

Stratigraphic separation of Laacher See Tephra and a discrete Younger Dryas Boundary fallout layer in southernmost Sweden

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ABSTRACT

The temporal relationship between the Laacher See eruption (LSE), the Younger Dryas Boundary (YDB) layer, and the abrupt onset of Younger Dryas (YD) climate change has long been debated. The Körslättamossen fen in southernmost Sweden provides the first robustly dated Scandinavian record demonstrating that these events are clearly separated stratigraphically and temporally. The Laacher See Tephra (LST) layer at 288.5 cm (~13,006 cal BP) lies 6–10 cm below a discrete PGE-rich horizon (282–279 cm) marking YDB deposition, interpreted here as a 3-cm-thick impact fallout layer. This interval has an onset Bayesian-modeled age of 12,861 ± 54 cal BP, ~150 years after the eruption, indicating that the LST and YDB deposition represent separate events. Within this fallout layer, Fe–Si microspherules with dendritic quench textures peak at 282–281 cm, while maximum PGE-bearing nanoparticle mass occurs at 280–279 cm, consistent with delayed settling of submicron particles. LA-ICP-MS reveals Si-rich microspherules containing PGE-bearing microdomains but negligible Ni, Co, and Cr. These compositions indicate that the microspherules are dominated by terrestrial target material rather than meteoritic metal, while the associated PGE-rich microdomains and nanoparticle populations record a minor but detectable extraterrestrial component. Single-particle ICP-TOF-MS detects a sharp Pt anomaly with Pt-dominant elemental ratios (e.g., high Pt relative to Fe and Ir), consistent with the platinum enrichment reported in the YDB in the GISP2 ice core. Immediately above the fallout layer, a dark, organic-rich horizon records the abrupt hydroclimatic shift to cooler, wetter YD conditions. These observations document three stratigraphically distinct horizons: the LSE, a separate YDB fallout layer, and the near-synchronous onset of YD climate change, providing a well-constrained European stratigraphic framework for evaluating mechanisms proposed for the YD onset.

INTRODUCTION

Younger Dryas climate transition and proposed mechanisms

The Younger Dryas (YD) represents one of the most abrupt climatic reversals of the Late Quaternary. During the Late Glacial period, the Northern Hemisphere experienced a sequence of rapid climatic oscillations. Following the Last Glacial Maximum, temperatures rose sharply during the Bølling-Allerød interstadial (~14.7–12.9 ka), a relatively warm interval characterized by widespread deglaciation and ecological expansion across much of the Northern Hemisphere [1,2]. This warming was followed by the YD climate interval, a return to near-glacial conditions lasting until ~11.7 ka and recorded in numerous terrestrial, marine, and ice-core sequences worldwide [3,4]. The onset of this cooling episode, commonly referred to as the Younger Dryas Boundary (YDB), corresponds to the transition from the Bølling-Allerød interstadial to the YD stadial.

Beginning ~12.8 ka, the YD cooling coincided with widespread environmental and ecological changes, including some megafaunal extinctions and cultural transitions [5–10]. Several competing mechanisms have been proposed to explain the onset of this abrupt climatic reversal. One explanation attributes the cooling to disruption of Atlantic meridional overturning circulation (AMOC) caused by meltwater discharge and rerouting associated with deglaciation of the Laurentide Ice Sheet [5,7]. Another proposed mechanism involves volcanic forcing, most notably the Laacher See eruption (LSE) in western Germany (~13 ka), which released large quantities of sulfur aerosols capable of producing short-term climatic cooling [11,12], although its ability to trigger YD climate change remains debated [13]. A third explanation is the Younger Dryas Impact Hypothesis (YDIH), which proposes that a cosmic impact or series of atmospheric airbursts generated widespread biomass burning and a short-lived “impact winter.” This event may have caused meltwater flooding and iceberg calving resulting from the destabilization of portions of the Laurentide Ice Sheet, thereby weakening AMOC and contributing to climatic change at the YD onset [14].

Support cited for the YDIH includes reports of peaks in a range of putative impact proxies at the YDB. These proxies include magnetic microspherules, enrichments in platinum and iridium, high-temperature meltglass, nanodiamonds, combustion products such as aerosols and soot, and shocked quartz, reported from numerous sites worldwide [14–32]. These signals have been reported from YDB-age deposits across North America, central Mexico, South America, South Africa, Europe, Greenland, the Middle East, and in a variety of sedimentary and ice archives [14,33,34], although their interpretation remains debated in some cases.

Laacher See eruption and chronological context

The Laacher See Tephra (LST) originates from the explosive eruption in the East Eifel Volcanic Field of western Germany dated to approximately 13,000 calibrated years BP [12].

Correlations between proximal and distal deposits have identified multiple eruptive phases, each with distinct glass chemistries: Lower Laacher See Tephra (LLST), Middle Laacher See Tephra (MLST), and Upper Laacher See Tephra (ULST), whose ash plumes dispersed along different trajectories [35–37]. At the northeastern fringe of dispersal, Körslättamossen in southernmost Sweden contains a high concentration of LST cryptotephra ($>65,000$ shards cm^{-3}) preserved in calcareous gyttja. This extends the known dispersal fan and provides a robust regional isochron even where attribution to specific eruptive phases within the MLST-ULST field remains uncertain [38].

Whether the LSE triggered the YD climatic episode or merely preceded it remains debated. Although the LSE was one of the largest Late Quaternary eruptions in Europe and dispersed tephra across much of northern and central Europe, the climatic significance of the eruption remains debated because other large Holocene and Late Pleistocene eruptions produced only transient cooling effects lasting years to decades rather than a millennium-scale climatic reversal [12,39,40]. Baldini et al. [13] aligned a prominent GISP2 sulfate spike at ~12.87 ka (Greenland Ice Core Chronology 2005, GICC05) with the LSE and the onset of Greenland Stadial 1 (GS-1) and suggested that volcanic aerosol forcing might have contributed to feedbacks involving sea ice and AMOC at the YD onset.

In contrast, high-precision dendrochronology and radiocarbon wiggle-matching of subfossil trees buried by the eruption have yielded an LSE age of $13,006 \pm 9$ cal BP [12], which is adopted here as the chronological age for the LST. This revised age has been used to anchor European lake varve chronologies and places the YD onset at $12,807 \pm 12$ cal BP, approximately two centuries after the eruption [12]. An independent German speleothem sulfur spike dated by $^{230}\text{Th}/\text{U}$ ($13,008 \pm 8$ BP) and statistically matched to a Greenland sulfate event likewise suggests that the LSE predates the YD by ~150–200 years [41]. Consistent with this phasing, a high-resolution lake record from Stará Jímka in the Bohemian Forest (Czech Republic) contains an LST horizon followed stratigraphically by a distinct microspherule layer interpreted by those authors as the YDB, dated to $12,755 \pm 92$ cal BP [42]. Complementary decadal-resolution chronologies from Lake Hämelsee in Germany place the initial ecosystem response at 12,820 cal yr BP and demonstrate regional synchronicity within decadal uncertainty. These findings highlight the value of LST-anchored terrestrial records for testing sub-centennial phasing among proposed triggers [43].

Together, these archives support interpreting the LSE primarily as a first-order chronostratigraphic marker that predates the YD and is therefore difficult to reconcile with hypotheses that require a near-synchronous volcanic trigger, although possible climatic effects of the eruption remain debated [12,41,43]. Although the presence of LST at Körslättamossen demonstrates that eruption products were dispersed across much of northern Europe, widespread tephra deposition alone does not establish that the eruption caused the YD climatic transition. Instead,

evaluating such a relationship requires independent chronological evidence demonstrating temporal coincidence between volcanic fallout and the onset of environmental change.

Study objectives

Here, we test these alternative explanations for the YDB and LST using a new sediment core from Körslättamossen (KSM 23-5) in southernmost Sweden, where the LST layer was previously identified. Our objectives are to (a) determine whether a YDB microspherule and geochemical anomaly, similar to those reported at other YDB sites, occurs within the Körslättamossen sequence, and (b) establish its chronostratigraphic relationship to the previously documented LST horizon at the site [38], thereby evaluating whether potential YDB proxy signals post-date the LSE locally in southern Scandinavia.

To achieve these goals, we conducted sediment analyses and optical microscopy to identify and quantify the abundance and stratigraphic position of Fe- and Si-rich microspherules and cryptotephra. In addition, we examined sediments for anomalous nanoparticle abundances using single-particle inductively coupled plasma time-of-flight mass spectrometry (SP-ICP-TOF-MS). This analysis revealed a YDB-age nanoparticle peak enriched in several platinum-group and siderophile elements, including platinum (Pt), iridium (Ir), osmium (Os), and palladium (Pd), accompanied by increases in nanoparticle elemental mass ratios such as Pt/Fe, Ir/Fe, Os/Fe, and Pd/Fe.

These observations allow us to evaluate the stratigraphic relationship between the YDB proxy layer and the LSE in southern Scandinavia.

STUDY SITE

The Körslättamossen (KSM) fen is on the Söderåsen horst (a raised crustal block uplifted between parallel faults) in north-west Scania, southernmost Sweden (~740 km NE of Laacher See) (Figure 1). The fen occupies a bedrock depression that once held a small lake. Today, it is partly pasture and mixed spruce-pine-birch forest, a land-use conversion achieved following ditch construction in the eastern half of the fen. Sediment coring was conducted in the eastern part of the original extent of the peatland at 56°05′32.8″ N, 13°03′50.0″ E [38,44]. The site lies ~118 m a.s.l., about 70 m above the local marine limit, in terrain deglaciated after ~17,000 cal BP, and drains a catchment of ~7.5 km². Beneath ~1.4 m of peat, Late Glacial to early Holocene lacustrine deposits include alternating units of silty clay gyttja and calcareous gyttja with shell fragments. This well-stratified, sealed minerogenic-calcareous sequence provides an excellent archive for cryptotephra and paleoenvironmental analyses [45].

Previous work at Körslättamossen documented multiple tephra layers corresponding to the Hässeldalen Tephra (~11.3 ka), Vedde Ash (~12.0 ka), and Laacher See Tephra (~13.0 ka) [38,44,45].

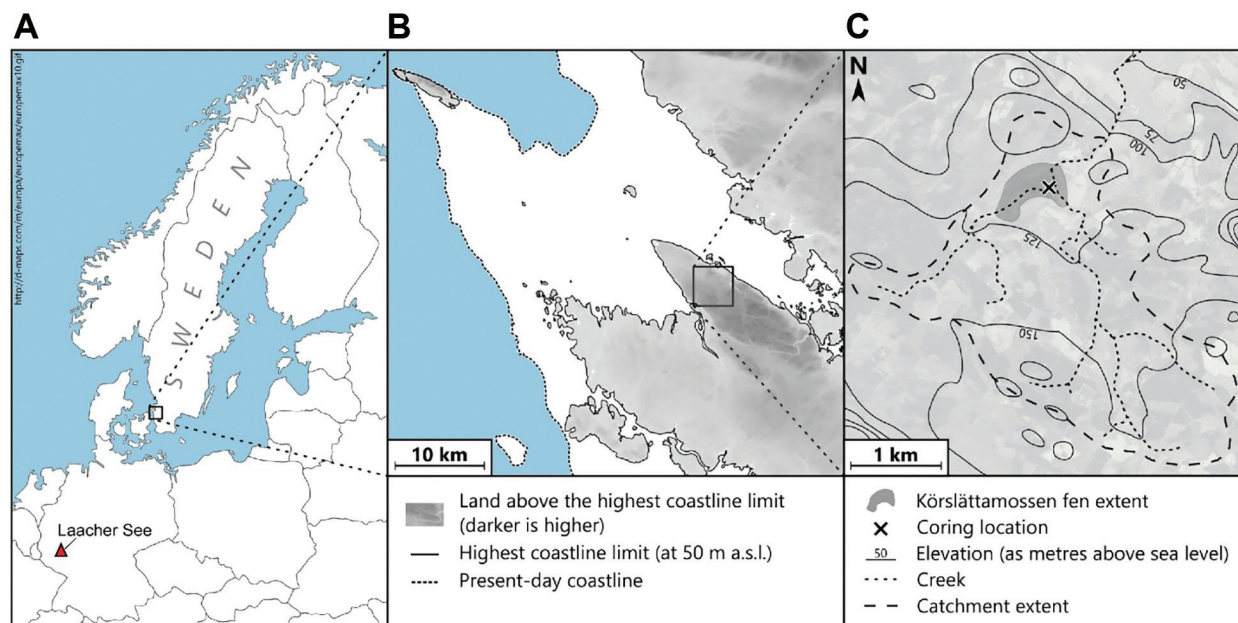


Figure 1. Location of Körslättamossen fen (56°05′33″N, 13°03′50″E), north-west Scania, southernmost Sweden. (A) Northern Europe overview with site position and the location of Laacher See. (B) Regional map of Scania showing land above the highest coastline limit (50 m a.s.l.; darker shading = higher ground) and the present coastline; blue = ocean; the box marks panel (C). (C) Local setting with fen extent (grey), coring location (x), catchment boundary (dashed), creeks (dotted), and elevation contours (m a.s.l.). Scale bars: 10 km (B) and 1 km (C); north arrow in (C). Base map for (A) from d-maps.com (<http://d-maps.com/m/europa/europemax/europemax10.gif>); regional and local base layers for (B, C) derived from Lantmäteriet and the Geological Survey of Sweden (SGU); symbology and annotations by the authors. Figure reused under CC-BY license from Larsson and Wastegård (2022) [44].

Lithostratigraphy

The KSM 23-5 core preserves a well-resolved Allerød-YD sedimentary succession that matches the previously established Körslättamossen lithostratigraphy of Larsson & Wastegård [38], with the depths of unit boundaries adjusted to the local sediment surface. The lowermost part of core KSM 23-5 (below ~303 cm) corresponds to Unit 6d from the earlier study core, consisting of calcareous gyttja, yellowish-brownish gray, faintly laminated, containing scattered shell fragments that become more common toward the upper contact.

This interval is overlain by Unit 6e (~303–297 cm), a slightly laminated clay-rich gyttja containing dispersed detrital grains and reduced carbonate content. This unit represents a subtle shift in sediment composition that has previously been interpreted as reflecting a minor cooling event temporally corresponding to the GI-1b event in the Greenland ice-core records [45].

Above this, Unit 6f (~297–277 cm) consists of faintly laminated calcareous gyttja similar to Unit 6d but containing more abundant shell fragments. It is interpreted to represent renewed carbonate-rich lacustrine deposition during the latter, warmer phase of the Allerød interstadial.

The upper part of the core contains the lower portion of Unit 7a (above 277 cm) which consists of increasingly dark brown, highly humified silty gyttja. These sediments exhibit a marked reduction in carbonate content together with increased accumulation and preservation of organic matter and evidence of enhanced leaching. The sequence of Units 6e, 6f, and 7a thus defines a clear stratigraphic succession from the late Allerød to the YD in core KSM 23-5, consistent with previously published Körslättamossen lithology [38,44].

METHODS

Coring and sample collection

Coring was conducted using a 7 cm-diameter, 70 cm-long peat corer similar to the design presented by Jowsey (1966) [46]. The sampling location used in previous work at the study site was revisited to collect cores with lithostratigraphy as similar as possible, thereby facilitating correlation and comparison with earlier results.

Tephra analysis

Tephra isolation followed Turney (1998) [47] with minor modifications: (i) samples were ashed at 550 °C for 3 h; (ii) residues were treated overnight in 10% HCl to dissolve carbonates; (iii) the remaining sediment was wet-sieved to retain 25–100 µm particles; and (iv) heavy-liquid separation was performed using sodium polytungstate (2.3–2.5 g cm⁻³). *Lycopodium* spore tablets were added to the purified fractions, which were mounted with Canada balsam and examined microscopically for glass shards, estimating shard concentrations by comparison to counts of *Lycopodium* spores. Sampling was conducted at 1-cm resolution across a 12-cm interval targeted using prior LST stratigraphic constraints [38].

Radiocarbon dating and Bayesian age-depth modeling

Radiocarbon measurements were obtained on bulk sediment and plant macrofossil material using accelerator mass spectrometry (AMS). Bulk samples consisted primarily of organic-rich gyttja and reed fragments collected from discrete depth intervals within the KSM 23-5 core. Samples were pretreated using standard acid-base-acid (ABA) procedures to remove carbonates and secondary humic acids prior to graphitization. Radiocarbon analyses were conducted at the University of Georgia Center for Applied Isotope Studies (UGAMS) and the Ångström Laboratory of Uppsala University, Sweden (Ua). Radiocarbon ages are reported as conventional ¹⁴C years BP with one-sigma analytical uncertainties.

Conventional radiocarbon ages were calibrated using the IntCal20 calibration curve within OxCal v4.4.4 [48,49]. Bayesian age-depth modeling was implemented using the P_Sequence model in OxCal to incorporate the known stratigraphic ordering of dated horizons. Each date was evaluated using the OxCal Agreement Index, where values above 60% indicate acceptable agreement between the data and the model. Dates failing the chi-squared agreement test were evaluated as potential outliers and excluded from the final model where appropriate. The complete OxCal code and modeling outputs are provided in the Supporting Information (“Bayesian code”).

Because the Körslättamossen sediments are derived from carbonate-influenced lacustrine deposits, bulk radiocarbon ages may incorporate a freshwater reservoir effect caused by the input of ¹⁴C-depleted dissolved inorganic carbon from groundwater and carbonate bedrock. To account for this effect, a site-specific reservoir correction was applied prior to calibration. The magnitude of the reservoir offset (ΔR) was estimated by comparison with an independently dated terrestrial macrofossil horizon from a nearby core from a previous study (Ua-66224), which yielded an age of 10,959 ± 70 ¹⁴C yr and is unaffected by hard-water inputs [44]. Reservoir offsets for bulk sediment samples were calculated as the difference between measured bulk-sediment radiocarbon ages and this terrestrial reference horizon. The resulting offsets were combined using inverse-variance weighting to derive a site-specific correction of ΔR = 800 ± 32 ¹⁴C yr. This correction was applied to the bulk radiocarbon determinations prior to calibration within the Bayesian age-depth model. This correction assumes that the freshwater reservoir offset remained approximately constant throughout the modeled interval spanning the late Allerød and earliest YD. Although temporal variability in reservoir effects cannot be completely excluded, the agreement between the corrected radiocarbon ages, the independently dated LST horizon, and the terrestrial macrofossil age suggests that reservoir offsets remained similar across this interval and large changes in ΔR did not occur.

All measured radiocarbon determinations, including both original uncorrected ages and reservoir-corrected values, are provided in Supporting Information, Table S1. Stratigraphic correlation between the KSM 23-5 core and previously

published Körslättamossen cores was established using lithologic markers and the independently identified LST horizon.

Bulk geochemistry

Bulk elemental concentrations were measured by Activation Laboratories (Actlabs, Ontario, Canada) using the Ultratrace 6™ ICP-MS package. Approximately 0.5 g of homogenized sediment was digested using a four-acid near-total dissolution ($\text{HF-HClO}_4\text{-HNO}_3\text{-HCl}$). Solutions were analyzed for 56 major, trace, and platinum-group elements using multi-element calibration standards with drift correction. Precision generally exceeds $\pm 5\%$ Relative Standard Deviation (RSD) for trace elements and $\pm 10\%$ for ultra-trace metals. Quality control included blanks, duplicates, and certified reference materials (OREAS, USGS, CANMET). Additional analytical details and full procedures are provided in the Supporting Information (“Detailed Methods”).

Microspherule extraction, counting, and confirmation

Sediments were ultrasonicated in sodium metaphosphate, wet-sieved at 20 μm , dried, and separated into $\geq 63\text{--}<125\text{ }\mu\text{m}$ and $\geq 20\text{--}<63\text{ }\mu\text{m}$ fractions. A bagged NdFeB magnet (three passes) was used to extract magnetic grains and Fe-rich microspherules. Non-magnetic fractions were also examined for glassy spherules. All candidates were mounted on carbon tape and confirmed by SEM-EDS following [15]. Counts were normalized to microspherules kg^{-1} .

Electron microscopy and microanalysis (SEM/EDS)

SEM imaging and qualitative EDS were conducted at Elizabeth City State University (NC) and the University of Utah following standard protocols. Instrument settings, calibration procedures, and analytical uncertainties are reported in the Supporting Information.

Single-particle ICP-TOF-MS (SP-ICP-TOF-MS)

Particle preparation. Approximately 100 mg of sediment was dispersed in ultrapure water, vortexed, ultrasonicated, allowed to settle for 24 h, and the upper suspension decanted. Suspensions were diluted 1:5000 immediately before analysis. Instrumentation and calibration. Analyses were performed using a TOFWERK SP-ICP-TOF-MS system with a MicroMist nebulizer and quartz cyclonic spray chamber [50–52]. Calibration used multi-element standards ($0\text{--}10\text{ }\mu\text{g L}^{-1}$) and NIST RM 8013 Au nanoparticles following the known-size method [53]. A 4.5% H_2/He collision gas enhanced Fe and Si sensitivity. Data were processed in TOFPilot v2.11.3 using Poisson thresholding [54]. Samples and blanks were run in triplicate.

Laser ablation ICP-MS

Microspherules were analyzed at the University of South Carolina using a Photon Machines 193 nm excimer laser (HELIX-2 cell) coupled to a Thermo Element 2 HR-ICP-MS.

Ablation used 40–50 μm beam spots at 8 Hz. Monitored masses followed [55]. Metal-rich spherules were normalized to ^{57}Fe using an assumed Fe concentration of 99 wt%, following the approach of Frisby [55] and Humayun [56]. Spectra were manually reduced following these methods.

Data and code availability

All raw and processed datasets, SEM images, SP-ICP-TOF-MS and LA-ICP-MS outputs, and OxCal modeling files are provided in the Supporting Information and the linked data repository.

RESULTS AND INTERPRETATION

Results are presented by analytical method, and interpretations are integrated in the Discussion.

Bayesian age modeling of the Younger Dryas Boundary sequence

Radiocarbon dates from the Körslättamossen (KSM 23-5) sequence are anomalously old relative to independent stratigraphic controls, indicating a substantial freshwater (“hard-water”) reservoir effect. Reservoir offsets of several hundred to more than 1000 ^{14}C years are widely documented in Scandinavian lakes and fens, including sites in both northern and southern Sweden where bulk sediment ages require correction using terrestrial macrofossil controls [57–59]. The ages observed in the Körslättamossen sequence are consistent with a substantial freshwater reservoir effect.

To quantify the reservoir effect, two independent chronological markers were used. The first is a radiocarbon age on a terrestrial leaf fragment from a nearby core (Ua-66224); the date is unaffected by hardwater inputs and dated to $10,959 \pm 70\text{ }^{14}\text{C yr}$ [44]. Correlation between the leaf-dated core and KSM 23-5 is based on distinctive lithologic markers, including the transition from calcareous gyttja to darker organic-rich sediments and the position of the LST. Minor depth differences among cores may occur because of sediment compaction or coring offsets, but these correspond to age differences smaller than the analytical and modeling uncertainties. The terrestrial leaf horizon thus serves as a reliable independent reference point for estimating the local freshwater reservoir offset.

A second independent marker is the LST, a precisely dated volcanic horizon identified at 288.5 cm with an eruption age of $13,006 \pm 9\text{ cal BP}$ [12]. The terrestrial leaf date was incorporated as a radiocarbon constraint, and the LST was included as an independent calendar-age tie-point within the Bayesian age–depth model. These constraints provide chronological control based on external stratigraphic markers but do not impose any assumptions regarding the timing of the YDB. No constraints were applied to the position or age of the microspherule or nanoparticle horizons, allowing their modeled ages to be determined independently from the radiocarbon data and stratigraphic ordering.

Of the eight measured radiocarbon determinations, seven required evaluation for reservoir influence. One age

(UGAMS-76085; 7990 ± 35 ^{14}C yr) was identified as a clear outlier and excluded (Supporting Information, Table S1). For the remaining six dates, the reservoir offset (ΔR) was calculated by subtracting the terrestrial leaf age (10,959 ^{14}C yr) from each bulk-sediment age, with uncertainties propagated using the ± 70 yr uncertainty of the leaf horizon. The inverse-variance-weighted mean yields a site-specific reservoir correction of $\Delta R = 800 \pm 32$ ^{14}C yr, indicating a substantial positive freshwater reservoir effect consistent with lacustrine offsets reported elsewhere in Scandinavia [57–59]. The terrestrial leaf was selected because it is stratigraphically adjacent to several bulk-sediment radiocarbon determinations and the spherule layer (discussed below), thereby minimizing assumptions regarding temporal variability in the freshwater reservoir effect. In contrast, the independently dated LST occurs substantially lower in the sequence, below both the spherule layer and nearly all radiocarbon determinations, and was therefore incorporated as an independent external chronological constraint in the reservoir-corrected age-depth model rather than being used to estimate ΔR . This approach assumes that the reservoir offset remained approximately constant over the modeled interval; the calculated correction lies within the range of freshwater reservoir offsets reported elsewhere in the region [57–59]. All measured radiocarbon determinations, including original and reservoir-corrected values, are provided in Supporting Information, Table S1.

Applying this reservoir correction ($\Delta R = 800 \pm 32$ ^{14}C yr) reduces the offset between bulk-sediment radiocarbon ages and independent stratigraphic markers such as the LST. After correction and calibration using the IntCal20 curve in OxCal v4.4.4 [49], modeled ages place the microspherule and nanoparticle peaks within the Greenland ice-sheet-anchored window for the YD onset and the established continental YDB interval (12,875–12,775 cal BP; updated with IntCal20) [60]. The correction improves the agreement between calibrated ages and depositional timing across the YD onset transition (Figure 2; Supporting Information, Tables S1 and S6; “Bayesian code”).

Interpretation

At Körslättamossen, the LST peak occurs at 288.5 cm and is dated to $13,006 \pm 9$ cal BP. Approximately 6–10 cm above the LST lies the YDB fallout interval (282–279 cm) with a spherule peak between 281–282 cm, whose midpoint at 281.5 cm yields a Bayesian-modeled age of $12,861 \pm 54$ cal BP. Using the Reinig et al. [12] LSE chronology, the modeled ages indicate a ~ 150 -year separation between the volcanic horizon and the YDB proxy horizon.

Within the YDB interval, peaks in extraterrestrial (ET)-related nanoparticles, Fe-Si microspherules, and high-temperature melt products are restricted to 282–279 cm and align with the modeled YDB age rather than the LST. This depth-age agreement demonstrates that the geochemical anomalies are stratigraphically and chronologically distinct from the LSE. The core sediments between ~ 286 and ~ 282 cm contain no

microspherules and only a trace amount of glass shards above the LST peak (289–288 cm) and none above 287 cm, further confirming that the volcanogenic layer is isolated from the microspherule horizon.

The stratigraphic position of the Swedish PGE-rich nanoparticles and microspherules falls within the YDB interval reported at other Northern Hemisphere sites. This correspondence is consistent with interpretations proposed under the Younger Dryas Impact Hypothesis (YDIH) that invoke a widespread influx of extraterrestrial material near ~ 12.8 ka cal BP [14,24,25,34,60–63].

These results provide robust stratigraphic and chronological evidence that the depositional pulse recorded at Körslättamossen fen was abrupt and temporally coincident with similar events at other YDB sites documented on multiple continents [14,16,27,64]. The integration of a locally derived reservoir correction with Bayesian modeling enhances chronological resolution and strengthens correlations among European lake and fen sequences and other continental records. The temporal precision achieved here is consistent with the interpretation that the YDB event represents a discrete influx of cosmic material temporally coincident with the onset of the YD cooling episode, further supporting the hypothesis proposing a large-scale climatic perturbation associated with the YDB event [16,23,60].

The YDB fallout interval spans approximately 3 cm of sediment (282–279 cm). Based on the Bayesian age model, this thickness could represent several decades of normal sediment accumulation, although the highly localized concentration of microspherules and PGE-rich nanoparticles suggest deposition was dominated by a short-duration input rather than prolonged background sedimentation. No evidence of extensive bioturbation, burrowing, root penetration, or sediment homogenization was observed within this interval, and the sharp confinement of both microspherule and nanoparticle enrichments argues against substantial post-depositional mixing. The slight stratigraphic offset between peak microspherule abundance (282–281 cm) and maximum PGE-rich nanoparticle concentrations (280–279 cm) is consistent with differential settling of larger melt droplets and finer vapor-condensed particles. Consequently, the 3-cm thickness is interpreted as recording an initial pulse of impact-generated melt products followed by continued atmospheric deposition of PGE-rich nanoparticle condensates over a longer interval of several decades, with only limited sediment reworking during subsequent accumulation.

Discrete microspherule and Tephra horizons in core KSM 23-5

An analysis of continuous sediment samples (1-cm resolution) from core KSM 23-5 has revealed an extremely large and stratigraphically-isolated Fe- and Al_2O_3 -rich microspherule abundance peak within a 3-cm interval (282–279 cm) (Figures 3 and 4 and Supporting Information, Table S5). The most prominent peak in microspherules occurs in the 281–282 cm sample (~ 72 k spherules/kg). This microspherule anomaly begins ~ 2 cm

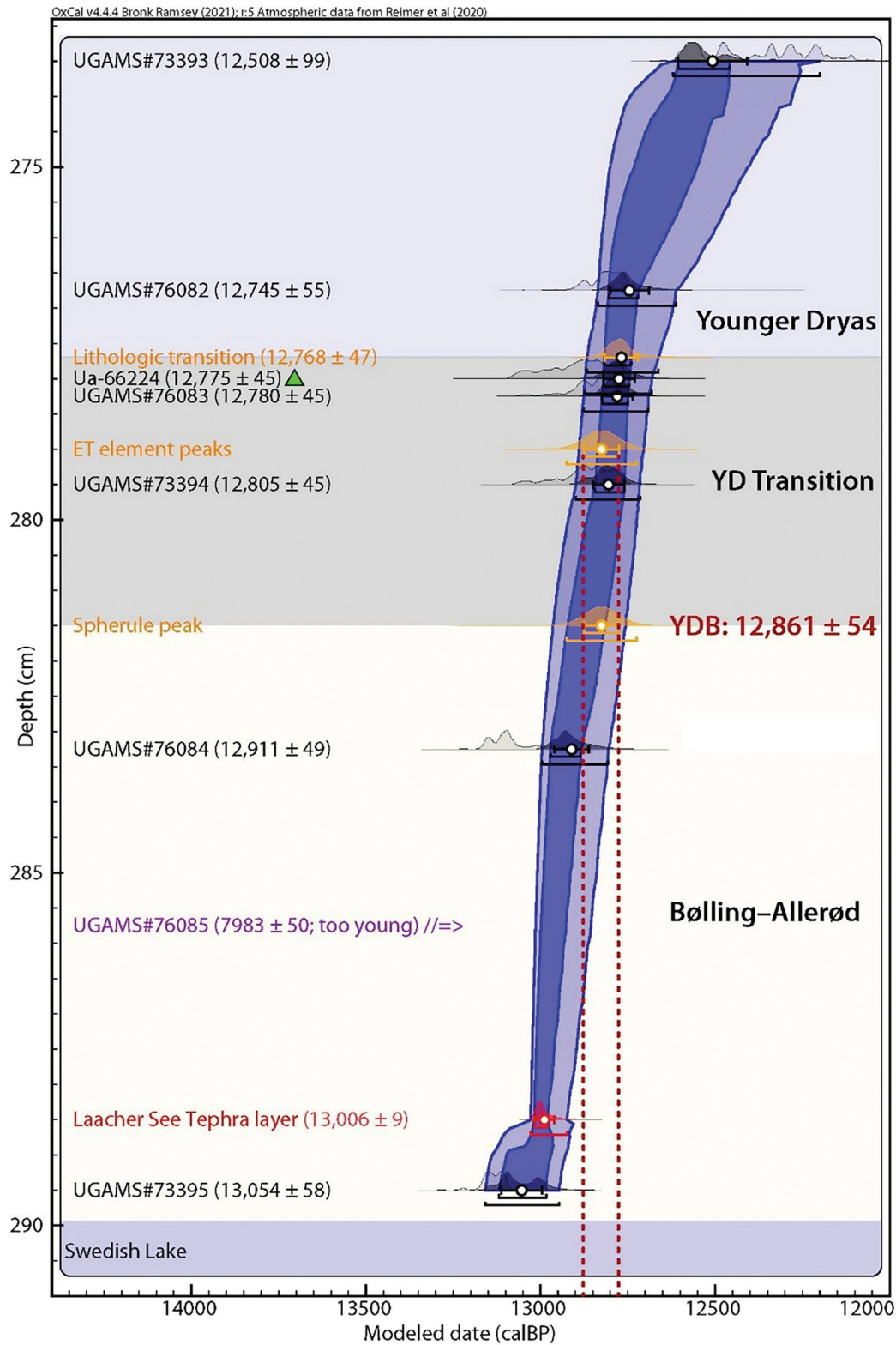


Figure 2. Bayesian age-depth model for the Younger Dryas Boundary sequence at K rsl ttamossen, southernmost Sweden. Figure modeled in OxCal v4.4.4 using IntCal20 with a reservoir correction of 800 ± 32 ^{14}C years. The model integrates multiple calibrated radiocarbon ages (UGAMS and Ua laboratories) spanning the late B lling-Aller d to early Younger Dryas. The Laacher See Tephra (red band) is included as a calendar-age tie-point at $13,006 \pm 9$ cal BP [12], providing an independent stratigraphic anchor. A green triangle marks the terrestrial leaf macrofossil age ($10,959 \pm 70$ ^{14}C yr; $12,891 \pm 87$ cal BP; $12,775 \pm 45$ Bayesian modeled age; Ua-66224) from a nearby correlated core, which occurs just below the lithologic transition and is used to constrain the freshwater

reservoir correction. The Younger Dryas Boundary (YDB; orange band) is defined by coincident peaks in spherule concentrations, with a modeled onset at $12,861 \pm 54$ cal BP and a peak in extraterrestrial element concentrations. The modeled age range encompassing the 3-cm-thick spherule layer (282–279 cm) spans 12,975–12,704 cal BP at 95.4% probability. The basal spherule peak at 281.5 cm has a Bayesian-modeled mean age of $12,861 \pm 54$ cal BP, consistent with the age range reported for the YDB proxy layer at many previously studied sites (12,875–12,775 cal BP; updated with IntCal20) [60]. See Supporting Information Tables S1 and S6 and “Bayesian code.”

below the lithologic transition between units 6f and 7a in the core, previously interpreted as representing the YD onset (see Larsson and Wastegård [38,44]).

In addition to the YDB microspherule peak, the LST occurs at 289–288 cm below surface (~ 288.5 cm), approximately 6–7 cm below the microspherule maximum (Figure 3). The LST horizon has previously been verified in Körslättamossen cores using electron-probe microanalysis (EPMA) and comparison of shard compositions with published datasets from proximal and distal LST deposits [38]. In this study, the LST is recognized by abundant vesicular phonolitic glass shards visible under transmitted light. These highly “bubbly” fragments are distinctive among Scandinavian tephras, which are otherwise Icelandic in origin and lack this vesicular morphology [65]. Optical microscopy examination of the LST layer revealed no microspherules.

Extraterrestrial nanoparticle concentrations

SP-ICP-TOF-MS measurements reveal pronounced enrichments in multiple highly siderophile and chalcophile elements within the YDB layer at Körslättamossen (Figure 5). This analytical approach provides simultaneous multi-element identification of individual nanoparticles, allowing semi-quantitative determination of elemental mass fluxes with nanogram-scale sensitivity.

Interpretation

Nanoparticle mass concentrations for all 12 analyzed elements show a sharp, coeval enrichment within the YDB layer (orange band in Figure 5), distinctly above the LST horizon and at the onset of lithologic change marking the early YD. These enrichments exceed typical crustal background levels and are not readily explained by volcanic or authigenic processes, particularly given the absence of correlated Ti–V–REE enrichments or volcanic glass components.

The magnitude and narrow stratigraphic confinement of these enrichments indicate a brief influx of material consistent with deposition from a high-temperature atmospheric event involving PGE-rich condensates. The association of these nanoparticles with Si- and Fe-rich spherules, nanodiamonds, carbon spherules, and meltglass reported from other YDB sites [14,16,27,34,66] supports this interpretation. No comparable abundance peaks occur in the underlying LST (blue band), indicating that the anomaly is not related to this volcanic horizon.

Extraterrestrial nanoparticle ratio profiles

Depth-resolved elemental mass ratios of platinum-group and transition-metal elements (Pt, Ir, Os, Pd, Ni, Co, Au, Cr,

Fe) in $<1 \mu\text{m}$ nanoparticles vary systematically across the Körslättamossen sediment sequence (Figure 6). The ratio profiles span the late Allerød to early YD interval, including the LST ($13,006 \pm 9$ cal BP), the overlying YDB horizon ($12,861 \pm 54$ cal BP), and the early YD. Multiple elemental ratios, including Pt/Fe, Ir/Fe, Os/Fe, Pd/Fe, and Au/Fe, display clear localized increases within the ~ 282 – 279 cm interval corresponding to the YDB microspherule layer. These elevated ratios are confined to a narrow centimeter-scale zone and form peaks well above background levels.

Interpretation

The LST interval shows measurable, element-specific fluctuations (e.g., Pt/Fe, Pd/Fe, Ni/Fe, and Co/Fe), but these variations are not consistently coordinated across multiple highly siderophile elements. In contrast, the YDB interval displays clear increases in several ratios, including Pt/Fe, Ir/Fe, Os/Fe, and Pd/Fe, within a narrow stratigraphic interval. This pattern, together with the presence of Fe–Si microspherules, indicates a distinct depositional process, whereas the LST fluctuations likely reflect the heterogeneous composition of volcanic glass shards and associated detrital inputs.

The nanoparticle total-mass ratios (Pt/Fe, Ir/Fe, Ni/Fe, Co/Fe, Os/Fe, Pd/Fe, Au/Cr, and Au/Fe) define two geochemically distinct horizons within the 303–268 cm interval at Körslättamossen: (1) a zone of element-specific fluctuations between ~ 291 – 288 cm within the LST interval, and (2) a multi-element enrichment centered at ~ 279 – 282 cm corresponding to the upper part of the YDB microspherule layer.

Within the YDB interval, multiple PGE-related ratios increase together. Pt/Fe and Ir/Fe (Panels A–B) show the strongest enrichments, while Os/Fe and Pd/Fe (Panels E–F) also peak within this interval. Au/Fe and Au/Cr (Panels G–H) increase in parallel, consistent with high-temperature fractionation of Au and PGEs during condensation of an oxidized metal-rich vapor plume [68]. In contrast, Ni/Fe and Co/Fe ratios (Panels C–D) remain low, consistent with SEM-EDS observations that metallic Fe–Ni phases are rare and that Fe–Si and Fe-oxide spherules dominate the assemblage.

Together, the depth-resolved nanoparticle ratios indicate that the YDB interval represents a brief depositional pulse marked by enrichment of PGEs and other siderophile elements. The coupled enrichments, characterized by elevated Pt, Ir, and Os and low Ni and Co, are consistent with formation under high-temperature, oxidizing conditions and are compatible with vapor-condensed material [68].

The confinement of the YDB anomaly to the ~ 282 – 279 cm interval suggests a short-duration depositional episode

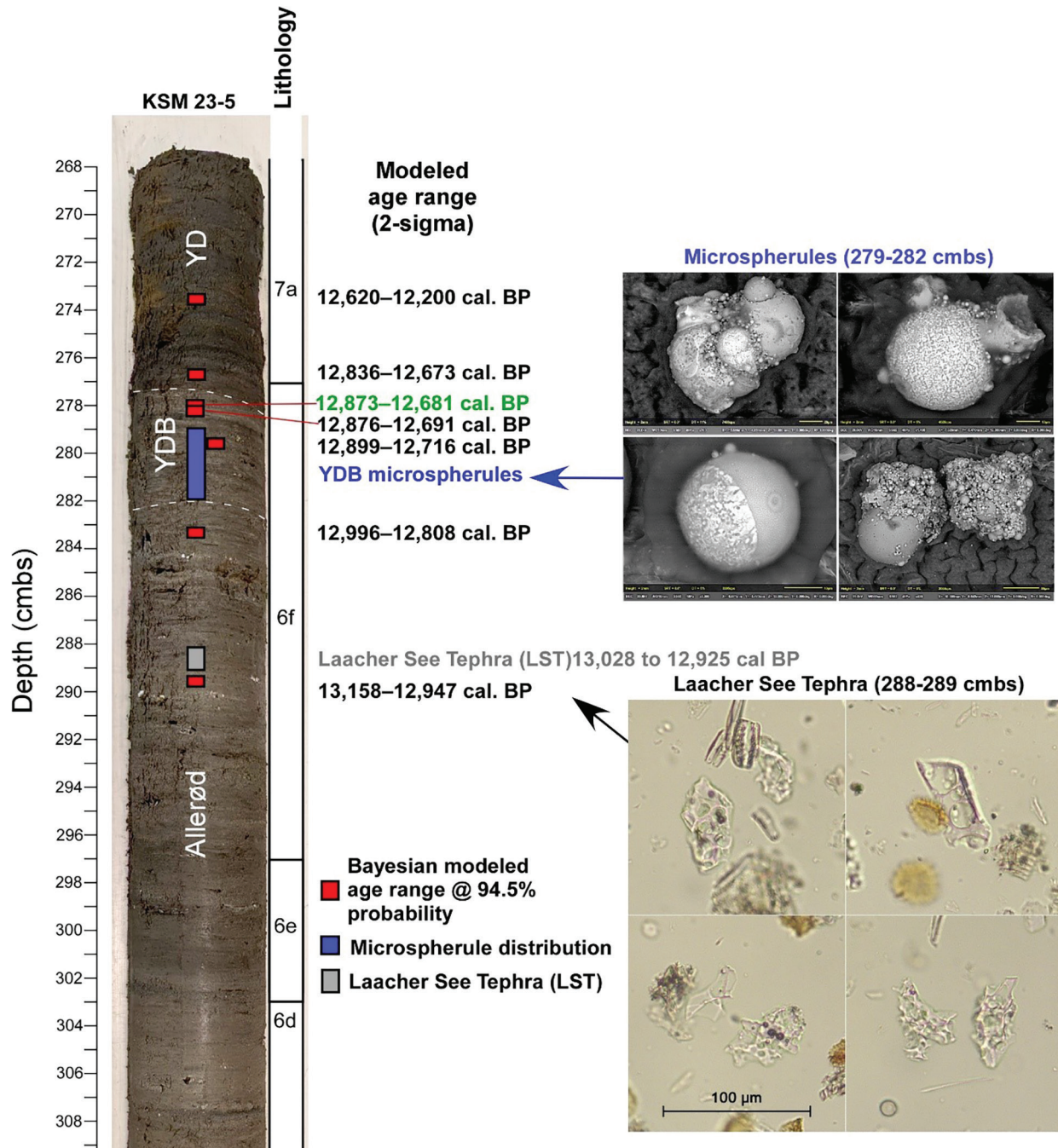


Figure 3. Core KSM-23-5 from the Körslättamossen fen on the Söderåsen horst, north-west Scania, southernmost Sweden (~740 km NE of Laacher See). Shown are the generalized lithology, Bayesian-modeled AMS dates (red rectangles), a single calibrated and Bayesian modeled AMS ^{14}C age on a terrestrial leaf macrofossil (green text) from an adjacent core just below the stratigraphic transition between lithologic units 6f and 7a (Larsson & Wastegård [44]); the Younger Dryas Boundary (YDB) microsphere range (blue bar), previously suggested as a chronostratigraphic datum (12,875–12,775 cal BP; updated with IntCal20 [60]); and the geochemically verified Laacher See Tephra (LST) peak horizon (gray text) (previously identified by Larsson & Wastegård, 2018 [38]; eruption age $13,006 \pm 9$ cal BP; Reinig et al., 2021 [12]; Bayesian-modeled age range 13,028–12,925; see also Riede et al. [37] for distal LST datasets). See Supporting Information Table S1 for unmodeled ages and S5 for modeled age ranges at 0.5 cm resolution.

consistent with fallout from a high-temperature atmospheric process [23,68–72].

A useful comparison can be made with the GISP2 ice-core Pt anomaly reported by Petaev et al. [23]. In the Greenland record,

Pt concentrations increased by more than two orders of magnitude and were accompanied by Pt/Ir ratios on the order of 10^3 , far exceeding chondritic, crustal, and most meteoritic values while Ir concentrations remained comparatively low [23].

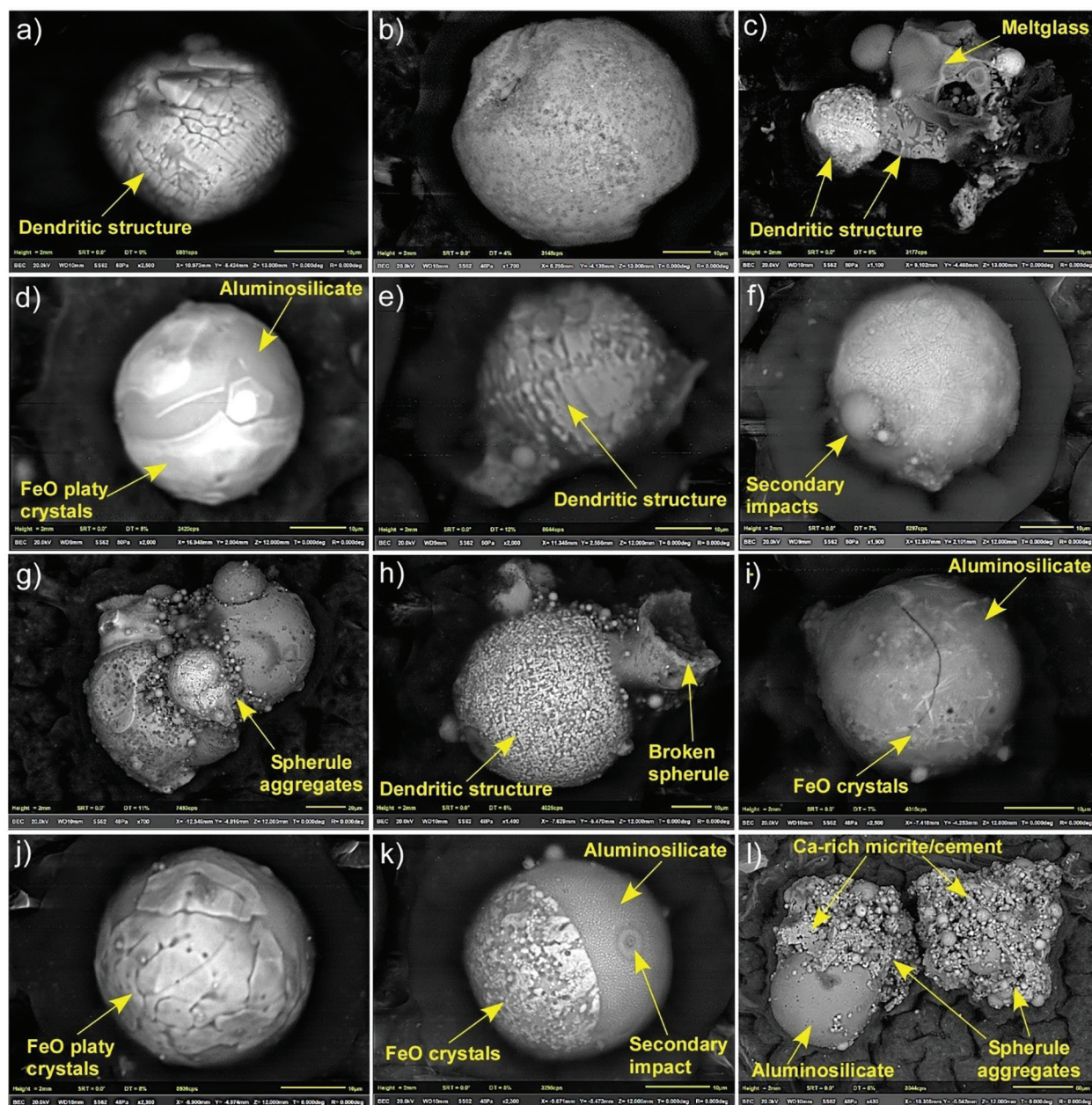


Figure 4. Representative Fe-rich and silica-rich microspherules and meltglass (a–l) from the Younger Dryas Boundary (YDB) layer in the KSM 23-5 core at Körslättamossen fen. Panels illustrate key microstructural features observed across the assemblage. Dendritic quench textures occur in Fe–Si spherules in panels a, e, and h, indicating rapid cooling from high-temperature melt. Meltglass and fused spherules are visible in panel c, where irregular glass envelopes partially melted droplets. FeO platy crystals characteristic of oxidized Fe-rich condensates occur in panels d and j, with additional FeO microcrystals in panel k. SEM-EDS compositions indicate Fe-dominant oxide phases consistent with Fe-oxide phases, possibly including wüstite (FeO) produced during high-temperature oxidation of Fe-rich melt droplets. Aluminosilicate spherules appear in panels d, i, and k, commonly intermixed with Fe-rich spherules. Secondary impacts, expressed as small adhering spherules or collision pits, are evident in panels f and k, and mechanically fragmented or broken spherules appear in panel h. Aggregates composed of dozens to hundreds of microspherules embedded within Ca-rich micrite or cement are shown in panels g and l. Together, these particles display diagnostic high-temperature morphologies including dendritic crystallization, meltglass textures, Fe-oxide crystal growth, fusion features, and aggregation structures. The aggregates shown in panels g and l collectively contain more than 1300 microspherules. Additional SEM images, EDS spectra, LA-ICP-MS compositions, and elemental maps are provided in Supporting Information, Figures S1–S37 and Tables S5 and S8.

In the Körslättamossen nanoparticle record, Pt/Fe and Pt/Ir ratios likewise show sharp localized increases confined to the YDB interval relative to surrounding sediments. Although the

analytical approaches and sample matrices differ substantially (bulk dissolved ice versus individual sediment nanoparticles), both records are characterized by Pt-dominant enrichments

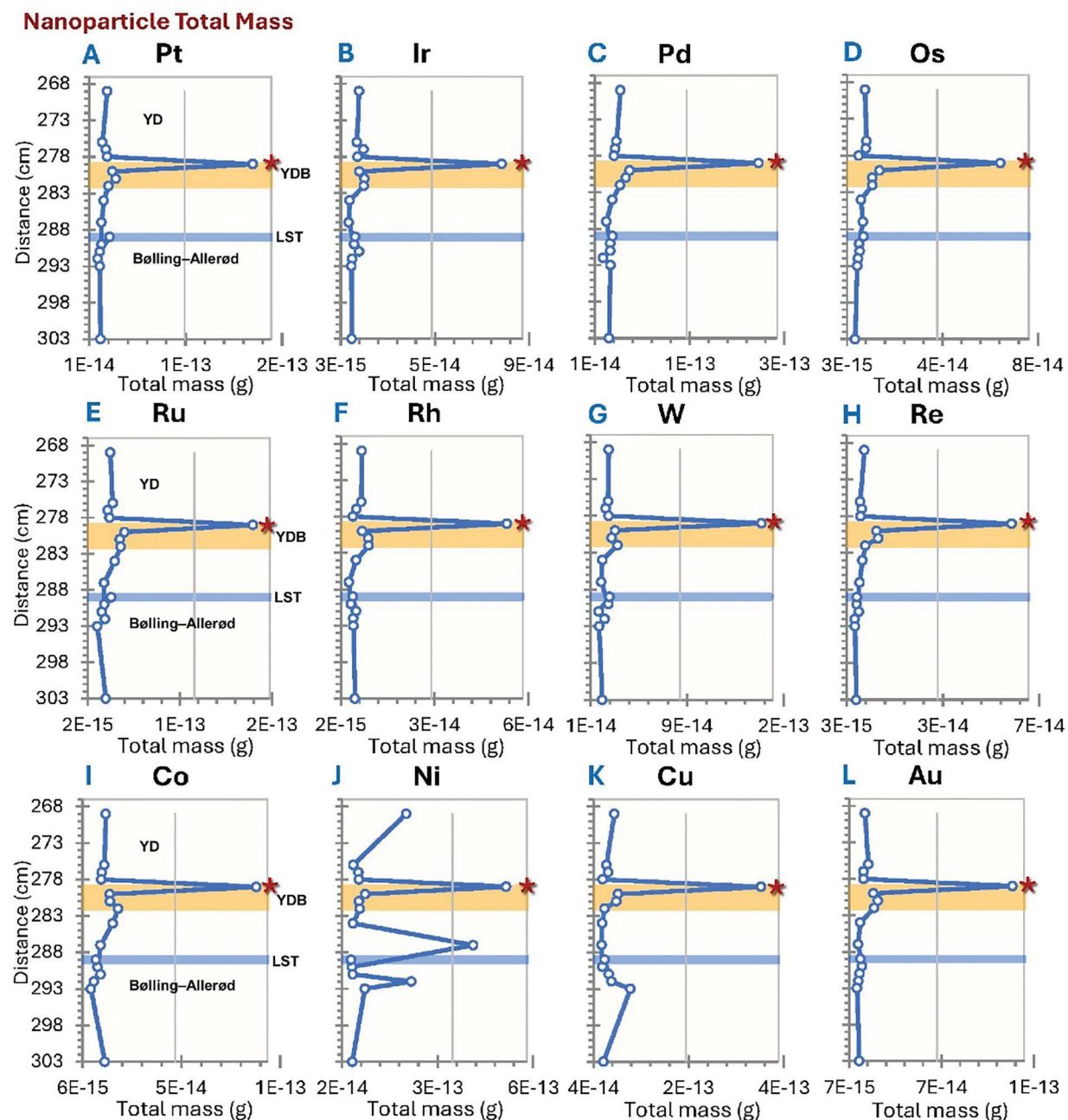


Figure 5. Total nanoparticle mass of extraterrestrial (ET) indicator elements in the K rsl ttamossen sediment sequence, southernmost Sweden. Values represent total nanoparticle mass (g) for each element as a function of depth, measured using SP-ICP-TOF-MS. Each panel (A–L) corresponds to a single element, as labeled. The orange band marks the Younger Dryas Boundary (YDB) layer, and the blue band denotes the Laacher See Tephra (LST) horizon dated to $13,006 \pm 9$ cal BP [12]. Red stars indicate peak nanoparticle mass values. All twelve elements show pronounced enrichments within the YDB layer, typically ~5–10x above background levels; most show little or no coordinated enrichment in the LST layer.

accompanied by relatively low Ir and Fe abundances compared with background levels. The similarity in relative Pt enrichment, despite differences in depositional environment and analytical method, is consistent with the interpretation that both records document an unusual Pt-rich depositional event near the YD onset [23].

Chondrite-normalized elemental ratios of spherules

Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) was used to determine elemental ratios in microspherules collected from the YDB layer in the K rsl ttamossen fen (Figure 7). The technique provides high spatial resolution and low detection limits for trace and siderophile elements,

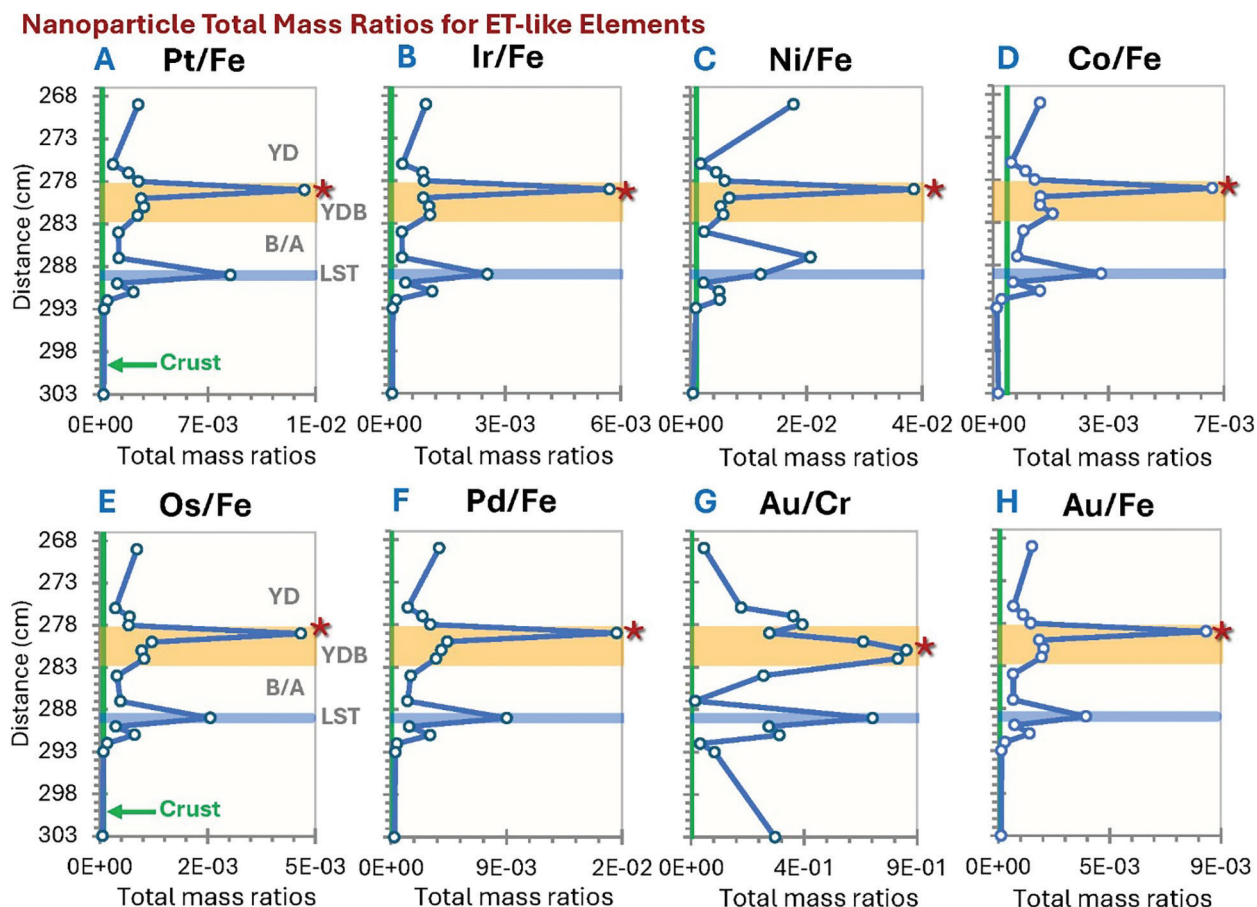


Figure 6. Depth profiles of total nanoparticle mass ratios for PGE- and transition-metal elements at Körslättamossen, southernmost Sweden, measured by SP-ICP-TOF-MS. Panels A–H show Pt/Fe, Ir/Fe, Ni/Fe, Co/Fe, Os/Fe, Pd/Fe, Au/Cr, and Au/Fe ratios plotted by core depth (303–268 cm). Higher ratios represent greater relative mass contributions of each element within the nanoparticle population at that depth. The orange band highlights the Younger Dryas Boundary (YDB) interval (~282–279 cm), where Fe-Si microspherules and PGE-rich nanoparticles were recovered. The horizontal blue band marks the Laacher See Tephra (LST) layer peak (~289–288 cm), which contains volcanic glass but no microspherules or correlated PGE enrichments. The red asterisk indicates the depth of peak total PGE-rich nanoparticle mass. The green vertical line represents upper crustal abundance for each ratio [67]. The Younger Dryas (YD) and Bølling-Allerød climate intervals are marked. At the YDB interval, several ratios (Pt/Fe, Ir/Fe, Os/Fe, Pd/Fe, and Au/Fe) show sharp, coeval increases, most parsimoniously explained by deposition of vapor-phase PGE-bearing nanoparticles associated with a high-temperature vapor plume. In contrast, Ni/Fe and Co/Fe remain low, indicating negligible meteoritic Fe-Ni alloy contribution and supporting condensation from an oxidized ET-derived vapor cloud rather than metal ablation. The LST horizon shows only minor, uncorrelated Pt increases and no elevated ratios in other PGEs, confirming its volcanic origin and its clear geochemical separation from the YDB layer.

enabling comparison of platinum-group and transition-metal ratios relative to CI chondritic and upper crustal values. Ratios of Fe/Pt, Cu/Cr, Co/Pt, Cu/Co, and Cr/Pt were normalized to CI chondrite compositions in order to stabilize variance and to differentiate between extraterrestrial or terrestrial origin.

Interpretation

The CI-normalized LA-ICP-MS ratios from the Körslättamossen YDB spherules exhibit substantial variability and do not conform to the characteristic patterns expected for a uniform chondritic or metallic extraterrestrial source. CI-normalized LA-ICP-MS trace-element ratios have been successfully used to characterize variability in matrix compositions of carbonaceous chondrites and to test for uniform extraterrestrial

signatures [73,74]. In the present case, the large scatter in element ratios among Körslättamossen spherules argues against a simple uniform chondritic source and is more consistent with heterogeneous terrestrial plus minor-ET mixing than a pure extraterrestrial deposit. Percent-level PGE concentrations observed in individual microdomains reflect localized inclusions and do not represent the bulk composition or population-level mass flux captured by SP-ICP-TOF-MS. Instead of the low Fe/Pt, Co/Pt, and Cr/Pt ratios anticipated from a Pt-rich chondritic component, all analyzed spherules display Fe/Pt ratios that are orders of magnitude above both CI and upper-crustal reference values, indicating either strong enrichment of Fe relative to Pt or undersampling of Pt-bearing nanoparticles during laser ablation. Such ratios argue against a

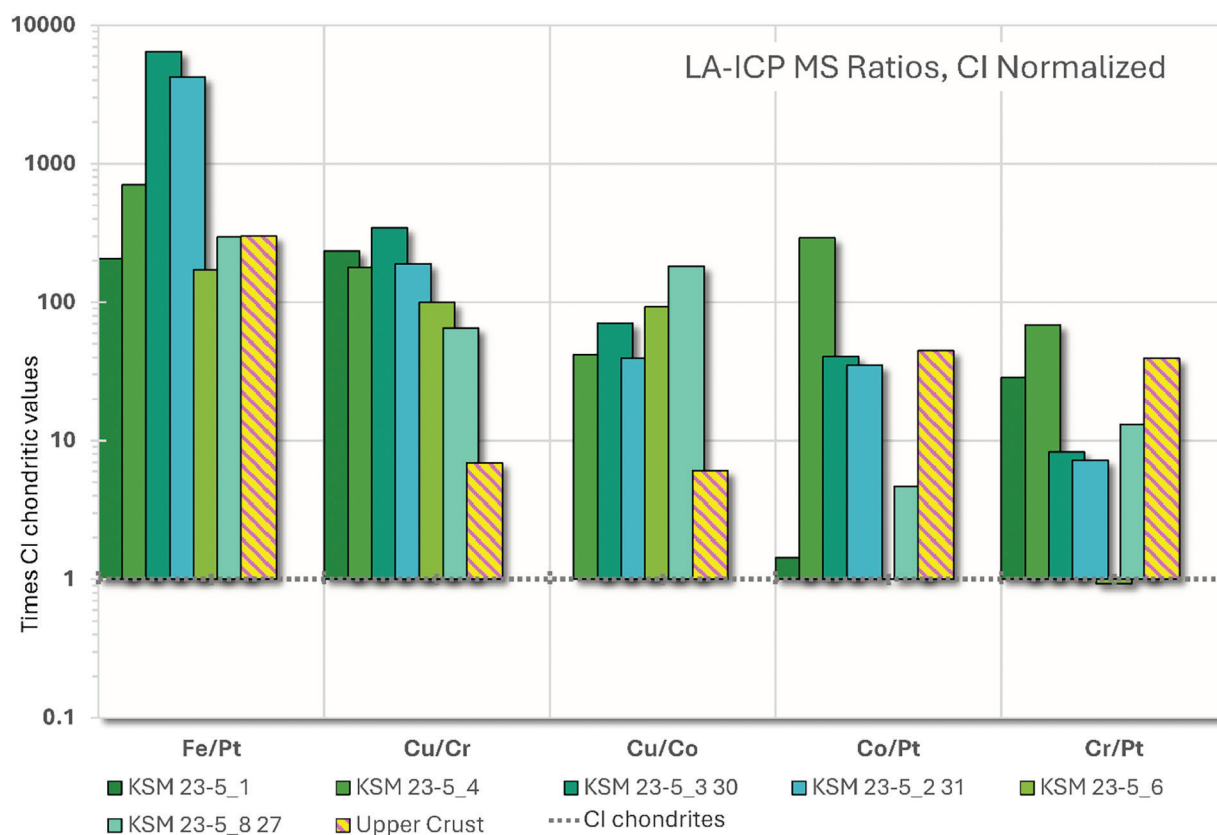


Figure 7. Chondrite-normalized LA-ICP-MS elemental ratios for microspherules from the Younger Dryas Boundary (YDB) layer at Körslättamossen. Bars show CI-normalized ratios for Fe/Pt, Cu/Cr, Co/Pt, Cu/Co, and Cr/Pt plotted on a logarithmic y-axis. Colored bars represent individual YDB microspherules (spherules numbers: KSM 23-5_1, 23-5_4, 23-5_3_30, 23-5_2_31, 23-5_6, and 23-5_8_27). The striped bar represents CI-normalized upper continental crust, shown as a terrestrial reference based on published UCC compositions [67]. Ratios >1 indicate relative enrichment of the numerator element with respect to the denominator compared with CI chondrites. Ratios that closely follow upper-crustal values suggest dominantly terrestrial compositions, whereas substantial departures from crustal patterns are consistent with incorporation of an extraterrestrial component. See Supporting Information, Table S8 for LA-ICP-MS elemental data and Table S9 for bulk sediment ICP-MS comparisons.

homogeneous ET alloy or undiluted chondritic projectile, but remain broadly consistent with highly siderophile element systematics documented for chondrites and impactors in which Pt, Ni, Co, and Cr are enriched relative to crustal values [75,76]. The elevated Fe/Pt ratios observed in bulk microspherules do not contradict the Pt enrichments identified by SP-ICP-TOF-MS. These analytical methods characterize different particle populations and operate at different scales. LA-ICP-MS primarily measures the bulk composition of individual Fe- and Si-rich microspherules, which are dominated by Fe-bearing oxide and silicate phases and therefore yield high Fe/Pt ratios despite containing localized PGE-rich microdomains. In contrast, SP-ICP-TOF-MS quantifies individual nanoparticles dispersed throughout the sediment matrix, including discrete Pt-, Ir-, Os-, and Pd-bearing particles that are not necessarily incorporated into the microspherules themselves. Consequently, high Fe/Pt ratios in bulk microspherules can coexist with elevated Pt/Fe ratios and Pt-rich nanoparticle populations within the same stratigraphic horizon. This relationship is consistent with a depositional scenario involving abundant Fe-rich melt droplets

together with a separate population of vapor-condensed PGE-bearing nanoparticles. The two datasets therefore provide complementary rather than contradictory evidence regarding the composition of the YDB layer.

These data are consistent with a heterogeneous or compositionally variable ET component, such as that observed in cometary materials. Stardust samples from comet 81P/Wild 2 show that cometary nuclei are weakly consolidated mixtures of nanometer-scale grains, ferromagnesian silicates, Fe-Ni sulfides and metal, and accessory phases, with pronounced lithologic and chemical variability at sub-milligram scales [77–79]. In such materials, melt products derived from different portions of the source would be expected to vary in PGE content, so that some microspherules could incorporate Pt-rich microdomains whereas others would contain little Pt. This variability, combined with the small ablation spot size, can produce elevated Fe/Pt ratios even when an ET component is present in dispersed or nanoparticulate form [77–79].

An alternative but complementary explanation is that the spherules represent mixed melts consisting primarily of Fe-rich

terrestrial target sediments diluted with a small proportion of ET material, analogous to projectile-target mixing observed in other impact settings [74,80]. Because continental crust contains far less Pt than chondritic material (Pt $\sim 1500\times$ crust; Ni 331 $\times$; Co and Cr 33.5 $\times$; Fe and Cu only $\sim 4\text{--}6\times$), even modest admixture of terrestrial melt would increase Fe/Pt and Cr/Pt ratios while masking intrinsic PGE enrichments. The wide scatter in Cu/Cr, Cu/Co, and Co/Pt ratios is consistent with such mixing, reflecting variable proportions of terrestrial meltglass, ET micro-inclusions, and recondensed high-temperature products. Chondritic values are from Lodders [81] and upper crust values from Rudnick and Gao [67].

Similar compositional variability is well documented in spherules and meltglass from confirmed or proposed impact events, including YDB sites and other small-crater fields, where projectile-to-target mixing and rapid quenching generate complex elemental ratios [16,24,27,34]. When considered alongside independent YDB proxies at Körslättamossen, including meltglass, metallic flakes, nanoparticle PGE anomalies, and high-temperature carbon spherules, the LA-ICP-MS results are consistent with spherules that incorporate a minor but detectable ET component overprinted by substantial terrestrial contributions. Both heterogeneous ET input and ET-terrestrial mixing remain viable explanations for the observed geochemical patterns.

Comparative elemental ratios: individual particles

To evaluate the geochemical affinity of individual nanoparticles within the YDB layer, we compared selected elemental ratios of single nanoparticles of highly siderophile elements (HSE) to those characteristic of nine extraterrestrial (ET) material forms, including known chondrites, iron meteorites, achondrites, ureilites, refractory metallic nuggets (RMNs), interplanetary dust particles (IDPs), lunar meteorites, Martian meteorites, and cometary materials. Each ratio reflects paired elemental abundances measured within a single YDB nanoparticle using SP-ICP-TOF-MS, and all ratios were normalized to CI chondritic values. In comparing each YDB nanoparticle directly to specific ET reference materials, the x-axis labels convey the following in three parts: (1) the ET material class used for comparison, e.g., RMNs, (2) the elemental ratio measured in the individual YDB nanoparticle, e.g., Pt/Fe and (3) the depth in the sediment core at which that specific YDB nanoparticle was found, e.g., 281.5 cm. (Figure 8 and Supporting Information, Table S10). The dataset derives from single-particle time-of-flight inductively coupled SP-ICP-TOF-MS analyses of HSE single nanoparticles.

Interpretation

Highly siderophile and chalcophile elements are typically enriched in extraterrestrial (ET) materials relative to upper continental crust, with Pt often $\sim 10^3\times$ higher and Ni and Co elevated by tens to hundreds of times. The CI-normalized elemental ratios of YDB nanoparticles at Körslättamossen exhibit extreme enrichments, up to $10^3\text{--}10^5\times$ above sediment background, and overlap diagnostic ratio ranges reported for

multiple extraterrestrial materials, including chondritic, iron, ureilitic, and cometary compositions. This pattern is consistent with chemically heterogeneous impactor material and high-temperature fractionation. The overlap across eleven diagnostic ratios (Co/Ni, Cr/Fe, Cr/Ni, Fe/Co, Fe/Ni, Ir/Fe, Ir/Pt, Ni/Co, Ni/Fe, Pt/Fe, and Pt/Ir) indicates a chemically heterogeneous source (Figure 8). Such variability is difficult to reconcile with derivation from a single, compositionally uniform bolide and is more consistent with a mixed or heterogeneous progenitor. This includes materials comparable to those observed in comet 81P/Wild 2 particles and chondritic-porous IDPs [77,78], and is compatible with fragmenting-body models such as those proposed for the Taurid complex [62].

The YDB layer in KSM 23-5 forms a discrete fallout bed extending from ~ 282 to 279 cm. Microspherule abundance reaches its maximum at 282–281 cm, whereas the highest Pt/Fe and Pt/Os ratios and total HSE nanoparticle masses occur 1–2 cm higher, at 280–279 cm. This slight upward offset is consistent with aerodynamic sorting and delayed settling of submicron particles, which can result in nanoparticle peaks slightly above the microspherule maximum. Both occur within a single, short-lived depositional episode as shown by the Bayesian age model (Figure 2).

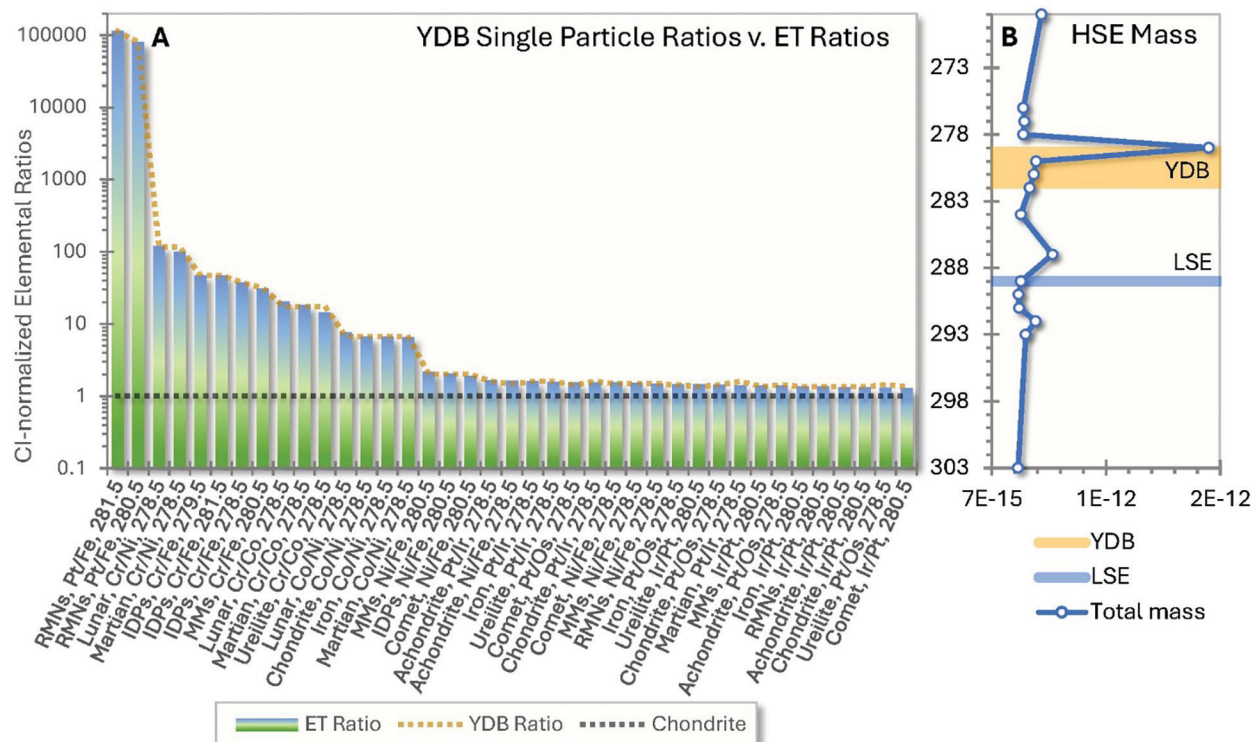
Bayesian age modeling assigns the basal YDB contact (spherule peak) at 281.5 cm an age of $12,861 \pm 54$ cal BP, consistent with the established global YDB interval of $\sim 12,875\text{--}12,775$ cal BP (updated with IntCal20) [49,60]. No PGE enrichments occur in the underlying LST layer, which remains geochemically and stratigraphically distinct. Accordingly, the Körslättamossen microspherule and PGE anomaly is not consistent with derivation from the LSE.

Comparable multi-element HSE peaks, similarly interpreted as impact-related condensates, are documented at numerous YDB sites across the Americas and the Middle East [17,18,24,27,33,34,60]. The Swedish record aligns with this broader geochemical pattern.

Stratigraphic and geochemical differentiation of the LST, YDB event layer, and early Younger Dryas horizon

The Körslättamossen sequence preserves a closely superposed set of volcanic, impact-related, and hydroclimatic signals across the Allerød-YD transition. In the late Allerød, the LST interval is marked by abundant glass shards and elevated Ca-rich minerogenic influx, expressed by higher Ca/Al ratios (~ 14) relative to background (~ 10) (Supporting Information, Table S9). Nanoparticle populations in this interval are dominated by detrital Fe oxides and REE-bearing phases, with no evidence for PGE-rich or high-temperature spherules (Supporting Information, Table S7). These characteristics indicate that, although the LST is a robust chronostratigraphic marker, its deposition produced only modest local environmental effects.

A fundamentally different signal appears in the overlying YDB interval ($\sim 282\text{--}279$ cm), which contains abundant microspherules, high-temperature melt particles, and PGE-bearing



Fe-Ti-Ni-Co nanoparticles not observed in significant abundance from the LST horizon (Supporting Information, Table S7). This assemblage defines a sharply bounded, high-energy depositional pulse. Redox-sensitive ratios (U/Th, V/Cr, S/Fe, Mo/Al) increase abruptly within the YDB layer, indicating intense but short-lived reducing conditions during early diagenesis (Supporting Information, Table S9). At the same time, Ca/Al remains elevated (~16–17) and Rb/Sr remains low (~0.1–0.2), demonstrating that the broader sedimentological regime had not yet transitioned to YD-type leaching. Together, these features show that the YDB layer represents a discrete event bed distinct from both the underlying Allerød sequence and the subsequent YD climatic transition.

Immediately above the YDB microspherule bed (Figure 3), the core transitions sharply into a dark, organic-rich horizon marking the onset of YD environmental conditions. Here, Ca/Al collapses to ~ 1.5 and Rb/Sr rises to ~ 0.5 (Supporting Information, Table S9), reflecting diminished carbonate influx and enhanced leaching under a cooler, wetter hydroclimate. Nanoparticle assemblages revert to Fe-oxide-dominated populations, PGE-bearing and high-temperature particle types decline sharply

(Supporting Information, Table S7), and redox-sensitive ratios decrease despite higher organic content, indicating that the most reducing conditions in the sequence are confined to the YDB event bed rather than the ensuing YD sediments.

DISCUSSION

The combined occurrence of the Laacher See Tephra (LST) and a discrete Younger Dryas Boundary (YDB) layer within the same well-dated Swedish sequence provides an opportunity to assess the temporal relationship between volcanic activity, putative extraterrestrial fallout, and the onset of the Younger Dryas (YD). At K rsl ttamossen, the presence of the LST at 288.5 cm provides a firm chronostratigraphic anchor at $13,006 \pm 9$ cal BP [12], whereas a geochemically distinct PGE- and microspherule-enriched horizon at $\sim 282\text{--}279$ cm is modeled at $12,861 \pm 54$ cal BP. This ~ 150 -year offset makes a direct causal link between the Laacher See eruption (LSE) and the YD onset unlikely at this site.

The YDB layer exhibits internal structure. Abundant Fe-Si microspherules peak at the base of the bed (282–281 cm), whereas the Pt-rich nanoparticle mass flux reaches its maximum 1–2

cm higher (280–279 cm). This vertical offset is consistent with aerodynamic sorting and delayed settling of submicron particles [82], and most likely represents stratigraphically adjacent components of a single, short-lived fallout episode.

Geochemical and mineralogical evidence for a discrete fallout layer

A sharp Pt anomaly occurs at ~280–279 cm and is unmatched elsewhere in the core at comparable magnitude. This interval displays a Pt-dominant, Pd-poor composition in which Pt accounts for most of the total highly siderophile element (HSE) nanoparticle mass, while Ir and Os contribute only minor bulk HSE mass despite being present in discrete PGE-bearing nanoparticles. SP-ICP-TOF-MS and LA-ICP-MS analyses show that this Pt enrichment coincides with elevated counts of Fe-, Cr-, Ti-, and V-bearing nanoparticles, with only minor Ni present, consistent with formation under high-temperature conditions rather than meteoritic metal or volcanic ash. Complementary ICP-MS data show no Ti–V or REE enrichments typical of tephra or basaltic inputs and no Fe–Ni–Cr co-enrichment indicative of detrital or anthropogenic contamination.

Volcanic aerosols and ash-leachates are typically dominated by soluble alkalis, alkaline earths, sulfur, and lithophile trace metals and are not known to produce Pt-dominant, Pd-poor nanoparticle assemblages or coordinated multi-HSE mass spikes of the type observed here [83–85]. Collectively, these datasets define a chemically isolated PGE-rich anomaly that is not readily explained by local volcanism, sedimentary reworking, or diagenetic mobilization. The underlying LST horizon contains no detectable microspherules or PGE enrichment. Similar multi-element highly siderophile element (HSE) enrichments and associated microspherule assemblages have been reported from numerous YDB sites worldwide [15,16,23,27,34].

SEM and microanalytical data show that Fe- and Si-rich microspherules are confined to the 282–279 cm interval, forming a sharply bounded horizon within the calcareous gyttja. These spherules display quench textures, vesiculation, dendritic iron-oxide microcrystals, and hollow interiors consistent with rapid cooling from high-temperature melts (Supporting Information, Figures S1–S37) [72,86]. LA-ICP-MS analyses document a broad compositional range from Si-rich glassy melts to Fe–Ca–Ti oxide variants, while trace-element data show uniformly low Ni, Cr, and V but measurable Ir and Pt. These features resemble high-temperature melt products described in impact-related contexts [70,71]. Geochemical relationships suggest derivation primarily from melted terrestrial sediments admixed with a minor extraterrestrial component, consistent with mixed spherule assemblages reported at other YDB sites [16].

Volcanic, impact-related, and hydroclimatic signals across the Allerød–YD transition

The Körslättamossen sequence reveals a tripartite structure distinguishing volcanic input, YDB-related fallout, and the onset of

YD climate change. The late-Allerød LST horizon serves as a key time marker but shows only modest geochemical and paleoenvironmental effects. Its Ca-rich minerogenic signature and detrital nanoparticle assemblage are consistent with volcanic ash deposition and do not indicate major ecological disruption at the site. In contrast, the YDB interval records a distinctive high-energy depositional signal. The concurrence of abundant Fe–Si microspherules, PGE-bearing nanoparticles, high-temperature melt phases, and transient redox enrichment indicates a brief depositional episode rather than a prolonged environmental transition. The overlying early-YD horizon reflects a different process: regional hydroclimatic reorganization. A sharp decline in Ca/Al, a rise in Rb/Sr, and the development of dark organic-rich sediments indicate enhanced leaching and cooler, wetter conditions during the early YD climate. Nanoparticle assemblages dominated by Fe oxides and diminished high-temperature phases indicate a return to baseline sedimentation.

This stratigraphic configuration, an LST layer, a distinct YDB fallout bed, and an overlying early-YD transition, demonstrates that volcanic input, particle deposition, and hydroclimatic change were not synchronous at this site and can be differentiated stratigraphically. The sequence mirrors that at Stará Jímka, Czech Republic, where Kletetschka et al. [42] documented a similar separation.

Alternative explanations

Several studies have questioned the Younger Dryas Impact Hypothesis or proposed alternative explanations for reported proxy assemblages [87–89]. The Körslättamossen record provides a framework to evaluate these possibilities.

Proposed non-impact mechanisms include volcanism, diagenetic remobilization, background cosmic dust accumulation, and contamination [13,87–92]. At Körslättamossen, these mechanisms do not readily account for the observed combination of microspherules, PGE enrichments, and nanoparticle compositions. Volcanic horizons, including the LST [38,44], show Ti–V–REE patterns typical of magmatic glass [93], unlike the YDB layer.

Baldini et al. [13] proposed volcanic forcing via sulfate aerosols. However, the YDB layer lacks the geochemical characteristics of volcanic aerosols and instead contains refractory particles not observed in the LST horizon. Green et al. [90] proposed a volcanic origin for the GISP2 Pt anomaly, noting that certain evolved magmas can produce Pt-enriched, Pd- and Ir-poor signatures. While the Pt-dominant, Ni–Co–Cr-poor nanoparticle composition at Körslättamossen shares some surface similarity with such magmatic signatures, three observations argue against a volcanic origin here. The YDB Pt enrichment is hosted within a refractory particle assemblage including Fe–Si microspherules with dendritic quench textures (Figure 4), features not produced by volcanic aerosols or ash-leachates [83–85]. Then, the layer lacks the coupled Zr–Nb–REE–Ti–V enrichment diagnostic of evolved silicate melts [93], which would be expected to accompany volcanically derived Pt signal. The directly underlying LST horizon (a geochemically characterized

phonolitic (alkaline) eruption deposited only ~150 years earlier) contains neither Pt-dominant nanoparticles nor microspherules, supporting that a large, proximal alkaline eruption did not generate the signature observed in the YDB interval.

Post-depositional processes are unlikely given the sharp confinement of the anomaly. Background micrometeorite flux would produce diffuse enrichment rather than a discrete peak [15,63]. Anthropogenic contamination is unlikely given the stratigraphic context.

These observations indicate that conventional volcanic and sedimentary processes do not readily explain the combined features observed at Körslättamossen. The YDB layer is therefore most consistent with deposition during a brief high-energy event involving high-temperature particle formation. Comparable assemblages have been reported from multiple YDB sites worldwide.

An important implication is that the Körslättamossen sequence provides a well-constrained European framework for evaluating timing near the YD onset. The LST horizon at $13,006 \pm 9$ cal BP [12] and the overlying YDB layer at $12,861 \pm 54$ cal BP demonstrate that volcanic activity, particle deposition, and hydroclimatic change represent distinct processes. This stratigraphic separation strengthens correlations among terrestrial, marine, and ice-core records.

CONCLUSIONS

The Körslättamossen core from southernmost Sweden preserves two distinct late Allerød depositional events separated by ~150 years: (a) the Laacher See Tephra (LST) at 288.5 cm, dated to $13,006 \pm 9$ cal BP; and (b) an overlying platinum-group-element (PGE)-enriched, Fe-Si microspherule horizon between 282 and 279 cm with a basal spherule peak at 281.5 cm yielding a Bayesian-modeled age of $12,861 \pm 54$ cal BP, consistent with the onset of the Younger Dryas (YD). Within this Younger Dryas Boundary (YDB) fallout bed, microspherules peak at its base, while a maximum PGE-bearing nanoparticle mass occurs 1–2 cm above, reflecting internal stratification within a single depositional episode marked by the delayed settling of submicron particles. Immediately above this layer, a sharp, dark, organic-rich horizon marks the onset of YD climatic change, expressed by reduced carbonate influx and enhanced leaching.

High-resolution SP-ICP-TOF-MS, LA-ICP-MS, and EDS analyses show that the YDB horizon contains a discrete Pt-dominated enrichment accompanied by Fe-Si microspherules with dendritic quench textures and PGE-bearing microdomains. Nanoparticle ratios (e.g., Pt/Fe, Pt/Ir, and Pt/Pd) exhibit strong Pt-dominant fractionation relative to crustal values, whereas Ir and Os contribute only minor bulk HSE mass despite being present in discrete nanoparticles, and Ti and V remain near background levels. This geochemical pattern resembles the Pt-rich anomaly reported from the GISP2 Greenland ice core, where Pt concentrations increased by more than two orders of magnitude and Pt/Ir ratios reached values substantially above chondritic, crustal, and most meteoritic materials while Ir remained comparatively low [23]. Together with similar

YDB-age records from Abu Hureyra (Syria) [17,18,94], Wakulla Springs (Florida, USA) [22], White Pond (South Carolina, USA) [95], Pilauco (Chile) [34], Stará Jímka (Czech Republic) [42], and Wonderkrater (South Africa) [64], the Körslättamossen sequence adds to a growing body of evidence for a geographically widespread Pt-rich depositional event near the YD onset. The absence of Fe-Ni-Cr alloy grains, negligible Co enrichment, and lack of Ti-V-REE co-enrichment are not consistent with typical meteoritic metal, volcanic glass, or diagenetic sources. Instead, the combined microspherule, nanoparticle, and elemental-ratio data are most consistent with deposition from a high-temperature vapor plume containing Pt-rich condensates and associated melt products.

Diagenetic or post-depositional remobilization is unlikely given the sharp confinement of the microspherule and nanoparticle anomalies and the absence of Fe-Mn enrichment patterns indicative of a migrating redox front. Although redox-sensitive elemental ratios indicate short-lived reducing conditions within the YDB bed, these conditions coincide stratigraphically with the discrete depositional horizon and do not, by themselves, demonstrate post-depositional remobilization of the PGE anomaly. Background micrometeorite flux would be expected to produce diffuse, low-amplitude PGE enrichment rather than a discrete multi-element peak. Anthropogenic contamination is unlikely given the stratigraphic context and depth of the deposits.

In contrast, the underlying LST horizon contains phonolitic glass with characteristic Zr-Nb-REE enrichment and near-crustal PGE abundances. Nanoparticle ratios in the LST reflect volcanic glass chemistry and lack Fe-Si microspherules or coordinated PGE enrichments. The stratigraphic and geochemical separation between the LST and YDB horizons indicates that these represent distinct depositional events and does not support a volcanic origin for the YDB anomaly.

Although this study documents a single, well-dated sedimentary sequence, the nanoparticle compositions, Pt-dominant fractionation patterns, and Fe-Si microspherule morphologies observed at Körslättamossen closely resemble those reported from multiple YDB sites across several continents. This correspondence suggests that the Körslättamossen record represents a regional expression of a broader depositional phenomenon rather than an isolated anomaly.

The multi-proxy datasets indicate that the Körslättamossen YDB horizon records a brief high-temperature fallout episode that includes geochemical and mineralogical signatures consistent with a component of extraterrestrial material. Its position directly beneath the early YD horizon suggests a possible temporal link to the onset of regional hydroclimatic change. The sequence provides a well-constrained European record of both the LST and an overlying YDB layer, offering a robust framework for evaluating the Allerød-YD transition.

SUPPORTING INFORMATION

SI. Supporting information. Additional figures, tables, and methods.

(PDF) <https://zenodo.org/records/19697133>

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DATA AVAILABILITY

Data are provided within the manuscript and the Supplementary Information files.

SAMPLE AVAILABILITY

Core samples for this study are largely depleted; however, limited material may be available from the corresponding author upon reasonable request.

AUTHOR CONTRIBUTIONS

C.R.M., S.A.L., A.W., M.A.L., and J.P.K. conceived and directed aspects of the project. All co-authors (C.R.M., S.A.L., Mo.B., Mi.B., M.A., A.W., M.A.L., J.P.K., G.K., J.C., A.V.A., and T.W.) contributed data and/or technical analyses and participated in writing, editing, reviewing, and approving the manuscript.

COMPETING INTERESTS

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all proceeds to CRG. The authors declare no other competing interests.

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