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Putting the Younger Dryas cold event into context

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ABSTRACT

The Younger Dryas event is by far the best studied of the millennial-scale cold snaps of glacial time. Yet its origin remains a subject of debate. The long-held scenario that the Younger Dryas was a one-time outlier triggered by a flood of water stored in proglacial Lake Agassiz has fallen from favor due to lack of a clear geomorphic signature at the correct time and place on the landscape. The recent suggestion that the Younger Dryas was triggered by the impact of a comet has not gained traction. Instead, evidence from Chinese stalagmites suggests that, rather than being a freak occurrence, the Younger Dryas is an integral part of the deglacial sequence of events that produced the last termination on a global scale.

No event in the climate record has received more attention than the Younger Dryas (YD), a millennial-duration cold snap that punctuated the termination of the last glacial period 12.9–11.7 ka ago. Much of the thinking regarding the origin of the YD has focused on a flood or some other catastrophic event peculiar to this termination. Instead, from study of the last four 100,000-year-duration asymmetric saw-toothed climate cycles, we have become convinced that the YD was an integral part of the sequence of events involved in glacial terminations. However, before the case for this alternate view is laid out, it is appropriate to summarize briefly what is known about the YD and to review the prevailing scenario put forward to explain its origin.

Perhaps the most important point to be made about the YD is that it shares the characteristics of the 24 or so millennial-duration Dansgaard–Oeschger (DO) cold spells that punctuate the glacial portion of the Greenland ice-core record (Stuiver and Grootes, 2000; Mangerud et al., 2009). These events are thought to have resulted from rapid reorganizations of the Atlantic Ocean's thermohaline circulation (Alley, 2007). In particular, they are times when deep-water formation in the northern Atlantic shut down, allowing fresh water to pool on the ocean surface. In the case of the YD, the result was the formation of an extensive winter sea ice cover, whose presence blocked the release of ocean heat, steered the westerly winds to a southern path (Brauer et al., 2008) and reflected away incoming sunshine. As a consequence, Siberian-like winter conditions prevailed over the northern Atlantic and adjacent land masses (Denton et al., 2005). This cooling of the northlands had widespread repercussions that extended southward into the tropics (Chiang and Bitz, 2005). The Asian monsoon was weakened (Wang et al., 2001) and the tropical rain belt was displaced to the south (Lea et al., 2003; Jennerjahn et al., 2004; Wang et al., 2004).

Although the involvement of ocean reorganizations, coupled with sea-ice formation, is now widely accepted, no agreement exists as to what triggered each DO cold event and whether or not a similar trigger initiated the YD. Most of what has been written about the YD involves the catastrophic release of fresh water from proglacial Lake Agassiz, which was situated along the southwestern front of the retreating North American ice sheet. This pulse of fresh water supposedly capped the northern Atlantic, bringing deep-water formation to a halt. The flood hypothesis was attractive because a significant drop in the level of Lake Agassiz occurred close to the time of onset of the YD. This drop was accompanied by a sharp increase in the ^{18}O to ^{16}O ratio in Gulf of Mexico foraminifera shells formed close to the mouth of the Mississippi River, which carried Lake Agassiz outflow (Broecker et al., 1989). However, the failure to locate any geomorphic evidence for the passage of flood waters along either an eastern route to the Gulf of St. Lawrence or a northern route to the Arctic Ocean dampened

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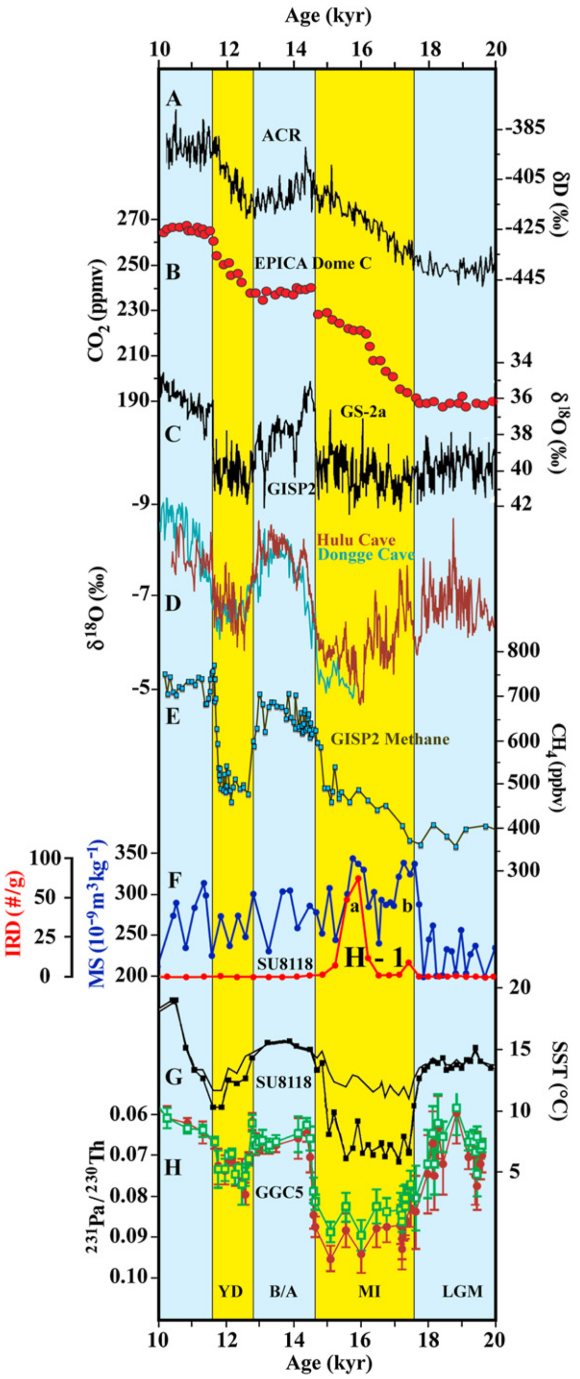

Fig. 1. The Mystery Interval and the Younger Dryas are marked by yellow background. (A) and (B) show deuterium and CO_2 records from the EPICA Dome C ice core on the East Antarctic plateau (Monnin et al., 2001) plotted on the GISP2 timescale as in Marchitto et al. (2007). (C) gives the GISP2 isotope record (Stuiver and Grootes, 2000). (D) shows the monsoon record based on isotopes from stalagmites in southeast Asian caves (Wang et al., 2001; Yuan et al., 2004). (E) is the methane record from the GISP2 ice core (Brook et al., 2000) plotted on the timescale from (Brook et al., 1996). (F) illustrates ice-rafted grains (IRD) in marine sediment core SU-8118 off Portugal (Bard et al., 2000). IRD is expressed as the number of grains per gram for the size fraction greater than 150 microns. The H-1a IRD peak features quartz and feldspars, with minor hematite-coated grains, glauconite, and volcanic shards. The H-1b IRD peak is largely detrital carbonate, with minor amounts of quartz and feldspar. (G) is sea-surface temperatures based on alkenone unsaturation ratios from marine sediment core SU-8118 (Bard et al., 2000). (H) is a $^{231}Pa/^{230}Th$ profile from core GGC5 from the Bermuda Rise (McManus et al., 2004). YD is Younger Dryas, B/A is Bølling/Allerød, MI is Mystery Interval, LGM is Last Glacial Maximum, and ACR is Antarctic Cold Reversal. Figure adapted in part from McManus et al. (1999; 2004). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

enthusiasm for the flood hypothesis (Lowell et al., 2005), leading to a challenge of the radiocarbon dates used to establish the time of the drop in Agassiz level (Fisher et al., 2008). Further, the ^{18}O decrease in the Gulf of Mexico foraminifera could just as well be explained by a reduction in the rate of ice sheet melting during the YD, rather than by a rerouting of the Lake Agassiz overflow.

Greenland ice-core ^{18}O records show that the onset of the YD followed a gradual cooling capped by a final century-duration cold plunge. Rather than the onset, it was the end of the YD that was ultra-sharp. Indeed, Steffensen et al. (2008) showed that the shift in the D to H ratio at the end of the YD occurred in 1–3 years. In contrast, the beginning of the YD was not especially abrupt compared, for example, with the onset of the North Atlantic climate anomaly about 8200 years ago (Alley, 2007; Kobashi et al., 2007). This younger event appears to be linked to the final, catastrophic drainage of Lake Agassiz through Hudson Strait (Barber et al., 1999). As indicated by the Greenland ice-core ^{18}O records, the rapid cooling at the onset of the 8200-year event is consistent with the timescale expected for a quickly applied fresh water cap on the regions of deep convection in the North Atlantic. From this viewpoint, the relatively slow onset of the YD appears inconsistent with a great catastrophe.

Here we present the case that, rather than being a freak add-on to the last termination, the YD was an integral and inevitable part of the deglacial sequence of events. This reasoning is based on the stable isotope and CO_2 records in Antarctic ice cores (Fig. 1). During the last termination, the rise in Antarctic temperature and atmospheric CO_2 stalled halfway between full-glacial and full-interglacial values during the Antarctic Cold Reversal (ACR 14.5–12.9 ka). Something had to occur to jar the climate system from this stalled condition in order for the Antarctic termination to be completed. That something was the YD.

Similarities shared by the YD (12.9–11.7 ka) and the "Mystery Interval" (17.5–14.5 ka (Denton et al., 2006)) merit mention because these two Northern Hemisphere events were coeval with the two pulses of warming and CO_2 release associated with the Antarctic termination. As described in Denton et al. (2006), the Mystery Interval involved numerous climatic anomalies, likely linked to expansion of North Atlantic sea ice in response to greatly reduced deepwater formation, as was the case for the YD. As indicated by the accumulation of opal in marine sediments from south of the Antarctic Circumpolar Current, there was a large burst of upwelling that brought silica to the surface of the Southern Ocean during each of the two Antarctic warming pulses. Anderson et al. (2009) suggested that these bursts released to the atmosphere CO_2 that had been stored in the deep sea during glacial time. Also, these bursts of upwelling may have mixed ^{14}C-depleted abyssal water back to the upper ocean, thus creating the observed decreases in the atmospheric and surface–ocean ^{14}C to C ratio. The two bursts of upwelling in the Southern Ocean also correspond to times when Marchitto et al. (2007) observed benthic foraminifera greatly depleted in ^{14}C in an intermediate-depth core off Central America and when McManus et al. (2004) documented unusually high ^{231}Pa to ^{230}Th ratios in abyssal North Atlantic sediment. Although their significance remains in debate, the three marine records of McManus et al. (2004), Marchitto et al. (2007), and Anderson et al. (2009) point to widespread changes in ocean operation during the YD that were similar in character to those associated with the 3000-year-long Mystery Interval (Denton et al., 2006). These observations reinforce the suggestion that the intervening northern Bølling–Allerød warmth and the coeval southern ACR constituted a stall in the processes that brought the last glacial period to a close.

Further support for the similarity between the Mystery Interval and the YD comes from records on land. As shown by Wang et al.

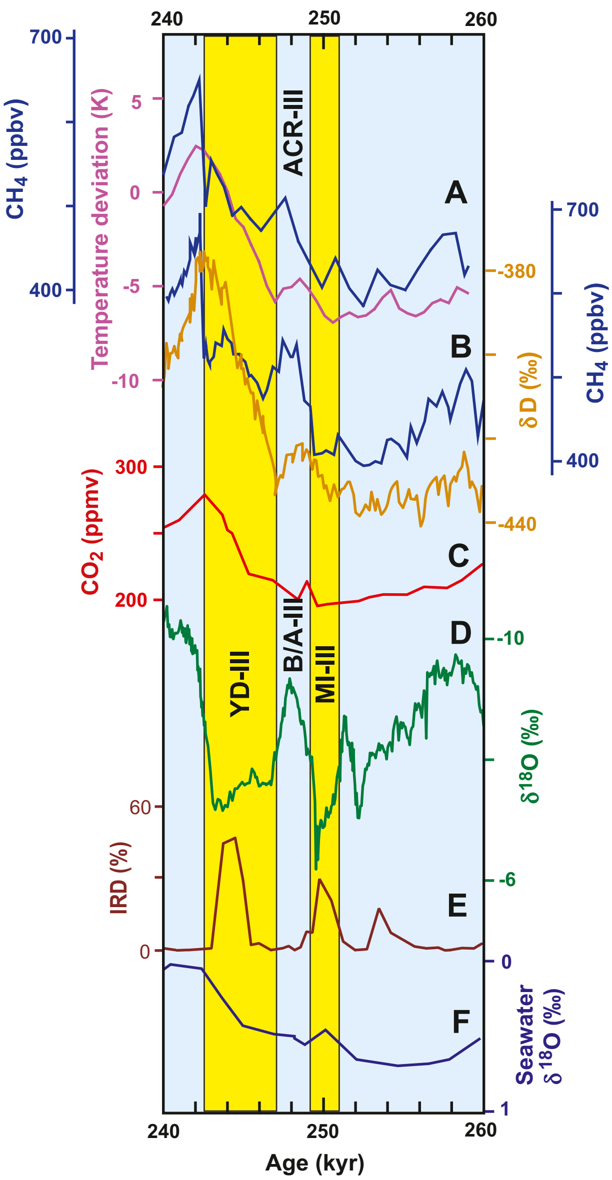

Fig. 2. Major events surrounding Termination III. (A) shows Vostok temperature deviation (purple) and CH_4 (blue) records (Suwa and Bender, 2008). (B) shows EPICA/Dome C (EDC) δD (orange) and CH_4 (blue) records (Loulergue et al., 2008). (C) is the Vostok CO_2 record (Petit et al., 1999). (D) is the absolute-dated Asian Monsoon record from Sanbao Cave, China (Cheng et al., 2006). (E) and (F) show IRD and inferred seawater $\delta^{18}O$ records from marine core ODP-980 (McManus et al., 1999). Both Vostok and EDC timescale were shifted in order to correlate the abrupt jump of the last portion of CH_4 in ice cores to the abrupt monsoon jump in panel (D) (Cheng et al., 2009). The ODP-980 records are on original timescales. Two Weak Monsoon Intervals (WMI) are marked by yellow background. Termination III events, analogous to the YD, B/A, ACR and MI are labeled: YD III, B/A III, ACR III and MI-III. Figure is simplified from that in Cheng et al. (2009). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

(2001), the ^{18}O record in Hulu Cave in China reveals two distinct weakenings of the Asian monsoon rains, one during the Mystery Interval and the other during the YD. Counterparts to these weakenings are brief spurts of stalagmite growth in otherwise dry caves in Brazil (Wang et al., 2004). Consistent with this southern stalagmite record are large spikes in river-borne silicate debris documented in continental-margin sediments off northeast Brazil (Jennerjahn et al., 2004). Grimm et al. (2006) observed increases in the ratio of pine to oak pollen in Florida's Lake Tulane during both the YD and the Mystery Interval. It is interesting to note that only Heinrich (H) events, but not DO events, show up in the records from northeastern Brazil and from Florida.

Such observations raise the following question. Can equivalents of the Bølling/Allerød/YD sequence be seen in records for earlier terminations? The answer is yes. In the Chinese stalagmite record, Termination II is punctuated by a several-century-duration interstadial event (Cheng et al., 2006; Wang et al., 2008). However, much more striking are the similarities between Terminations I and III. New Asian monsoon data for Termination III (Cheng et al., 2009; Fig. 2) reveal an equivalent of the Mystery Interval that lasted almost 2 millennia, followed by a Bølling/Allerød equivalent lasting ~2 millennia, in turn followed by a YD equivalent that lasted ~4 millennia, all before the Asian monsoon reached interglacial strength. The combined duration of the equivalents of the Mystery Interval and the YD during Termination III was about 8000 years. In light of these new observations of the Asian monsoon, we reexamined the Antarctic ice-core records for Termination III (Kawamura et al., 2007; Suwa and Bender, 2008). Indeed, we can identify an analogue to the ACR, as well as a lowering of the slope of the CO_2 rise, which likely correspond with a Bølling/Allerød analogue during Termination III (Cheng et al., 2009). Overall, the Chinese cave records show that each of the last four terminations featured weak Asian monsoons spanning about 6000 years. These weak monsoons occurred either in one long interval (Terminations II and IV, when large and rapid rises in northern insolation quickly drove deglaciations to completion) or else in two shorter intervals (Terminations I and III, when slower and smaller rises in northern insolation resulted in prolonged, punctuated deglaciations) (Cheng et al., 2009). Each weak-monsoon interval is tied to cold North Atlantic conditions, which in turn appear to have driven the Southern Ocean/Antarctic pulses of warming and of CO_2 rise. These pulses may have produced much of the termination in southern latitudes, augmenting the effect of orbitally lengthening summers (Huybers and Denton, 2008) while the associated CO_2 rises augmented the melting of Northern Hemisphere ice sheets.

Based on these observations of the climate signatures during several terminations, we conclude that there is no need to call upon a one-time catastrophic event to explain the YD. More likely, the YD was a necessary part of the last termination. This being said, we do not wish to downplay the importance of Heinrich ice armadas as pacemakers. The evidence is reasonably strong that H-1 occurred close to the beginning of the Mystery Interval. Claims have also been made that a seventh ice armada (i.e., H-0) occurred at the onset of the YD (Andrews et al., 1995). Indeed, Anderson et al. (2009) show that upwelling events in the Southern Ocean accompanied the first four H events and their companion "bumps" in the atmospheric CO_2 record.

One might argue that a one-time event such as a catastrophic flood or even the impact of an extra-terrestrial object (Firestone et al., 2007) served to pre-trigger a YD cold episode that was destined to happen on its own. Of course, this is a possibility, but when viewed in the context of the last four terminations, cold reversals equivalent to the YD seem to be integral parts of global switches from glacial to interglacial climate. No one-time catastrophe is required.

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