Deglacial Floods in the Beaufort Sea Preceded Younger Dryas Cooling

Supplementary Information

Extended Data

1. Site surveying

Sites were surveyed on USCGC Healy using the hull mounted multibeam swath bathymetry system, and a Knudsen 320B/R sonar. The Knudsen system, also hull mounted, operates at a central frequency of 3.5 kHz and sweeps between 2 and 6 kHz which makes it "chirp."

2. Stratigraphy

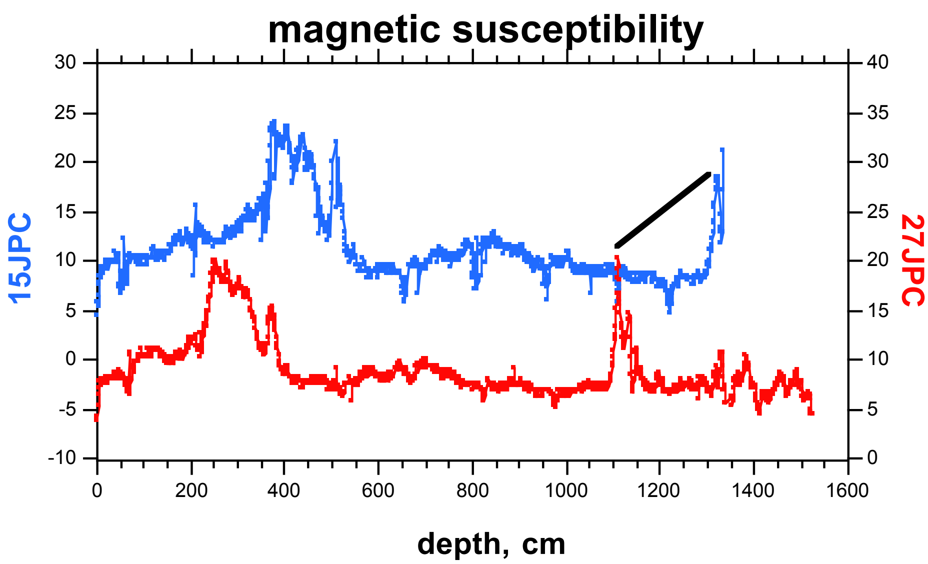


Fig. ED1. Magnetic susceptibility records of HLY1302 cores JPC15/27 from the same location at 690 m on the continental slope east of Mackenzie River (JPC15: 71°06.222'N, 135°08.129'W; JPC27: 71°06.360'N, 135°09.640'W). To make a 1729 cm composite section, we patched to JPC-15 at 1329 cm the data below 1125 cm in JPC-27 (with a +205 cm offset).

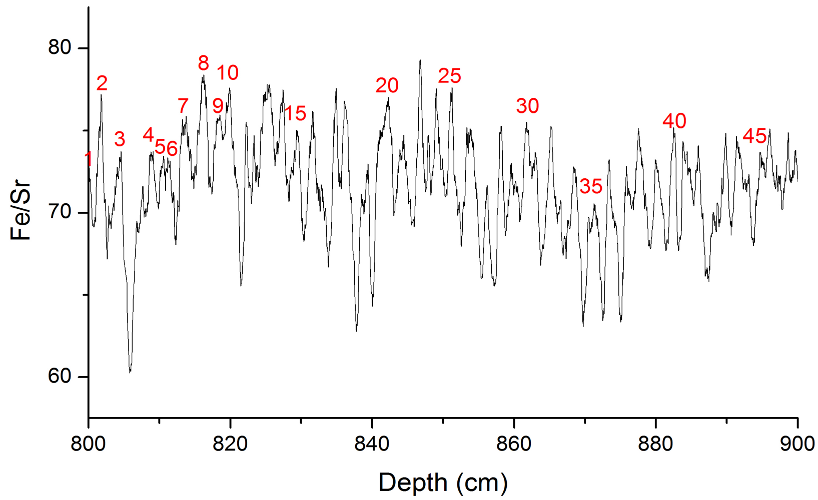


Fig. ED2. Laminae counted using Fe/Sr variability of a one-meter section in HLY1302 JPC15. Many other elemental pairs show similar variability. High Fe/Sr suggests greater terrestrial content. The resolution of the data is 0.4 mm and the data are smoothed with a 19-point running mean. There are about 50 peaks in this section with 2 cm/cycle on average, and the number of cycles varies little with counting method. We counted ~300 laminae between 600 cm (13460 ka) and 1201 cm (14408 ka) where the deposition rate is uniformly high, and those reflect ~300 oscillations in terrigenous input to the continental slope that are probably not annual (300 laminae/948 years = 0.32 laminae/yr) unless the age model underestimates the rate of sedimentation. Note that the calendar ages give lower accumulation rates than those using conventional ^{14}C years as in Fig. 2F.

3. Sampling and stable isotopes

Core JPC15 was initially chosen for study because of its position east of Mackenzie Trough and because of its typical looking magnetic susceptibility. Not knowing what was present, we began with samples ~20 g dry every 50 cm. Based on early $\delta^{18}O_{Nps}$ results, sampling was increased to every 10 cm. About 20 clean and clear (not infilled) specimens of Nps were chosen for stable isotope measurements using standard methods[55]. Although the focus of the stable isotopes in this paper is $\delta^{18}O$, $\delta^{13}C$ was measured and is reported in **Supplementary Table 2**. Note that the $\delta^{13}C$ data are featureless for both Nps and *C. neoteretis*. They compare well with the $\delta^{13}C$ of dissolved inorganic carbon reported from the eastern Beaufort Sea[56].

4. Chronology

4.1 Gulf of Mexico

Leventer et al.[54] was the first study to improve on the original Kennett and Shackleton[4] $\delta^{18}O$ data with a new higher resolution series from piston core EN32 PC6 in anoxic Orca Basin and with bulk organic ^{14}C dates. That was before AMS dating, so as the interest in meltwater diversion and the origin of the YD grew in the 1980s, Broecker et al.[9, 57] used AMS methods to redate the core. Unfortunately, their results contained substantial age reversals. We include Leventer et al.[54] data in Figure 5 because they provide a Holocene context for the higher resolution and better dated $\delta^{18}O$ series of Williams et al.[5]. The two data sets are in good agreement where they overlap. However, this was achieved by (selective) use of the available AMS dates at 29.5, 436.5, 471.0, 486.5, and 809 cm (refs 9, 57) and calibration using ΔR=0.

4.2 Beaufort Sea

Levels for AMS dating (at NOSAMS) were identified based on the $\delta^{18}O_{Nps}$ results, and resampled so that as much as 80 g dry were picked to get sufficient Nps. Where possible, only clean specimens of Nps and *C. neoteretis* were selected from the size fraction >150 µm. This was easy for *C. neoteretis* because the test is transparent**,** but for Nps we set aside clean and empty specimens and cleaned the remainder mechanically as described elsewhere[58]. If that did not clean them sufficiently, we cleaned them ultrasonically, always setting aside clean ones at each step. Ultrasonic cleaning broke up most tests, but clean fragments were sometimes selected for inclusion in the dated sample. Our chronology is based on a Bayesian age model (Figure ED6) using the Nps dated levels (**Supplementary Table 1**, **Fig. ED3**).

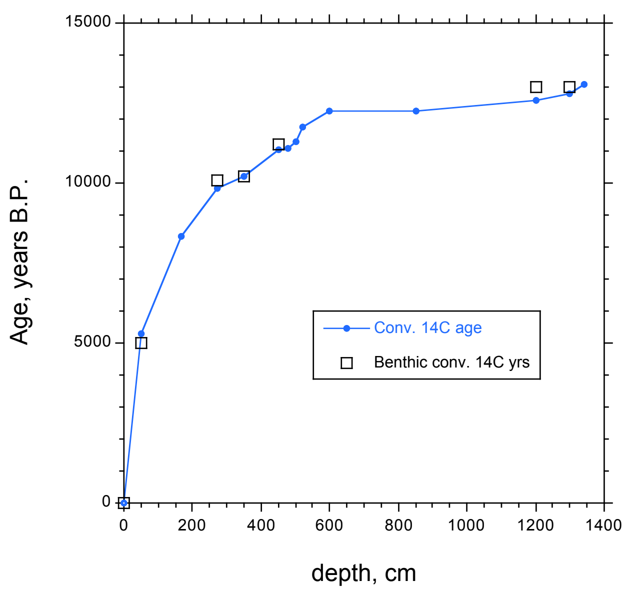


Fig. ED3. Age-depth relationship of conventional AMS ^{14}C dates on Nps (blue circles) and *C. neoteretis* (open black squares) from JPC-15.

4.3 Choice of ΔR

A. Pre-bomb ΔR

Any discussion of ΔR should begin with the modern, or better yet, the pre-bomb ocean. For the Beaufort Sea, the pre-bomb ΔR has been estimated based on radionuclide tracers for Arctic processes[30, 59] (Fig. 5), and in pre-bomb museum specimens of mollusks (especially bivalves[60]). These are very different data sets and the resulting ΔRs are not directly comparable because the mollusk data came from specimens collected along the nearshore continental shelf whereas the ice station data (and our core sites) are far offshore. One notable thing about the Ostlund et al.[30] analysis is discussion of the ^{14}C measurement on surface waters in the east Greenland Current in 1957 that leads them to "safely assume" that shelf water had a pre-bomb $\Delta^{14}C$ of -48 ± 3 ‰. (These data were published first by Fonselius and Ostlund[61] before international standardization.) Although east Greenland is about as far as you can get in the Arctic from the Beaufort Sea, Ostlund and Hut[59] showed that the residence time of shelf and near surface waters in the Arctic is only ~10 years. However, they had no shelf water data from the west Arctic where there

Fig. ED4. Locations of pre-bomb bivalve data[60] from off Alaska on left, downstream in the Amundsen Gulf (middle), and far to the east in Foxe Basin. These sites were chosen to define a flow path where Bering Strait water always hugs the coast and turns right. Today the shelfbreak current has been traced to the entrance of Amundsen Gulf[36], but the bivalve ^{14}C data have a Pacific signature as far to the east as northern Foxe Basin.

is low "preformed" $\Delta^{14}C$ from the Pacific, based on the bivalves.

McNeely et al.[60] compiled mollusk ^{14}C data from all around Canada for the specific purpose of knowing ΔR at continental shelf depths. In the Beaufort-Chukchi Seas they reported dates on 7 bivalve specimens collected from two stations (**Fig. ED4**). Six bivalves were suspension feeders and one was a deposit feeder; that one is significantly older than the others (ΔR=610 yrs). Excluding that datum, the others have a mean ΔR of 440±101 yrs, or a mean $\Delta^{14}C$ close to -100 ‰. That result is greatly different than the $\Delta^{14}C$ of -48 ‰ directly measured in in East Greenland shelf waters[30].

The missing element in the Ostlund and Hut[59] and Ostlund et al.[30] analysis was a source of relatively old waters from the NE Pacific via the Alaska Coastal Current and, through Bering Strait, to the shelf break current in the Beaufort Sea. The shelf break current can be traced as far east as Amundsen Gulf, by which point it is dissipated without evidence of entering the Gulf[36], but the pre-bomb mollusk data[60] can be used to trace transport to the Labrador Sea through the Canadian archipelago in recent times. Forty $\Delta^{14}C$ measurements of Pacific mollusks (Victoria, BC to Bering Strait), excluding deposit feeders, average ΔR=388 ±86 yrs, not significantly different from the Chukchi/Beaufort value cited above (440 ±101 yrs). By Amundsen Gulf, where McNeely et al.[60] have 7 observations from 5 sites (Fig. ED4), the result, ΔR=350±116, is within uncertainty of the Bering Strait source waters. However, by Foxe Basin, ΔR=286 ±74 yrs (n=8), significantly lower (younger) than the Beaufort/Bering Strait data. We choose Foxe Basin as an end point because it represents a pathway that is least likely to encounter younger Atlantic shelf waters, and for the same reason we only use those data on the south side of the strait that connects Gulf of Boothia to Foxe Basin. Nevertheless, a trend of increasing $\Delta^{14}C$ in pre-bomb mollusks from the Gulf of Alaska to Foxe Basin suggests mixing with a young North Atlantic component. These data are substantially older than the East Greenland mollusks, where ΔR=92 ±67 years (n=12).

The east Greenland shelf is the only place where pre-bomb $\Delta^{14}C$ has been measured in both shelf waters (-48±3 ‰) and in mollusks (-61±7 ‰), and with results in reasonable agreement. However, this does not mean that shelf ΔR should be used to calibrate ^{14}C ages from foraminifera on the Beaufort continental slope for a few reasons. (1) The shelfbreak waters that carry the old signal from Bering Strait are well inshore of the surface water overlying our core sites[36]. (2) Although we do not know the pre-bomb ^{14}C age of Beaufort Sea surface waters (Fig. 4), the rather close agreement of paired benthic and planktonic ^{14}C ages suggests the planktonics live in water influenced by the Atlantic layer even in the Holocene. During pre-Holocene time (>11 ka), before Bering Strait was flooded[26, 27], the Atlantic layer might have shoaled in the absence of Pacific water, all else being equal (pers. comm. 2016 from R. Pickart and M. Spall). However, most importantly, (3) the absence of old Pacific water in the pre-Holocene Arctic means that shelf waters must have had much lower ΔR than today prior to 11 or 12 ka.

B. **ΔR in the Nordic Seas**

There are no data from the western Arctic Ocean that can be used to estimate ΔR, so we turn to the Nordic Seas where waters feeding the Arctic surface circulation flow northward along the coast of Norway, and southward from Fram Strait along the Greenland coast to the Labrador Sea. The only useful data sets for this come from Bondevik et al.[28] and Cao et al.[29]. Cao et al.[29] synthesized existing ^{14}C data from the high latitude North Atlantic and presented new data on solitary corals from Orphan Knoll (1600 m water depth). They concluded that the Allerod warm period had a ΔR similar to today (~0 years), and that ΔR was likely about 200 yrs greater during the YD. The Bondevik et al.[28] data contributed greatly to that conclusion. Orphan Knoll data do not reflect coastal conditions but rather the ventilation of the central Labrador Sea, with an unknown transit time from the surface to ~1600 m.

Accordingly, we base our surface reservoir corrections for the eastern Beaufort Sea on the Bondevik et al.[28] data for samples where pairs of marine and terrestrial (atmospheric) ^{14}C dates came from within 1-cm of each other in their cores, and not including data the authors rejected as coming from out-of-place fossils. The difference in conventional ^{14}C age between the marine and terrestrial data is defined as ΔR, and terrestrial dates have been recalibrated using Calib 7.1 using the Marine 2013 curve.

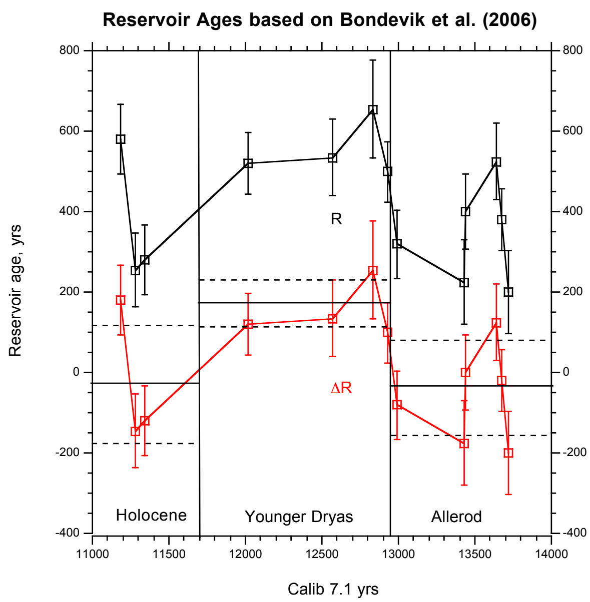


Fig. ED5. Summary of R and ΔR for the Allerod through the early Holocene based on pairs of marine and terrestrial ^{14}C dates from Bondevik et al.[28]. Vertical error bars are ±1σ. Horizontal lines show mean values for the three time intervals, with dashed lines representing ±1σ.

For the Allerod there are seven marine-terrestrial pairs of AMS dates[28] that return a mean of -36 ± 116 years (1σ) (**Figure ED5**). For the Younger Dryas and Holocene, the statistics are 170 ± 60 (n=3) and -28 ±148 (n=3), respectively. Although these data essentially come from only one location and are highly variable, they are the only dates that meet our requirement of being in the flow of coastal waters either entering or leaving the Nordic Seas. The low Allerod and higher YD ΔR are consistent with the synthesis of Cao et al.[29] and it makes sense that, during that relatively warm period with better North Atlantic ventilation, the reservoir effect would have been similar to the Holocene. The Holocene results are generally concordant with the pre-bomb estimate of Ostlund[30]. For calibration purposes we chose ΔR = 0 ± 100 years for the Holocene and the Allerod, and 200 ± 100 for the YD. These values are increased somewhat from the measured values (Fig. ED5) because there is some evidence for increased ΔR with latitude along the Norwegian coast, but even the authors who made that observation do not agree about its significance[62]. Note that for dating the beginning of the YD it is important to use the Allerod ΔR, not that of the YD. This is because if the YD flood caused a decrease in the AMOC, and if that caused the increase in ΔR through changes in storage and exchange in the ocean-atmosphere carbon system, then the Allerod ΔR is more appropriate than the YD ΔR.

4.4 Bayesian age modeling.

As recommended by an anonymous reviewer, we developed an age model for JPC15/27 using the "Bacon" software of Blaauw and Christen[63] (2011). This method evaluates rates of sedimentation for discrete sections of the core, and these are informed by results in surrounding sections. The appropriate command settings for our model are: Bacon("JPC-15", 25, acc.mean=2, acc.shape=1.1, normal=TRUE, remember=FALSE, depths.file=T), agedepth(rotate.axes=TRUE, rev.yr=TRUE). We input our ^{14}C dates with the higher ΔR during the YD, we fixed the core top to equal zero years, and the calibration was done using the Marine 13 curve. The resulting age-depth relationship (**Fig. ED6**), illustrates the mean age of levels in the core and the 95% confidence interval. Of critical importance is the calendar age of the sample at 514 cm, where $\delta^{18}O$ is about halfway to its minimum value: 12,939 calendar years B.P., with a minimum age of 12,786 years and a maximum age of 13,080 years, or about 12.94 ± 0.15 ka. The abrupt decrease in $\delta^{18}O$ lies within the 95% confidence interval of 13 ka, the nominal date for the diversion of meltwater from the Gulf of Mexico[5], and before the ~12,850 year start of the YD on the Greenland ice core timescale[34].

We experimented with other age models, to test the robustness of our result. Using a constant ΔR of 0 ± 100 yrs for the entire record gave about the same age for the sample at 514 cm with the variable ΔR model, so we know that the "bacon" age is not influenced by the decrease of sedimentation rate and increase in ΔR during the YD. Likewise, doubling the uncertainty in ΔR for the entire record returns the same ages but with less confidence. In sum, our conclusions are driven mostly by the choice of ΔR; we cannot reject the hypothesis that the flood down Mackenzie River was coincident with the beginning of the Younger Dryas cooling using any DR that is consistent with the Allerod data (Fig. ED5). Using our preferred age model (Fig. ED6), we summarize ages and uncertainties associated with the $\delta^{18}O_{Nps}$ evidence for the YD flood in JPC15/27 in **Supplementary Table 3**.

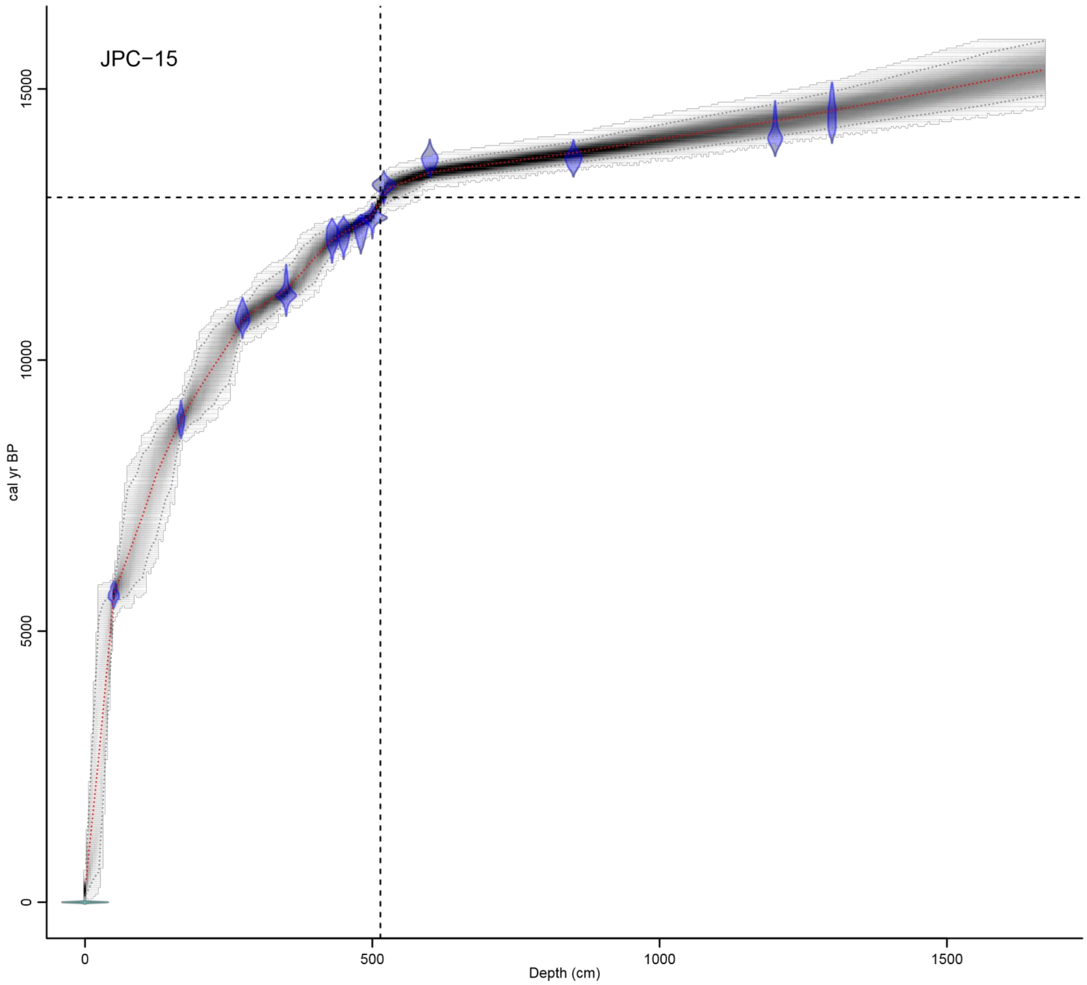
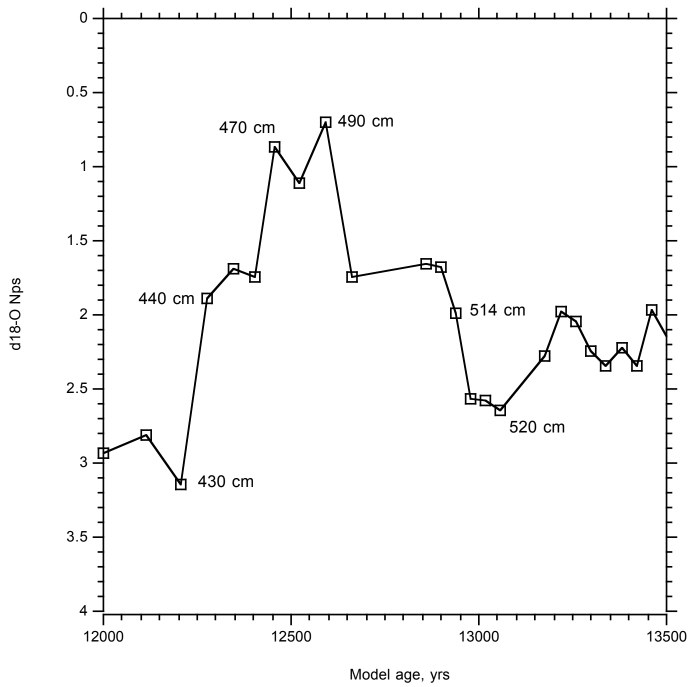


Figure ED6. Age model for JPC15/27 using the Bayesian method "Bacon"[63]. Horizontal dashed line is at 13 ka and vertical dashed line is at 514 cm. The model gives an age at 514 cm of 12.94 ± 0.15 ka. A blow-up of the critical $\delta^{18}O_{Nps}$ data 12-13.5 ka is shown in Figure ED7.

5. Regional summary of oxygen isotope data

5.1 New core data from this study

It is important to determine the spatial extent of the YD flood within the Beaufort Sea because Coriolis forcing would drive a buoyant flow to the right from Mackenzie River, and northward along the Canadian Archipelago toward Fram Strait. Such a direct path to the North Atlantic might have the most climate impact because the surface waters would be freshest. On the other hand, wind forcing could counteract the Coriolis driven



ED Fig. 7. Blow-up of $\delta^{18}O_{Nps}$ data associated with the YD flood at JPC15/27. The depth of important features is indicated for reference to Supplementary Dataset 3. We interpret these data to mean that the flood was underway as early as 12940 ± 150 years ago, the age of the sample at 514 cm.

flow and perhaps allow more mixing with Beaufort Gyre. In that case, the freshening in the North Atlantic region might have been less but may have lasted longer.

Here we summarize the stratigraphic data from cores extending from JPC15/27 in the east, which we consider to be a "type section," to other cores as far west as Barrow, AK (**Fig. ED8**). West of Mackenzie River at JPC-09 we have identified a $\delta^{18}O_{Nps}$ minimum at about 13 m below the seafloor. It reaches 1 ‰, close to the minimum at JPC15/27 and it occurs a meter below a prominent maximum in magnetic susceptibility. This phasing is similar to results at JPC15/27, and the AMS date at JPC-09 falls within the range of dates constraining the flood event to the east. The brief peak in magnetic susceptibility at JPC15/27 at ~500 cm is not matched at JPC-09 probably because the ice rafting, which becomes common >1300 cm, stopped the corer. If we calibrate the YD ^{14}C ages from JPC-09 (Supplementary Table 1) with ΔR=200±100, the $\delta^{18}O_{Nps}$ changes are well-matched at the two cores (Fig. 5, Fig. **ED9**).

JPC-09 is very close to core P45 of Andrews and Dunhill (2004)(Fig. 1), so we recalibrated the age model for that core using ΔR= 0±100 (post YD) and plotted their $\delta^{18}O_{Nps}$ with the new data from this study (Fig. ED9). The agreement between these cores is good, although the age model may make the bottom of P45 too old because their oldest date was on benthic foraminifera. Note that the minimum in $\delta^{18}O_{Nps}$ was not found by Andrews and Dunhill (2004), most likely because the corer failed to penetrate the ice rafted layer at about 5 m subbottom.

Continuing farther west of Mackenzie River, the $\delta^{18}O_{Nps}$ at JPC-06 records only a small minimum before the main peak in magnetic susceptibility (Fig. ED8). This suggests that the YD meltwater plume must have been very localized to the region east of this site with only minor salinity lowering of the near surface ocean. Of the samples examined, a small peak in ice rafting is associated with the small minimum in $\delta^{18}O_{Nps}$.

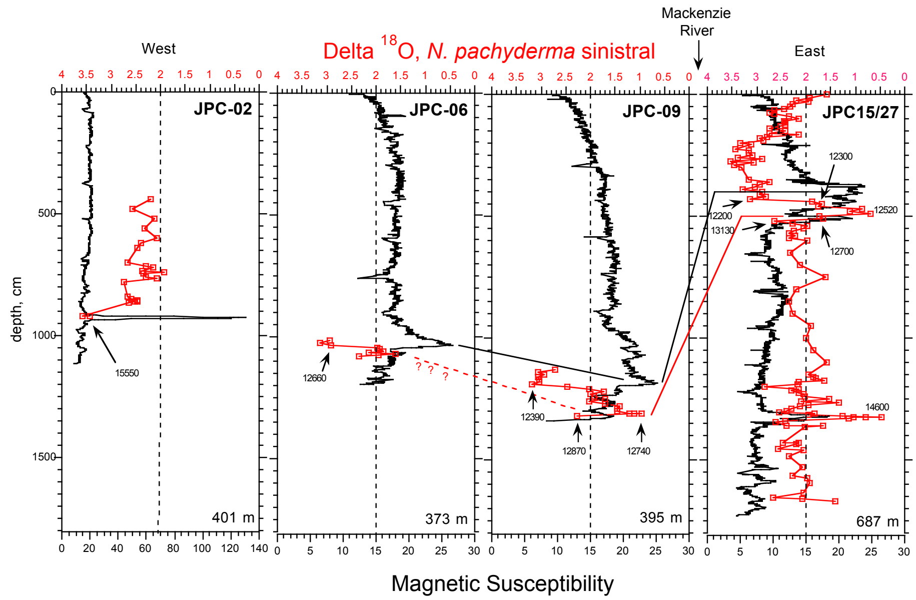


Figure ED8. Comparison of magnetic susceptibility and $\delta^{18}O_{Nps}$ stratigraphies in a zonal transect of cores from east of Mackenzie River (JPC15/27) to Barrow, AK (JPC-02). The vertical dashed line in each core marks the baseline $\delta^{18}O_{Nps}$ as reference for surface freshening. The solid black and red lines correlate the magnetic susceptibility $\delta^{18}O_{Nps}$ peaks, respectively. Note the decreasing influence of $\delta^{18}O_{Nps}$ lowering (freshening) from east to west.

In the Chukchi Sea off Barrow, AK, the most notable feature of JPC-02 is an IRD and magnetic susceptibility peak at ~920 cm that dates to 15.55 calibrated ka and includes a 6-cm dark non-carbonate dropstone. Because this event is not recorded far to the east at JPC15/27, and is >1000 years older than the 14.6 ka event at that site, it gives a maximum age for the bottom of the composite section at JPC15/27, assuming the event came from the Canadian Archipelago and would probably have spread across the Beaufort Sea. That maximum age (15.5 ka) agrees well with the 15.4 ka extrapolated age for the end of the JPC15/27 $\delta^{18}O_{Nps}$. Also of note is the maximum in $\delta^{18}O_{Nps}$ coincident with this IRD layer; this is the opposite of what we see in the YD and 14.6 ka events closer to Mackenzie River and it is the heaviest we have measured in this study.

Most of the $\delta^{18}O_{Nps}$ data fall higher than the 2 ‰ reference level for the entire record <15.5 ka (Fig. ED8), similar to the nearby Holocene results from Keigwin et al.[26]. Thus, taking into account the ice volume effect on $\delta^{18}O$, we conclude that the near sea surface off Barrow was fresher than today during most of the deglaciation, but there must also have been a salinity gradient from the Chukchi Sea to the eastern Beaufort Sea. This points to Mackenzie River as the source of the freshening, but the absence of evidence for the YD flood off Barrow suggests that floodwaters were not diluted much by mixing in the Beaufort Gyre. If supported by further data, this could mean that the YD flood was brief compared to the mixing time of the Beaufort Gyre and might have been especially potent in affecting the AMOC.

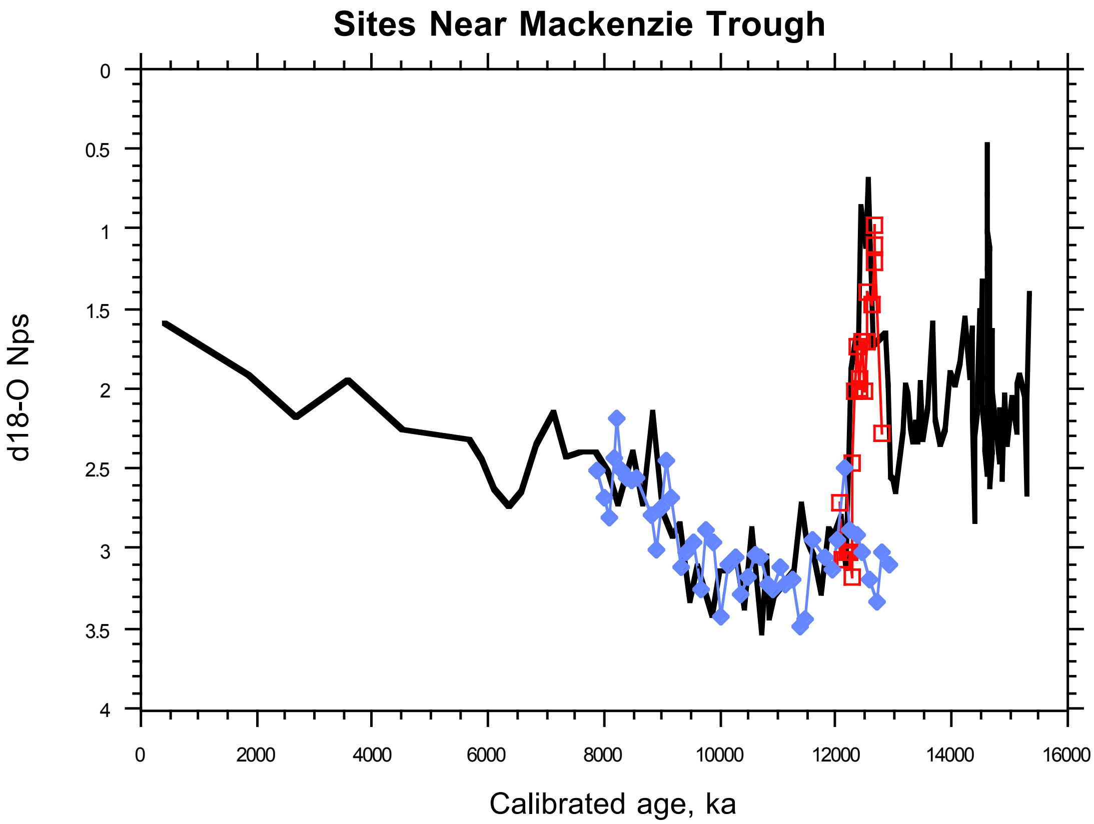


Fig. ED9. Comparison of $\delta^{18}O_{Nps}$ data between JPC15/27 (black line), JPC-09 (red squares) and core P45 (blue diamonds)[64]. Note the excellent agreement of minima in $\delta^{18}O_{Nps}$ from this study.

5.2 Other published core data

Several papers report stable isotope and radiocarbon data from the western Arctic (Mendeleyev Ridge) including, for example, Poore et al.[65]and Polyak et al.[66]. We cannot directly correlate our results from the eastern Beaufort Sea with those because they have much lower rates of sedimentation and fewer ^{14}C dates. Given that we also cannot correlate to our own core off Barrow (**Fig. ED8**), which does have high rates, it is possible that there was substantial spatial variability in near surface ocean conditions in the western Arctic during deglaciation. As an example of this, both Poore et al.[65] and Polyak et al.[66] found deglacial minima in $\delta^{18}O_{Nps}$ that are 0 ‰ or even lower. These are probably not evidence of the YD flood from Mackenzie River because the $\delta^{18}O_{Nps}$ is lower than we observe closer to the source, and the rates of sedimentation are probably too low to resolve such a brief event.

Closer to the Beaufort Sea, on the Chukchi Borderlands, Polyak et al.[67] do find a $\delta^{18}O_{Nps}$ minimum of about 1‰ that could be related to one of those we see at core 15/27.

However, using ΔR=0, their benthic foram calibrated date for that event is 13.8 ka which falls between the events we have found. That event is associated with a small peak in ice rafting (but not magnetic susceptibility), and below that there is a much larger undated IRD event coincident with a large peak in magnetic susceptibility.

In addition to the comparisons discussed above, we can also correlate to results from Mackenzie Trough near our JPC-13 (ref. 41). One of their cores sampled the same high $\delta^{18}O_{Nps}$ (3.11 ±0.28 ‰, n=9) interval ~10-12 ka as in JPC15/27. The Schell et al. [41] data fall mostly between 10.9 and 10.6 ka when recalibrated.

Extended Data references:

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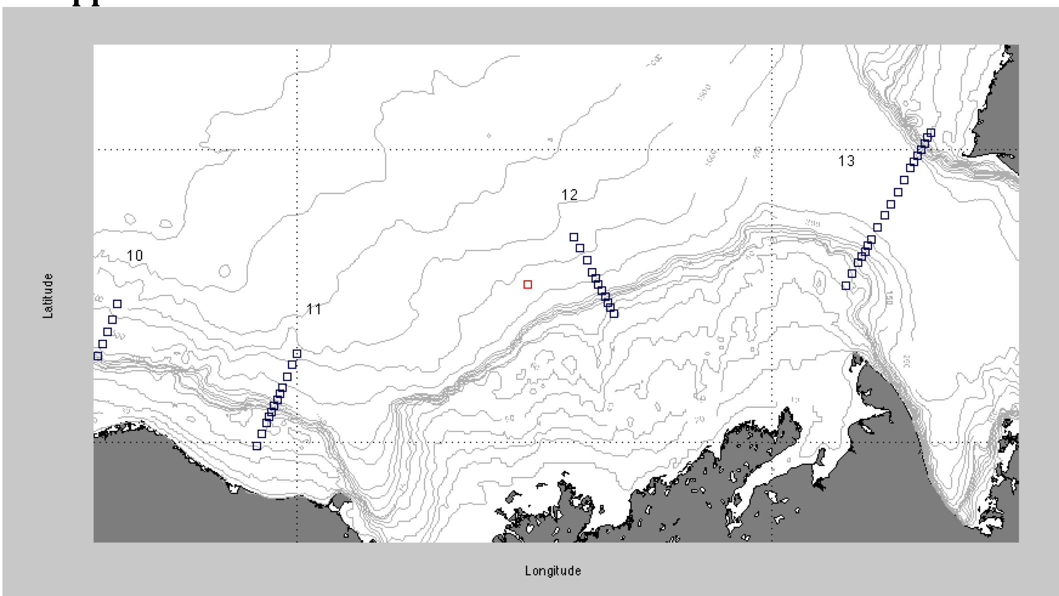
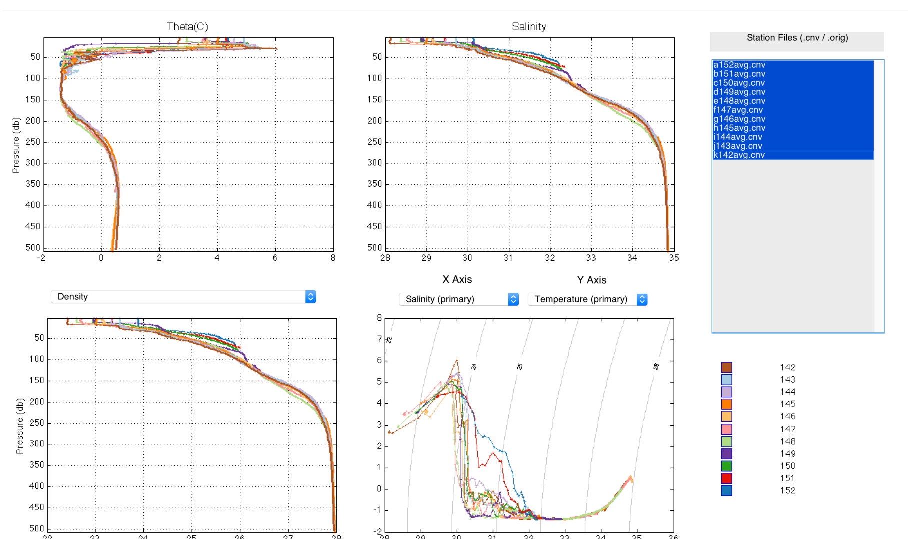
ED Appendix 1.



ED Appendix Fig. 1. HLY1003 Station positions for the hydrographic data in ED Appendix Fig. 2 provided by Dr. Robert Pickart (WHOI). The position of HLY core JPC15/27 is shown as a red square.



ED Appendix Fig. 2. Data for section 12 presented vs pressure (~depth) as potential temperature (upper left), salinity (upper right), density (lower left), and T vs S (lower right). All hydrographic data are available at: http://aon.whoi.edu.