., R.C.G., J.A.M., and M.J.D. contributed data and technical analysis for the paper. T.W. assisted in the collection of the material from core 52.

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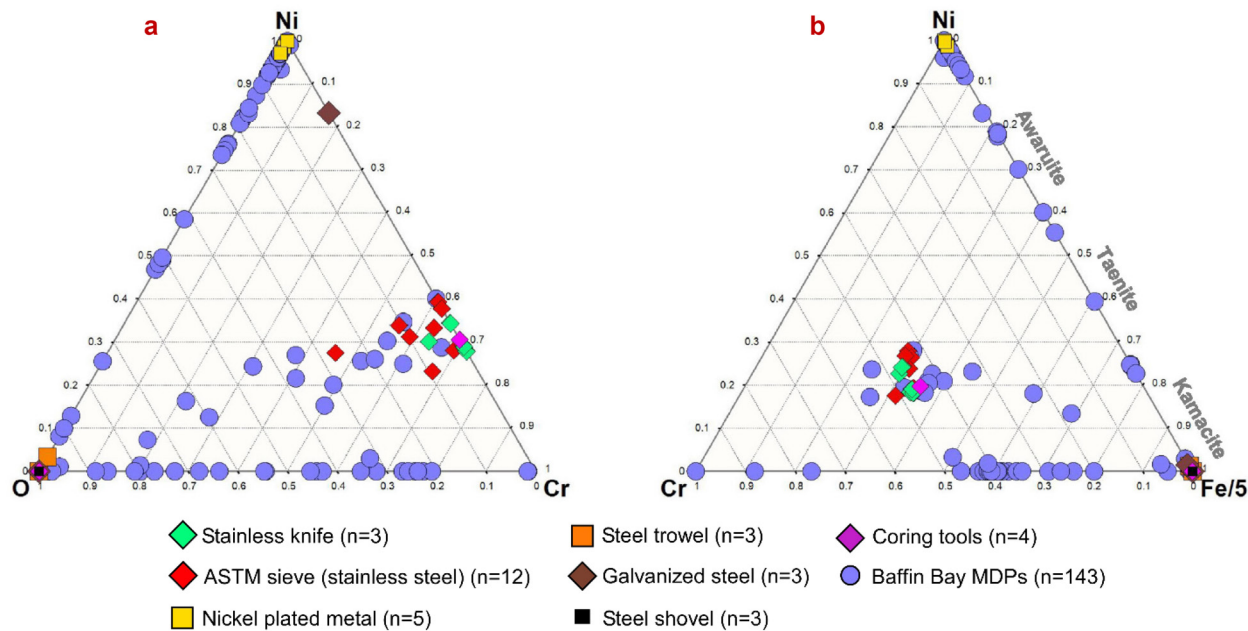
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Appendix A



Appendix Figure A1: Ternary plot for Baffin Bay metallic dust particles (MDPs) and potential sources of anthropogenic contaminants. Most Baffin MDPs do not overlap with anthropogenic/industrial metallic particles, which typically group at the vertices. Clusters of nearly pure nickel-plated neodymium magnet coatings overlap with some MDPs, but contamination is unlikely because the magnets were shielded from the sample. Alternatively, cometary material can contain blebs of native nickel and native iron. **a)** O-Cr-Ni plot. Some MDPs in the middle of the plot display similar ratios of Cr to Ni but with highly variable amounts of oxygen. Most are inconsistent with the plotted contaminants and, thus, are likely to be terrestrial or ET chromite grains. **b)** Cr-Fe-Ni plot. The Fe abundances were divided by 5 to increase the clarity of the plot. Note that the contaminants are grouped at the vertices on the righthand Fe-Ni axis, and none overlap the MDPs along the rest of the axis. The axis is marked to show awaruite (~77 wt% Ni), taenite (~20-65 wt% Ni), and kamacite (5-10 wt% Ni), which are very rare terrestrially but common in ET material, supporting the conclusion that these are ET particles. The ternary plot was made using ProSim Ternary Diagram software. See SI, Table S13 for data (<https://zenodo.org/records/14681287>).

Appendix Table A1: Oxygen isotope results.

	$\delta^{17}\text{O}\text{‰}$	1SD	$\delta^{18}\text{O}\text{‰}$	1SD	$\Delta^{17}\text{O}\text{‰}^{**}$	1SD
Obsidian - internal standard	3.67	0.02	7.01	0.01	0.00	0.02
Obsidian - internal standard	3.81	0.05	7.28	0.00	0.00	0.04
Obsidian - internal standard	3.80	0.00	7.27	0.01	-0.01	0.00
						2SD
				MEAN	-0.01	0.01
Core 64 272-274 cm	5.16	0.03	10.06	0.01	-0.11	0.03
Core 64 286-290 cm	5.77	0.02	11.18	0.04	-0.08	0.03
Core 64 312-318 cm	7.44	0.01	14.37	0.03	-0.07	0.03
Core 64 323-325 cm	7.27	0.02	13.99	0.01	-0.05	0.03
Core 67 25-26 cm	6.14	0.07	11.84	0.06	-0.06	0.04
Core 67 26-28 cm	5.60	0.01	10.75	0.02	-0.02	0.01
Core 67 28-30 cm	5.47	0.04	10.57	0.02	-0.06	0.03
Core 67 30-32 cm	5.82	0.02	11.16	0.00	-0.02	0.02
Core 67 32-35 cm	6.10	0.02	11.71	0.01	-0.03	0.02
Core 67 35-36 cm	5.88	0.00	11.34	0.02	-0.06	0.01
						2SD
				MEAN	-0.06	0.05

******Linearized slope = 0.5247.

Appendix B

Microspherule, CDP, and nanoparticle global influx

For particles falling through the atmosphere, fallout times are highly variable depending on particle size and atomic weight. J. Kasten [182] and Grainger et al. [183] give the velocity of various-sized particles (or see Figure 2 of Grainger et al. [184]). At an altitude of 30 km, 20- μm particles have a falling speed of 1 cm/s, or almost a kilometer a day, thus taking ~ 30 days to fall out. Micron-sized particles have a falling speed of about 0.1 mm/s at an altitude of 15 km, taking ~ 2 -3 years to reach the ground. Nanometer-sized particles could likely take many years to decades to fall out, consistent with the results of Petaev et al. [52], who reported a 20-year window of continuous YDB Pt deposition in the GISP2 ice core. For influx estimations, we assume an average fallout time of 6 months for all particles, even though the fallout time range spanned hours to years.

Microspherule influx

We infer the YDB event to have been global or near-global. This assumption is based on (i) the identification of YDB proxies at ~ 60 sites across six continents and (ii) the modeling of Rafizadeh and Vempolu [182], who calculated that during Earth's encounter with the trail of a 100-km comet, $\sim 35\%$ of fragments would be captured into Earth orbit, forming a near-spherical shell around the planet. The influx of MSp is estimated to be ~ 4.8 million tonnes, most of which is assumed to have been produced from surficial sediments during airbursts (Appendix Table B1). The latter value is

reasonably close ($\sim 2\times$ less) to the 10 million tonnes of YDB MSp estimated by Wittke et al. [43]

The hypothetical debris swarm modeled here encounters Earth at 30 km/s and consists of dust, pebbles, and boulders, as seen in the satellite infrared of the Comet Encke trail and in showers from the Taurid Complex. Fragments up to approximately 100 meters would be ablated in the mesosphere [7, 121, 124]. However, this ablated material would likely be nanoscale and go undetected in the core samples during optical microscopy or SEM analysis, and thus, CDP flux estimates are not included in this study.

A comparison can be drawn between the global estimate from the YDB based on Baffin Bay results and the current annual influx of cosmic debris. Micrometeorites collected over the years at Dome C in Antarctica indicate a yearly influx of 5200 ± 1500 metric tonnes (range: 3700-6700) [30] (Appendix Table B2). Various satellite studies support this figure, although it fluctuates over time due to encounters with meteor streams, either cometary or asteroidal in origin. The estimated flux for Baffin Bay is approximately three orders of magnitude higher than the current background flux. The most plausible explanation for such a high flux rate is that Earth encountered a dense comet stream [7, 121-124], resulting in the YDB impact event, as proposed by the YDIH.

CDP influx

Extrapolating from the influx of CDPs into four ocean cores from Baffin Bay, the global influx during ~ 6 months is estimated to be 8.8 million tons, most of which fell as micro- to nano-sized cosmic dust particles (Appendix Table B2).

Appendix Table B1: Analysis of YDB Microspherule (MSp) Influx.

Microspherules (MSp)	Value
Average diam. (μm); range 4-163 μm	64
Average # of microspherules per YDB layer	20
Average mass of 75 Baffin Bay microspherules (g)	4.24E-07
Total mass of microspherules per YDB layer (g)	8.48E-06
Surface area of samples collected (cm^2)	9
Area of Earth (cm^2)	5.10E+18
Ratio of Earth $\text{cm}^2 \div$ Baffin Bay cm^2	5.67E+17
Total mass of microspherules on Earth (g)	4.81E+12
Number of g per metric ton (g/mt)	1.0E+06
Influx of Microspherules (# mt/6 mos)	4.81E+06

This table analyzes the estimated influx of microspherules (MSp) globally using the data from Baffin Bay cores. Based on an average diameter of 64 μm and an estimated number per layer ($n = 20$) from Baffin cores, the flux of YDB microspherules is estimated to be ~ 4.8 million metric tonnes, assuming a 6-month atmospheric fallout time, potentially extending to several years for smaller MSp. This estimate represents ~ 1849 times the typical 6-month flux rate of cosmic material of all diameters to Earth, estimated at 5200 tonnes/yr [30]. These values are $\sim 6\times$ lower than, yet comparable to, predictions ranging from 400 to 30 million tonnes of cosmic dust expected from a ~ 100 -km diameter disintegrating comet in a short-period orbit [7]. The estimated mass of MSps deposited globally (~ 4.8 million metric tonnes) constitutes a minute percentage (0.0000009%) of the mass of a 100-km-wide comet. For this analysis, we assume that: 1) the comet was ~ 100 km in diameter; 2) the compositions of MSps are homogeneous with an average density of 50 wt% SiO_2 and 50 wt% Fe for mass calculations; 3) all particles entered Earth's atmosphere over 24 hours and depending upon their size and density, took about 6 months to be deposited into Baffin Bay; and 4) concentrations and mass values in Baffin Bay are representative of those across the entire planet. Justification for assumption #4 comes from Wittke et al. [43], who estimated that ~ 10 million tonnes of melted microspherules were deposited at the YDB over 50 million square kilometers on four continents, suggesting global or hemispheric deposition of YDB impact proxies. Of the MSp, only approximately 2% by weight are inferred to be cosmic in origin, with most suggested as melted target rocks from YDB airbursts and impacts. These calculations have significant uncertainties.

Nanoparticle influx

Baffin core enrichments of nanoparticles indicate that elements with higher density (Pt and Ir) are concentrated contemporaneously or immediately above the microspherules peak. Lower-density elements (Co, Cr, Cu) peak a few cm above the microspherule peak (see Figures 9 and 10). This phenomenon

is likely attributed to the prolonged settling time of nanoparticles in both the atmosphere and water column, which contrasts with the more rapid settling of denser microspherules. The estimated influx of YDB nanoparticles ranges from 6800 to 3400 tonnes, exceeding the normal daily flux rate of cosmic material by >200–400 times (Appendix Table B3).

Appendix Table B2: Analysis of YDB Cosmic Dust particle (MDP) influx.

Cosmic dust particles (MDPs)	Value
Average diam. (μm); range 5–100 μm	30
Average # of particles per YDB layer (#)	30
Average mass of 24 Baffin particles, MDPs (g)	5.2E–07
Total mass of particles per YDB layer (g)	1.5547E–05
Surface area of samples collected (cm^2)	9
Area of Earth (cm^2)	5.10E+18
Total mass of particles on Earth (g)	8.81E+12
Number of g per metric ton (g/mt)	1.0E+06
Influx of Cosmic Dust Particles (mt/6 mos)	8.81E+06
Estimated annual influx of cosmic dust	5200
Estimated influx of cosmic dust (mt/6 mos)	2600
Ratio of YDB flux $\div$ Earth flux	3390
Comet mass, 100-km (mt)	5.2E+14
Ratio of YDB mass to the comet (g)	1.68E–08
Percent of 100-km comet	1.68E–06
Percent of 100-km comet	0.000002

The table analyzes the estimated influx of CDPs globally based on data from Baffin Bay cores. Based on an average diameter of 30 μm and an estimated number per layer ($n = 30$) from Baffin cores, the global flux of CDPs is ~ 8.8 million metric tons, assuming a 6-month atmospheric fallout time, potentially extending to several years for smaller CDPs. This estimate represents ~ 3390 times the typical 6-month flux rate of cosmic material to Earth, estimated at 5200 tons/yr [30]. These values are $\sim 3\times$ lower than, but still comparable to predictions ranging from 400 to 30 million tons of cometary dust expected in the trail of a 100-km diameter disintegrating comet in a short-period orbit [7]. For this analysis, we assume that 1) all particles were homogeneous with an average density of Fe; 2) all particles were introduced to Earth's atmosphere during 24 hours but most likely took 6 months to be deposited into Baffin Bay; 3) concentrations and mass values in Baffin Bay are representative of the entire planet and; 4) the diameter of the YDB comet was a 100 km. Justification for assumption #3 comes from Wittke et al. [43], who estimated ~ 10 million tons of melted microspherules were deposited at the YDB over 50 million square kilometers on four continents, suggesting global, near-global, or hemispheric deposition of YDB impact proxies, including CDPs. These calculations are estimations with large, inherent uncertainties.

Appendix Table B3: Analysis of YDB nanoparticle Influx.

Nanoparticles, description	Value	Value
Average excess mass of Baffin Bay nanoparticles (g)	2.4e–10	1.2e–10
Average number of nanoparticles per YDB layer	2.10e+11	2.10e+11
Surface area of samples collected (cm^2)	9	9
Flux of nanoparticles for one hemisphere (mt/day)	6800	3400
Estimated annual influx of cosmic dust (mt/yr)	5200	5200
Estimated daily influx of cosmic dust (mt/day)	14.25	14.25
Ratio of Baffin Bay nanoparticle flux $\div$ Earth flux	477	239

We calculated the mass of YDB NPs that exceed background concentrations. The estimated flux of YDB nanoparticles ranges from 6800 to 3400 tonnes within 24 hours, representing >200–400 times the normal daily flux rate of all cosmic material, estimated at 5200 tonnes/yr [30]. For this analysis, we made the following simplistic assumptions: 1) the nanoparticles are homogeneous, 2) all nanoparticles were introduced to Earth's atmosphere over a duration of 24 hours but probably took considerably longer to fall out into Baffin Bay, and 3) concentrations and mass values in Baffin Bay are representative of the entire planet. These calculations have large uncertainties but serve as a useful model to understand the potential flux of cosmic material to Earth at the YD onset.