WAS THERE A METEORITE IMPACT OR VOLCANIC ERUPTION AT THE ONSET OF THE YOUNGER DRYAS?

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Introduction: The Younger Dryas (YD; 12,900 – 11,700 yr) was an abrupt cooling period following the termination of a warm period, Allerød. It is recorded in Greenland ice cores as Greenland Stadial-1 (GS-1) [1,2]. The YD cooling event is thought to have resulted from freshwater flooding of the northeast Atlantic and/or the Arctic Oceans that prevented deep water formation [3,4]. The proposed cooling triggers include 1) catastrophic freshwater drainage of proglacial Lake Agassiz [5], 2) meteorite-induced destabilization and/or melting of the Laurentide Ice Sheet [6], and 3) large sulfate aerosol loading in the stratosphere from the explosive eruption of Laacher See volcano in Eifel, Germany.

Evidence for the latter two triggers comes from the Greenland Ice Sheet Project 2 (GISP2) ice core. Petaev et al. [7] observed an anomalous Pt spike with a high Pt/Ir ratio of ~1200 at the onset of YD (~12,870 years before A.D. 2000; b2k, henceforth referred to as yr). They attributed the Pt anomaly to the impact of a 0.8 km diameter Sikhote-Alin type iron meteorite. Baldini et al. [8] synthesized recent revisions in ice-core chronology and connected a large sulfate peak observed in the late Allerød (12,917 yr) in GISP2 to the recently revised age of Laacher See volcanic eruption at 12,930 ± 40 yr [9,10]. They suggested that the contemporaneity of the late Allerød sulfate peak with the Laacher See eruption shows possible volcanic aerosol cooling as the YD initiation trigger. However, the physical evidence for each of the above two mechanisms remains elusive [11-13].

Here, we investigate whether there was a one-time catastrophic event or a series of events that led to the YD cooling using chemical and Os and Pb isotopic signatures in the Greenland Ice Core Project (GRIP) ice core transecting the YD onset. In addition, we analyzed Laacher See tephra for Os and Pb isotopes. If there was a meteorite impact at the YD onset, the GRIP samples should display a significant increase in Ir, Pt, and Os flux above the present-day cosmic dust flux with $^{187}Os/^{188}Os$ ratios that lie between 0.13 (=chondritic meteorite) and 0.19 (= iron meteorite) [14,15]. Similarly, if the late Allerød sulfate peak seen in GRIP is from the Laacher See eruption, Os and Pb isotope fingerprints of the peak sample should be consistent with those of the Laacher See tephra.

Measurements: We examined the GRIP (drilled at Summit, Greenland; 72° 34' N, 37° 38' W) ice core from a depth of 1659.35 m to 1664.30 m (12,939 yr to 12,810 yr based on the Greenland Ice Core Chronology 2005 (GICC05) time scale [1,2]). Each ice core sample had a time resolution of ~2 years. Prior to analyses, the ice core segments were decontaminated [16,17] in a cold laboratory (-17 °C) at the Korea Polar Research Institute (KOPRI). All 54 clean core samples, each ~60 g, were stored and thawed in 125-mL Teflon bottles. Melt-water samples were then split into two aliquots. One aliquot at KOPRI was split further to analyze for O and H isotopes (Picarro), major ions (ion chromatography, Dionex), trace metal elements (Sector Field- ICP-MS, Element 2), and Pb isotopes (TRITON). The other aliquot at Dartmouth was split further to analyze for Ir and Pt (triple quadrupole- ICP-MS, Agilent 8900) and Os isotopes (TRITON). Previously characterized samples of Laacher See tephra were analyzed for Pb and Os isotopes at Dartmouth (TRITON).

Results and Discussion: From the synchronization of GISP2 and GRIP cores [1,2], the GISP2 Pt spike [7] is expected between 12,863 yr and 12,879 yr with a time-integrated Pt flux of 339 pg cm^{-2} yr^{-1} (Fig 1). If this anomaly resulted from the impact of a Sikhote-Alin type iron meteorite [7], an Os flux of 1190 fg cm^{-2} yr^{-1} with a $^{187}Os/^{188}Os$ ratio of 0.13 would also be expected. However, no significant Pt enrichment is observed (Fig 1) and the estimated Os flux during this time period ranges from 5.1 to 13 fg cm^{-2} yr^{-1} with a mass-weighted average $^{187}Os/^{188}Os$ ratio of 0.40. Moreover, no Fe or Ni enrichment is observed.

Our analyses also reveal that all platinum metal peaks have non-chondritic Os/Ir ratios with $^{187}Os/^{188}Os$ ratios ≥ 0.2, indicating that their origin is volcanogenic rather than extra-terrestrial. However, a sample at 12,820 yr displays spikes of Os, Ir, and Pt fluxes with Os/Ir and Pt/Os ratios of 1.05 ± 0.10 (2 S.D.) and 32 ± 12 (2 S.D.), respectively. The $^{187}Os/^{188}Os$ ratio of this sample is 0.145 ± 0.005 (2 S.D.; Fig 1) and the estimated Os flux for this sample is 235 fg cm^{-2} yr^{-1}, which is 24 times the present-day Os flux of cosmic dust to the earth [18]. The isotopic signature and platinum metals of the sample appear to be consistent with that of a type IIIB iron meteorite [15]. However, this sample does not show anomalously high Fe or Ni fluxes. Instead, the platinum metals flux increase is accompanied and preceded by a spike in the Cu flux, which is likely volcanogenic (Fig 1).

For the late Allerød sulfate peak, we find high sulfate levels associated with two samples at 12,917 yr and 12,915 yr (Fig 1). The estimated Os fluxes of these samples are 14 fg cm^{-2} yr^{-1} and 11 fg cm^{-2} yr^{-1}, respectively, and $^{187}Os/^{188}Os$ ratios are 0.45 and 0.40, respectively. In comparison, the $^{187}Os/^{188}Os$ ratio of the Laacher See tephra ranges from 0.117 to 0.30. The 12,917 yr and 12,915 yr sulfate peak samples have $^{206}Pb/^{207}Pb$ ratios of 1.170 and 1.159, respectively and $^{208}Pb/^{207}Pb$ ratios of 2.450 and 2.434, respectively. These ratios are uniquely unradiogenic and inconsistent with those measured for the Laacher See tephra ($^{206}Pb/^{207}Pb$ =1.213 and $^{208}Pb/^{207}Pb$ = 2.504). These data indicate that the late Allerød sulfate peak in GRIP cannot come from the Laacher See eruption. From a compilation of all Quaternary volcanoes using the GEOROC database [19], we find that only the volcanoes in Iceland's Northern Volcanic Zone (NVZ), especially lavas from Þeistareykir volcanic field, have the uniquely unradiogenic Pb isotope ratios.

Conclusion: Our key finding is that there is no evidence of a meteorite impact or Laacher See eruption at the YD onset. Instead, the initiation of YD cooling appears to follow and coincide with multiple volcanic eruptions in the Northern Volcanic Zone in Iceland. While there is evidence of a 24-fold increase in extra-terrestrial Os flux at 12,820 yr, which could be attributed to the impact of a IIIB iron meteorite, the associated sample lacks Fe or Ni enrichment.

We hypothesize that an increase in volcanism in Iceland resulted from post-glacial isostatic rebound combined with rising sea level, caused a part of the southern Icelandic Ice Sheet to collapse. Thus, the destabilization of the Icelandic Ice Sheet may have contributed to the YD onset through freshwater flux to the North Atlantic.

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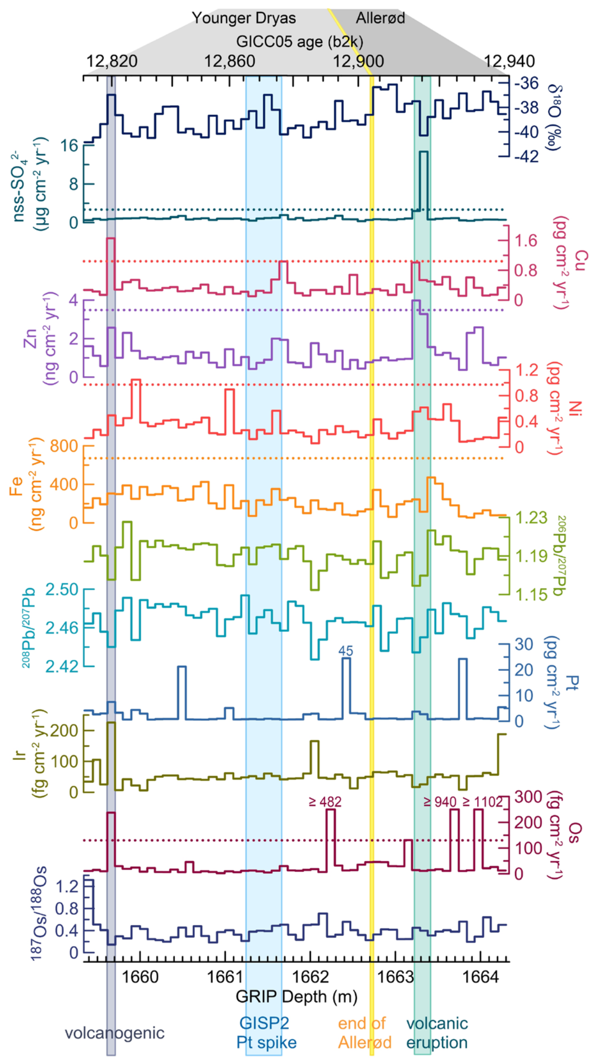

Fig 1. Chemical and isotopic properties of the GRIP core at onset of the Allerød/YD transition. Color shades mark a volcanic eruption (green), end of Allerød (yellow), GRIP depth corresponding to GISP2 Pt spike (blue), and volcanogenic (gray) based on Pt, Ir, and Os isotopes. The dotted lines are the 2 sigma brackets of log-normal. Peaks above these lines indicate significant spikes in the record.