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Does the Trigger for Abrupt Climate Change Reside in the Ocean or in the Atmosphere?

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Two hypotheses have been put forward to explain the large and abrupt climate changes that punctuated glacial time. One attributes such changes to reorganizations of the ocean's thermohaline circulation and the other to changes in tropical atmosphere-ocean dynamics. In an attempt to distinguish between these hypotheses, two lines of evidence are examined. The first involves the timing of the freshwater injections to the northern Atlantic that have been suggested as triggers for the global impacts associated with the Younger Dryas and Heinrich events. The second has to do with evidence for precursory events associated with the Heinrich ice-rafted debris layers in the northern Atlantic and with the abrupt Dansgaard-Oeschger warmings recorded in the Santa Barbara Basin.

The last glacial period was punctuated by a series of large and abrupt climate changes. Although a large body of evidence regarding the magnitude, timing, and geographic extent of these changes has been obtained, the physics behind them remains poorly understood. The problem is that no one has been able to come up with a satisfactory scenario that meets four major requirements. First, the scenario must characterize the states among which the climate system has jumped. Second, it must identify a mechanism by which the system can be triggered to jump from one of these states to another. Third, it must invoke a telecommunication system by which the message can be rapidly transmitted across the planet. Fourth, it must have a flywheel capable of holding the system in a given state for many centuries.

Current thinking falls into two distinct camps. One focuses on multiple states of the ocean's thermohaline circulation that appear prominently in model simulations and the other on changes in the dynamics of the tropical atmosphere-ocean system. For the first camp, the catastrophic input of fresh water to the northern Atlantic constitutes a mechanism to trigger switches in the mode of thermohaline circulation. The flywheel is the sluggish internal dynamics of the ocean. What is lacking in this scenario is the chain of interactions capable of producing immediate, large, and widespread atmospheric impacts. Adherents of this approach come largely from the ranks of ocean modelers and paleoclimatologists. The alternate view (*1*) focuses on the tropical ocean-atmosphere system. Its adherents contend that, because tropical convective systems constitute the dominant element in the planet's climate system, the trigger more likely resides in the region that houses the El Niño–La Niña cycle. If so, the telecommunication problem that plagues the ocean-based scenario largely disappears. However, this scenario suffers from the absence of any evidence that Earth's tropical atmosphere-ocean system has more than one discrete mode of operation into which it can become locked. Further, unless the deep ocean is brought into play, there does not appear to be any flywheel capable of locking the atmosphere into one of its alternate states for many centuries. The proponents of this scenario come largely from the ranks of atmospheric physics and decadal variability studies.

The abrupt changes that are of interest fall into two main categories, those associated with Dansgaard-Oeschger (DO) events and those associated with Heinrich (H) events. The former are jumps between a state of intense cold and a state of intermediate cold that dominate portions of the Greenland ice-core ^{18}O record. In addition to local air-temperature changes, the ice cores record abrupt changes in the infall of dust and sea salt (*2*) and in the content of methane in the atmosphere (*3*). The climate system remains trapped in a given state for many centuries. H events (*4*) show up in the northern Atlantic Ocean as sedimentary layers dominated by ice-rafted debris spaced at roughly 7000-year intervals during the last glacial period. They have been shown to result from the melting of armadas of ice launched from eastern North America. Although not prominently recorded in the Greenland ice record, impacts associated with H events are seen in records from distant places, including the tropics (*5*).

In a category all its own is the Younger Dryas (YD), a millennium-long cold snap that punctuated Termination I (i.e., the transition from the last glacial period to the Holocene). Although in many ways similar to the DO events, the YD is of particular interest because the global pattern of its impacts is by far the best documented, and also because it appears to have been triggered by a catastrophic release of fresh water to the northern Atlantic (*6*). Because there is no evidence that a similar millennium-long cold episode punctuated earlier glacial terminations, the YD appears to be a one-time event made possible by a quirk in the relation between the glacially excavated topography and the position of the retreating ice front. The Antarctic ice-core methane record is particularly relevant in this regard, because there is no repeat of the prominent YD methane drop associated with the three earlier terminations (*7*).

The Younger Dryas

The prevailing view of this cold snap is that it was triggered by a catastrophic release of fresh water stored in proglacial Lake Agassiz (*6*). This release was initiated when the retreating margin of the Laurentide ice sheet opened a lower outlet, allowing much of the lake's stored water to flood across the region now occupied by the northern Great Lakes into the St. Lawrence valley and from there into the northern Atlantic (Fig. 1). On the basis of reconstructions of the pre- and post-diversion shorelines of Lake Agassiz, it has been estimated that ~9500 km^3 of water was released (*6*). If released over the course of a single year, this flood would match today's net annual input of fresh water to the Atlantic Ocean region north of 45°N. In most ocean models, an input of this magnitude cripples formation of deep water in the northern Atlantic (i.e., it greatly weakens or even shuts down the model's conveyor circulation).

In support of such a shutdown is evidence for a dramatic rise in surface-ocean ^{14}C to ^{12}C ratio. As documented by radiocarbon measurements on planktonic foraminifera from calendar-dated annual layers in a core from the Cariaco Basin, immediately after the onset of the YD (marked by a sharp change in the color of the sediment), the ^{14}C to ^{12}C ratio in the local surface water began to rise (*8*). This rise continued for about 200 years and reached a ratio ~5% higher than that before the YD's onset. Such a rise is consistent with a shutdown of deepwater production in the

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northern Atlantic, because currently this pathway supplies ~75% of the radiocarbon atoms needed to balance radiodecay in the entire deep sea (*9*). On the basis of the ^{10}Be record in Greenland ice, a claim has been made that at least part of the ^{14}C increase was the result of an increase in the production of ^{14}C rather than a shutdown of deepwater formation (*10*). The evidence for this is inconclusive, and Hughen's conclusion that the ^{14}C rise was primarily the result of a shutdown of the conveyor seems more likely to be correct.

Except for the Antarctic continent, everywhere on the globe where an adequate record has been obtained, conditions during the YD appear to have been more glacial-like than those characterizing the preceding Bölling-Allerød warm period. Summarized in Fig. 2 are sites where the YD has been documented and its onset adequately radiocarbon dated. In Antarctic ice cores, a marked departure is seen (*11–13*). In seven out of eight of these records, the YD is a time of pronounced warming. Those who favor the ocean-based scenario call on an alternation in the relative strengths of deepwater formation in the northern Atlantic and in the Southern Ocean as the cause for Antarctica's anomalous behavior. However, it must be stated that the record in the Taylor Dome core located near the margin of the Antarctic cap more closely resembles those from Greenland (*14*). The importance of this curious departure remains to be understood.

A test of the flood hypothesis is to make use of radiocarbon dating to determine whether the release of Agassiz water occurred at the time of the YD onset. However, a complication must be taken into account: The radiocarbon clock is imperfect. For a period of about 200 years before 11,100 ^{14}C years ago, the clock stalled (because of a decline in the atmosphere's ^{14}C to ^{12}C ratio) and subsequent to this time, for a period of 200 or so years, the ^{14}C clock ran three times too fast (because of a rise in the atmosphere's ^{14}C to ^{12}C ratio). This anomalous behavior complicates a novel approach by Hajdas *et al.* (*15*) to precisely date the onset of the YD. This approach takes advantage of the late Allerød Laacher See tephra, which is found in Swiss and German lake sediments. Counting annual layers in these sediments shows the interval between the tephra layer and onset of the YD to be about 200 years. On the basis of 12 terrestrial plant macrofossil ^{14}C ages derived from above and below the tephra in sediments from Soppensee, Holzmaar, and Schalkenmehrener Maar, these authors interpolated an age of 11,230 ± 40 years for the tephra. Had the ^{14}C clock run smoothly, this would place the age of the YD onset at 11,030 ± 40 years. Recent radiocarbon measurements on four samples from a poplar tree buried in the Laacher See tephra 10 km from the eruption site all yielded ages within 25 years of 11,065 ^{14}C years B.P. (before the present) (*16*). Again assuming an ideal clock, the onset of the YD would be placed at 10,865 ± 25 ^{14}C years B.P. However, the conversion of the 200–calendar year offset to ^{14}C years depends on the timing of the Laacher See eruption relative to the ^{14}C age plateau. Were it to have occurred toward the beginning of the plateau, then the 200-year correction would translate to only a very small change in the onset ^{14}C age. Alternatively, were it to have occurred near or beyond the end of the plateau, the correction could be as large as 500 years. Hence, this seemingly clever way to establish the ^{14}C age of the onset of the YD turns out to be fraught with uncertainty. A better strategy is based on ^{14}C ages for both late Allerød and early YD sediments in the same sediment sections. An age of 10,900 ± 65 ^{14}C years on a sample from 300 calendar years above the tephra layer suggests that the eruption occurred toward the beginning of the plateau and, hence, that the ^{14}C age of the YD onset must be close to 11,000 years (*15*).

With one exception, the radiocarbon ages for the onset of climatic impacts associated with the YD at widely separated places on Earth cluster around 11,000 years. The exception is dates on wood from the Waiho Loop moraine on New Zealand's South Island (*17*). As shown in Fig. 3, these ages range from 10,650 to 11,520 years. Twenty-seven out of 37 ages are greater than 11,000 years (i.e., they predate the onset of the YD). Perhaps most of this wood formed during the Allerød time and was preserved in avalanche deposits formed during that time and subsequently exhumed by the advancing YD ice. However, these results could equally well be taken to indicate that the glaciation in New Zealand began as much as 500 years earlier than the onset of the YD in the Northern Hemisphere. Resolution of this question is of the utmost importance, because hanging in the balance is the documentation of interhemispheric synchroneity.

One approach to resolving this question is the comparison of ages based on the in situ production of ^{10}Be in quartz from surficially exposed erratic boulders present in moraines in the Swiss Alps and in the New Zealand Alps. Although questions remain regarding the exact dependence of ^{10}Be production on latitude and elevation, because these locales are nearly equidistant from the equator and at nearly the same elevation, the age differences are not dependent on the exact calibration. ^{10}Be measurements obtained for the Swiss Alps and for the New Zealand Alps show no notable differences (*18*). However, the uncertainty in this age difference (~500 years) is still too large to allow the YD cooling to be declared synchronous between the hemispheres. The mean of the nine ^{10}Be ages on

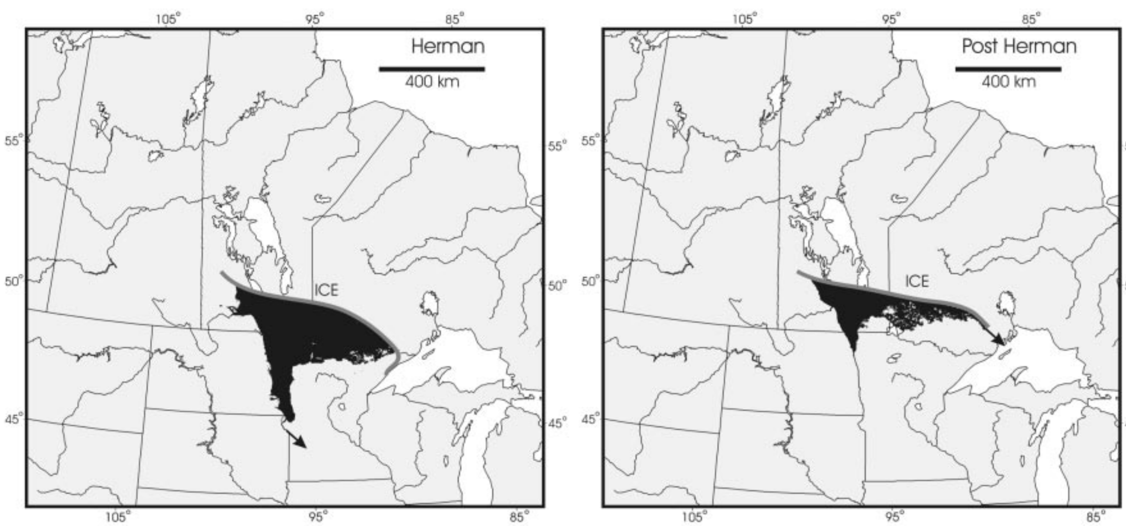

Fig. 1. (**Left**) The outline of Lake Agassiz just before the catastrophic flood. At that time its outlet was to the south into the Mississippi drainage. (**Right**) The outline after the opening of the eastward outlet. A volume of 9500 km^3 of water was suddenly released to the northern Atlantic through the St. Lawrence Valley (*42*).

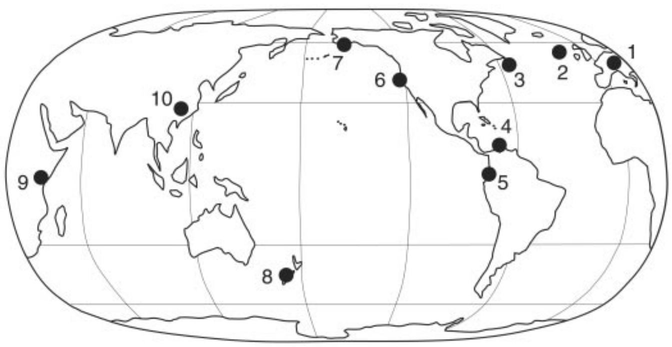

Fig. 2. Locations of records where the sudden onset of the YD impacts have been precisely radiocarbon dated: 1 (*15*), 2 (*43*), 3 (*44*), 4 (*8*), 5 (*45*), 6 (*41*, *46*), 7 (*47*), 8 (*17*), 9 (*48*), and 10 (*39*).

Wind River range (Wyoming, United States) boulders (*19*) is consistent with those from the Swiss Alps.

The age of the Agassiz flood is based on radiocarbon measurements on three wood samples from the beaches of the lake's Moorhead low-water phase formed after its outburst into the Great Lakes and the North Atlantic. The ages are 10,960, 10,820 and 10,810 years (*20*–*22*). These ages set a minimum for the flood. An independent estimate comes from the age of 11,110 years on mixed planktonic shells in Gulf of Mexico sediment cores marking the onset of the interval indicating the shutdown of the flow of low ^{18}O Agassiz water into the Mississippi drainage (*21*). To the measurement uncertainty of 130 years on this shell sample must be added the uncertainty associated with the assumed 400-year reservoir correction to the marine shell date. Thus, although the documentation remains somewhat thin, the ^{14}C age of the flood is consistent with the hypothesis that it triggered the YD.

The most definitive chronological information comes from Greenland's ice. Here, no need for radiometric dating exists. The time differences of interest can be obtained by directly counting annual layers in the ice. The large increase in dust content at the YD onset (*2*) coincides exactly within the time of Greenland's ^{18}O-based cooling and drop in snow-accumulation rate (*23*). Because the dust has been shown to come from the Asian deserts (*24*), this suggests that the increase in the frequency of intense windstorms occurred there at the same time as the cooling in Greenland. The concentration of NaCl in the ice underwent a similar increase (*2*). Thus, it appears that storminess over the ocean also increased at this time. Of course, both of these changes could be attributed to washout efficiency rather than source strength. Of even greater interest is the observation that the drop in atmospheric methane content as measured in the gas trapped in the ice occurred within decades of the time of the Greenland cooling that heralded the onset of the YD. The uncertainty resulting from the ~70-m initial offset between the ice record and the trapped-gas record was eliminated by measuring the ^{15}N to ^{14}N ratio in N_2 (*25*). During the abrupt air-temperature rises, an enrichment of ^{15}N due to thermal diffusion in the firn is seen (*25*–*27*). The onset of the associated methane rise lags the warming by no more than a few decades (*26*). Severinghaus and Brook (*26*) have found a corresponding thermal diffusion–induced decrease in ^{15}N resulting from the cooling at the onset of the YD. This methane drop (*3*, *28*) is thought to be largely the result of a decrease in the extent of tropical wetlands (*29*). Hence, a case can be made that the tropical climate change accompanying the onset of the YD was nearly synchronous with that at the high northern latitudes. Because the Greenland ice-core record cannot be directly radiocarbon dated, a small leap of faith is required to postulate that the abrupt YD onsets at other sites on the planet were coincident with that in Greenland. Indeed, the Greenland ice-core dust and methane records lend support to this assertion.

There is another way to assess the timing of these changes. On the basis of the methane records (*28*), events in Antarctica can be closely tied to those in Greenland. This tie tells us that the pause in Antarctic warming and the pause in the atmospheric CO_2 rise (*30*) that characterize the Bölling-Allerød time interval came to an end very close to the onset of the YD. The warming and CO_2 rise then continued throughout the course of the YD. Thus, although the YD temperature change in Antarctica was in the opposite sense as that in Greenland, it began at very nearly the same time.

In summary, it can be said that, with the exception of that for New Zealand, the chronological evidence is consistent with a sudden global onset of the YD impacts at about 11,000 ^{14}C years B.P. Further, the radiocarbon age of the release of 9500 km^3 of water stored in Lake Agassiz is indistinguishable from that for the YD onset. If advocates of a tropical trigger discount the role of the Agassiz flood as the trigger for the YD, then they must attribute this apparent synchroneity either to coincidence or to a climate change initiated elsewhere as the cause of the flood.

Heinrich Events

Six layers dominated by ice-rafted debris have been identified in a series of cores extending from the Hudson Straits across the northern Atlantic to the coast of France (*4*). This material has been shown to have been released during the melting of armadas of ice launched from eastern Canada. Although the hypothesis that these armadas resulted from gigantic surges of the Hudson Bay lobe of the Laurentide ice sheet (*31*, *32*) is widely accepted, alternate hypotheses involving Jökulhlaups (*33*) and shattered ice shelves have been proposed. Regardless of their mode of origin, it is clear from the associated reduction in planktonic ^{18}O accompanying each event that the melting of these ice armadas reduced the salinity of northern Atlantic surface waters by a large enough amount to impact conveyor circulation. Indeed, as for the YD, far-field climatic impacts roughly matching the times of each H event have been documented (*34*). Far-field impacts include times of the greatest glacial cooling in the Mediterranean Sea (*35*) and in the Atlantic Ocean off the Iberian Margin (*36*), sediment-discharge events off eastern Brazil (*37*), pine events in central Florida (*38*), and sharp weakenings of the monsoons in the Chinese Hulu Cave record (*39*). Thus, it is tempting to conclude that these impacts were triggered by disruptions of thermohaline circulation caused by freshwater inputs to the northern Atlantic.

Precursory Events

Perhaps the most important means of distinguishing between the oceanic and tropical hypotheses is through a search for and study of precursory events. The first demonstration of the existence of such events was the discovery of the presence of pulses of volcanic glass and hematite-stained mineral grains just

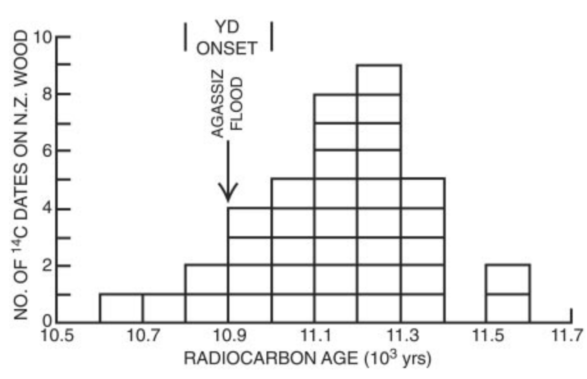

Fig. 3. Histogram of the radiocarbon ages on wood from the Waiho Loop moraine on the South Island of New Zealand (*17*). As can be seen, most of this wood formed before the onset of the YD. If indeed this moraine is a YD equivalent, then the wood entrained by the advancing glacier must have been reworked from avalanche deposits. Alternatively, the onset of the moraine formation predates the YD.

before the onsets of the deposition of each of the Heinrich layers (*40*). Because both lithic types originate far to the north of the core sites, a cold ocean favors their delivery by ice rafting. Further, the relative abundance of cold-loving *Neogloboquadrina pachyderma* (left coiling) reached a maximum during these precursory events (*40*). The existence of such events must certainly be troubling to those who view the Heinrich's ice armadas as stochastic events whose onset is dictated by conditions at the base of the Hudson Bay lobe of the Laurentide ice sheet (i.e., isolated from the overlying climate). However, even if the armadas were somehow triggered by a cooling, one could still contend that the far-field climate impacts were the result of a shutdown in conveyor circulation induced by the freshwater input rather than by the precursory cooling event itself.

Evidence for precursory events associated with the DO events as recorded in Santa Barbara Basin sediment has been recently discovered (*41*). If the abrupt warmings found at the base of each of the anaerobic layers (recorded by sharp decreases in planktonic ^{18}O) are correlated with the DO warmings in the Greenland record, then one could look for precursory events in the bioturbated sediment immediately underlying each of these sudden warmings. For two of the warmings, there is clear evidence (based on ^{18}O measurements in benthic foraminifera) for a precursory warming of the deep-basin water (*41*). This warming is attributed to a strengthening of the contribution of thermocline water moving northward from the tropics. Clearly, if proven correct, this hypothesis will be music to the ears of the advocates of a tropical trigger.

Conclusions

Although model-based simulations provide useful clues to what might lie behind these abrupt climate changes, they do not provide compelling proof that any given hypothesis is the correct one. Such proof, if it is to be obtained, must come from the record created by these events. The key to success will be the determination as to whether the far-field climate changes predate the changes attributed to ocean reorganizations. Ideally, this evidence would come from precise dating of the times of onset of the far-field impacts. But, because of the abrupt nature of these transitions, this quest may be doomed, for if the changes happened at very nearly the same time everywhere, it will not be possible to obtain a definitive answer. Hence, a more promising approach may be the search for and study of precursory events.

So where do we stand? First, the evidence that reorganizations of the ocean's thermohaline circulation accompanied the YD and H events appears to be very strong. Although these ocean reorganizations could well be consequences of climate changes initiated elsewhere, there are good reasons to believe that they constitute the primary trigger. Somehow these oceanic changes must have perturbed tropical dynamics which, in turn, drove the global atmospheric changes. Missing, of course, is the link necessary to meet the requirement that the message was transmitted from the deep ocean to the tropical atmosphere on the time scale of a few decades.

In any case, we are still a long way from understanding how our climate system accomplished the large and abrupt changes so richly recorded in ice and sediment. However, despite this ignorance, it is clear that Earth's climate system has proven itself to be an angry beast. When nudged, it is capable of a violent response.

References and Notes

1. M. Cane, A. C. Clement, in *Mechanisms of Global Climate Change at Millennial Time Scales*, P. U. Clark, R. S. Webb, L. D. Keigwin, Eds. (Geophysical Monograph 112, American Geophysical Union, Washington, DC, 1999), pp. 373–383.
2. P. A. Mayewski *et al.*, *Science* **263**, 1747 (1994).
3. E. J. Brook, T. Sowers, J. Orchardo, *Science* **273**, 1087 (1996).
4. S. R. Hemming, in preparation.
5. W. S. Broecker, S. R. Hemming, *Science* **294**, 2308 (2001).
6. J. T. Teller, D. W. Leverington, J. D. Mann, *Quat. Sci. Rev.* **21**, 879 (2002).
7. J. R. Petit *et al.*, *Nature* **399**, 429 (1999).
8. D. A. Hughen *et al.*, *Nature* **391**, 65 (1998).
9. W. S. Broecker, T. H. Peng, *Tracers in the Sea* (Eldigio, Palisades, NY, 1982).
10. R. Muscheler, J. Beer, G. Wagner, R. C. Finkel, *Nature* **408**, 567 (2000).
11. J. Jouzel *et al.*, *Clim. Dyn.* **11**, 151 (1995).
12. T. Blunier *et al.*, *Geophys. Res. Lett.* **24,** 2683 (1997).
13. V. Morgan *et al.*, *Science* **297**, 1862 (2002).
14. E. J. Steig *et al.*, *Science* **282**, 92 (1998).
15. I. Hajdas *et al.*, *Radiocarbon* **37**, 149 (1995).
16. T. Litt, H.-U. Schmincke, B. Kromer, *Quat. Sci. Rev.* **22**, 7 (2002).
17. G. H. Denton, C. H. Hendy, *Science* **264**, 1434 (1994).
18. S. Ivy-Ochs, C. Schlüchter, P. W. Kubik, G. H. Denton, *Geogr. Ann.* **81A**, 313 (1999).
19. J. C Gosse, E. B. Evenson, J. Klein, B. Lawn, R. Middleton, *Geology* **23**, 877 (1995).
20. S. R. Moran, L. Clayton, M. Scott, J. Brophy, *N. Dak. Geol. Surv. Misc. Ser.* **53**, 1 (1973).
21. W. S. Broecker *et al.*, *Nature* **341**, 318 (1989).
22. J. M. Licciardi, J. T. Teller, P. U. Clark, in *Mechanisms of Global Climate Change at Millennial Time Scales*, P. U. Clark, R. S. Webb, L. D. Keigwin, Eds. (Geophysical Monograph 112, American Geophysical Union, Washington, DC, 1999), pp. 177–201.
23. R. B. Alley *et al.*, *Nature* **362,** 527 (1993).
24. P. E. Biscaye *et al.*, *J. Geophys. Res.* **102**, 26765 (1997).
25. J. P. Severinghaus, T. Sowers, E. J. Brook, R. B. Alley, M. L. Bender, *Nature* **391**, 141 (1998).
26. J. P. Severinghaus, E. J. Brook, *Science* **286**, 930 (1999).
27. J. P. Severinghaus, A. Grachev, M. Battle, *Geochem. Geophys. Geosyst.* **2**, 2000GC000146 (31 July 2001).
28. E. J. Brook, S. Harder, J. Severinghaus, M. Bender, in *Mechanisms of Global Climate Change at Millennial Time Scales*, P. U. Clark, R. S. Webb, L. D. Keigwin, Eds. (Geophysical Monograph 112, American Geophysical Union, Washington, DC, 1999), pp. 165–175.
29. A. Dallenbach *et al.*, *Geophys. Res. Lett.* **27**, 1005 (2000).
30. E. Monnin *et al.*, *Science* **291**, 112 (2001).
31. D. R. MacAyeal, *Paleoceanography* **8**, 767 (1993).
32. D. R. MacAyeal, *Paleoceanography* **8**, 775 (1993).
33. R. G. Johnson, S.-E. Lauritzen, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **117**, 123 (1995).
34. W. S. Broecker, S. R. Hemming, *Science* **294**, 2303 (2001).
35. I. Cacho *et al.*, *Paleoceanography* **16**, 40 (2001).
36. D. Pailler, E. Bard, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **181**, 431 (2002).
37. H. W. Arz, J. Patzold, G. Wefer, *Quat. Res.* **50,** 157 (1998).
38. E. C. Grimm, G. L. Jacobson Jr., W. A. Watts, B. C. S. Hansen, K. A. A. Maasch, *Science* **261**, 198 (1993).
39. Y. J. Wang *et al.*, *Science* **294**, 2345 (2001).
40. G. Bond, R. Lotti, *Science* **267**, 1005 (1995).
41. I. L. Hendy, J. P. Kennett, E. B. Roark, B. L. Ingram, *Quat. Sci. Rev.* **21**, 1167 (2002).
42. D. W. Leverington, J. D. Mann, J. T. Teller, *Quat. Res.* 174 (2000).
43. W. S. Broecker *et al.*, *Paleoceanography* **3,** 1 (1988).
44. R. J. Mott, D. R. Grant, R. Stea, S. Occhietti, *Nature* **323**, 247 (1986).
45. C. M. Clapperton *et al.*, *Quat. Res.* **47**, 13 (1997)
46. I. L. Hendy, J. P. Kennett, *Paleoceanography* **15**, 30 (2000).
47. I. Hajdas, G. Bonani, P. Bodén, D. M. Peteet, D. H. Mann, *Geology* **26**, 1047 (1998).
48. N. Roberts *et al.*, *Nature* **366**, 146 (1993).

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