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Supplementary Information

A 100 year record of ocean temperature control on the stability of Jakobshavn Isbrae, West Greenland

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1. Site location

Cores 343300, 343310, 343320 and 343410 (Figure DR1, Table DR1) were taken during cruise MSM05/03 with the German Research Vessel "Maria S. Merian" in 2007 (Harff *et al.*, 2008). All sites lie below the modern flow path of the West Greenland Current (WGC). Core 343310 was chosen as the main core for our study based on the high sedimentation rate of this core and the high abundance and preservation of benthic foraminifera.

Table DR1. Location of cores collected during R/V "Maria S. Merian" cruise in 2007

Core	latitude	longitude	Water depth (m)	Coring device
343300	68°28,311'N	54°00,118'W	520	Multi-core
343310	68°38,869'N	53°49,486'W	852	Multi-core
343310	68°38,861'N	53°49,493'W	856	Gravity core
343320	68°51,879'N	53°19,719'W	862	Multi-core
343410	69°10,998'N	51°29,499'W	399	Multi-core

2. Age / depth model for multi-cores

A robust chronology has been developed for the multicore 343310 based on ^{210}Pb and supported by ^{137}Cs, ^{14}C dates and additional sedimentological information.

2.1. ^{210}Pb / ^{137}Cs chronology

Samples for analysis were freeze-dried and ground to a fine powder in a ball mill. A known mass of homogenised sample was packed into a 40 mm PTFE tube. The sample tube was then closed with a rubber Supraseal and the seal painted with paraffin wax to form an air tight barrier to prevent ^{222}Rn gas escape. The tubes were then left to stand for at least 21 days to allow the unsupported ^{210}Pb activities to reach equilibrium with ^{222}Rn.

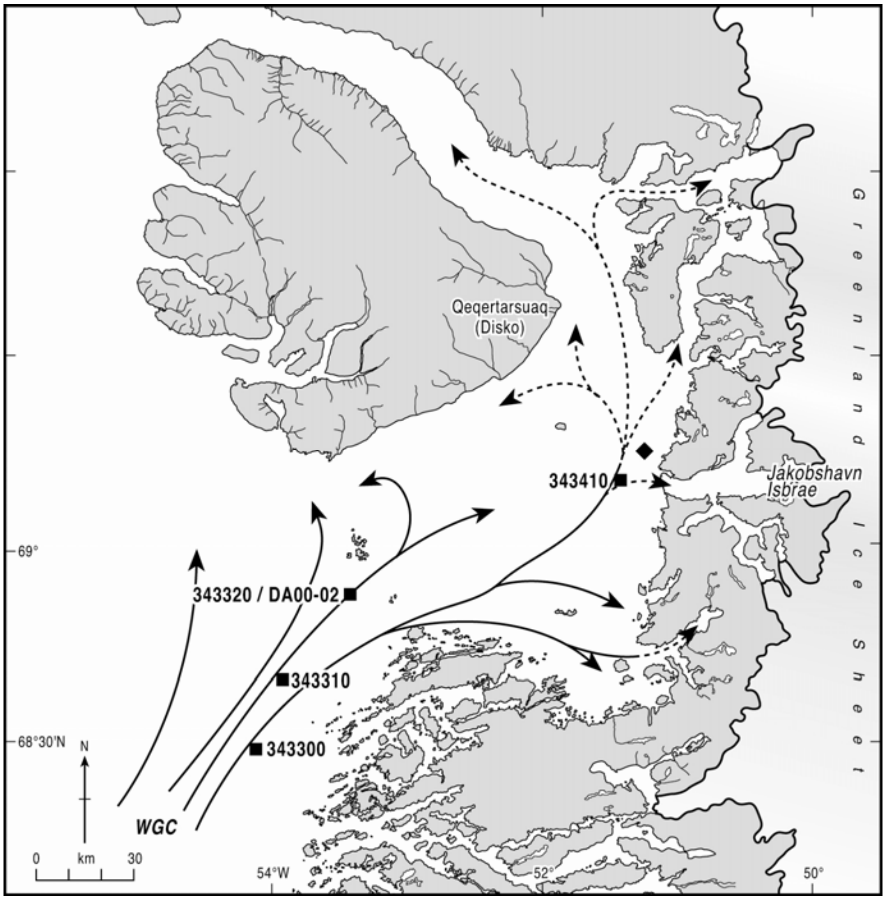

Figure DR1. Map of Disko Bugt showing location of additional multi-cores. Location of core DA00-02 (collected in 2000) is shown along with location of surface samples POR20 and POR21 collected in 1999. WGC - West Greenland Current.

A low background hyper pure germanium well detector was used to perform the analysis. The endcap well has a diameter of 10mm and a depth of 40mm. The germanium crystal has an active crystal volume of 232cm^3. A DSPEC Jnr 2.0 amplifier was a set to 8000 channels with the gain adjusted to give a spectral range from 30 to 1500keV.

The energy, FWHM and Efficiency calibrations were performed using 3 sets of certified sealed standards (Eckert & Ziegler Nuclitec GmbH) encapsulated into the same type of PTFE tubes as are used for the samples. The individual calibration standards consist of ^{210}Pb, ^{226}Ra (for ^{214}Pb) and a mixed standard of ^{241}Am, ^{137}Cs, and ^{60}Co (for ^{137}Cs). The calibration standard activities give a dead time of <7%. Sample count times were typically in excess of 450,000 seconds and counting errors were typically less than 10%. Monthly background counts were taken and stripped from measured spectra using the ratios of live times using EG&G GammaVision® software.

For multicore 343310, the relationship between log ^{210}Pb activity and depth is almost linear, but the full ^{210}Pb inventory is not recovered. Because of this, the constant flux:constant sedimentation model was fitted. The cumulative dry mass was used instead of depth in the model.

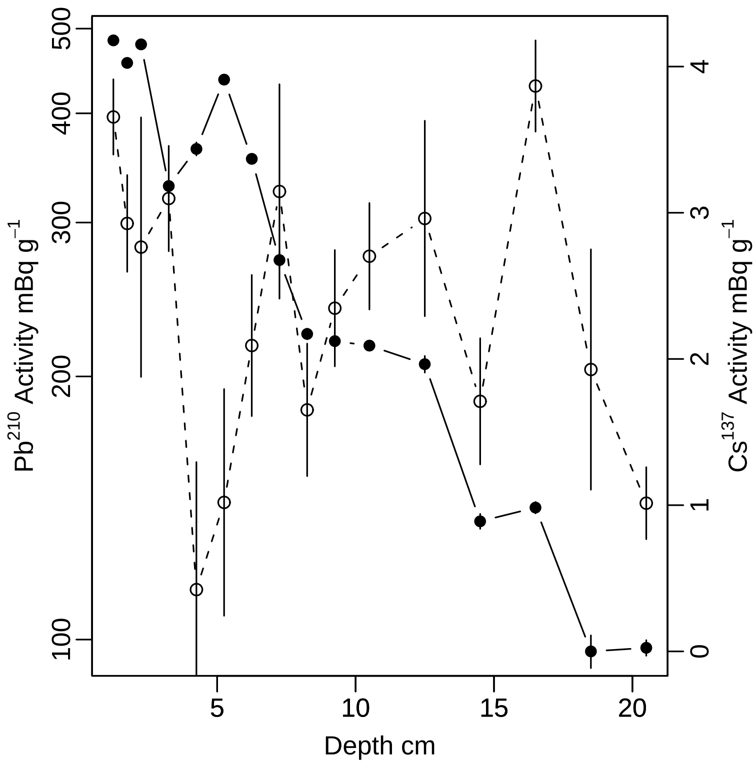

Figure DR2. ^{210}Pb (filled circles) and ^{137}Cs (open circles) activities for multicore 343310.

^{137}Cs activities in Arctic waters peaked about 1963 (Aarkrog *et al.*, 1999), followed by a slow decline as ^{137}Cs from weapons testing fallout is augmented by reprocessing discharges and the Chernobyl accident. The peak in the sediment may postdate 1963 because of bioturbation. The ^{210}Pb model passes very close to the ^{137}Cs peak (Fig. DR2).

2.2.AMS^{14}C chronology

AMS radiocarbon dates (Tables DR3 and DR4) were calibrated with the Marine09 (Reimer *et al.*, 2009) calibration curve using OxCal 4.1 (Bronk Ramsey, 2009). The marine reservoir offset was estimated using Reimer and Reimer (2001). This database includes six entries for Disko Bugt. Three samples are from *Mytilus edulis* collected in shallow water. These samples, measured in the 1970s, have a ΔR of less than 80 years (two are negative), with large uncertainties (Krog and Tauber, 1974). A fourth sample of seal bones, has a ΔR of 75 years (Tauber, 1979). These shallow water, or mobile, samples may not accurately reflect sub-surface conditions in Disko Bugt, so we focus on the two dates from deeper (60-70m) water (McNeely *et al.*, 2006). These two dates are duplicates on the suspension feeder *Astarte montagui* and have a higher and more precise estimate of the ΔR than the shallow water samples. We, therefore, use a value of 140 ± 30 yr for ΔR in this study.

Radiocarbon dates younger than the reservoir age were assumed to indicate the incorporation of bomb radiocarbon. Bomb radiocarbon in the North Atlantic began to rise rapidly in the late 1950s and early 1960s (Kalish *et al.*, 2001). Dates younger than the reservoir age and with less than 100% modern carbon are assumed to be from between 1950 and 1962, those with more than 100% modern carbon are assumed to post-date 1962. For multicore 343310, the dates support the ^{210}Pb model and the choice of ΔR (Fig. DR3).

Table DR3. Multicore and box core (DA00-02 taken in 2000) radiocarbon dates.

core	depth (cm)	Lab. code	Material	Mass mgC	^{14}C date yrs BP (pMC)	Years (A.D.)
343310	1-3	Poz-30979	N. labradorica	0.4	101.0 ± 0.4 pMC	NA
343310	5.5-6.5	Lu-8700	mix benthic forams	0.31	101.6 ± 0.7 pMC	NA
343310	8.5-10.5	Lu-8701	mix benthic forams	0.17	101.3 ± 0.7 pMC	NA
343310	12.5-14	Poz-30980	mix benthic forams	0.32	23 ± 33 (99.7 ± 0.4 pMC)	NA
343310	13-17.5	Lu-8702	mix benthic forams	0.19	215 ± 60 (97.4 ± 0.7 pMC)	NA
343310	22.5-24	Lu-8703	mix benthic forams	0.14	600 ± 60 (92.8 ± 0.7 pMC)	AD 1950 - 1810
343310	26.5-27	Poz-30981	Shell	0.7	542 ± 29 (93.5 ± 0.3 pMC)	AD 1950 - 1880
343310	26.5-27.5	Lu-8704	mix benthic forams	0.25	575 ± 60 (93.1 ± 0.7 pMC)	AD 1950 - 1830
343310	29.5-31	Lu-8705	mix benthic forams	0.28	545 ± 60 (93.4 ± 0.7 pMC)	AD 1950 - 1850
343310	31.5-32.5	Poz-30982	N. labradorica	0.3	565 ± 35 (93.2 ± 0.4 pMC)	AD 1950 - 1860
343320	16	Poz-28421	mix benthic forams	NA	101.8 ± 0.4 pMC	NA
343320	29	Poz-28422	mix benthic forams	NA	540 ± 26 (93.5 ± 0.3 pMC	AD 1950 - 1890
343320	50	Poz-28423	mix benthic forams	NA	627 ± 35 (92.5 ± 0.4 pMC)	AD 1950 - 1810
DA00-02	14	AAR10551	mix benthic forams	NA	Modern	NA
DA00-02	36	KIA27912	mix benthic forams	0.5	510 ± 40	AD 1950 - 1890
343410	1-3	LuS-8476	mix benthic forams	NA	30 ± 60 (99.6 ± 0.8 pMC)	NA
343410	2.5-3	LuS-8475	Shell	NA	101.7 ± 0.6 pMC	NA
343410	14-15.5	LuS-8699	mix benthic forams	NA	20 ± 60 (99.8 ± 0.8 pMC)	NA
343410	34-36	LuS-8474	mix benthic forams	NA	720 ± 60 (91.4 ± 0.7 pMC)	AD 1830-1660
343300	25-28	Poz-35009	mix benthic forams	NA	700 ± 28 (91.6 ± 0.3 pMC)	AD 1810-1690

2.3. Other chronological evidence

2.3.1. Holocene Sedimentation rates

Long gravity cores are available from sites 343310. If the sedimentation rate in the multicore is assumed to be equal to or similar to that in the upper metre of the gravity core, this can be used as a check on the chronologies used on the multicores.

The chronology for gravity core 343310 (Table DR4 and Figure DR4) is based on 20 AMS ^{14}C dates calibrated with OxCal4.1 (Bronk Ramsey, 2009) and fitted with a mixed effect model. The sedimentation rate for the upper metre of gravity core 343310 is 3.5 mm/yr, very close to the value for the multi-core calculated based on the ^{210}Pb model of 3.7 mm/yr.

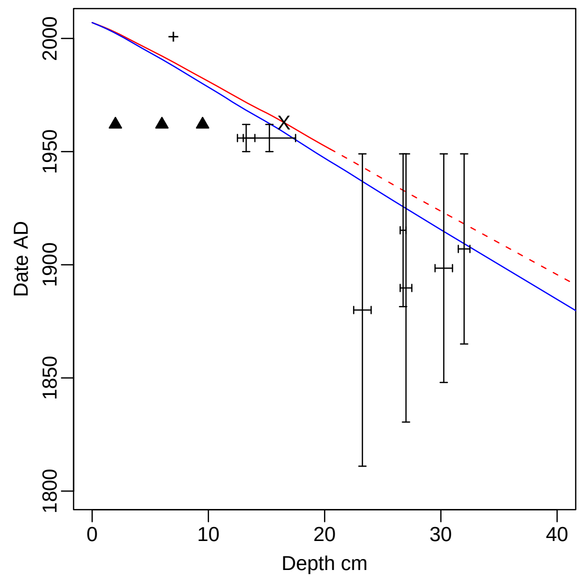

Figure DR3. Chronological data for multicore 343310, ^{210}Pb constant flux:constant sedimentation - red line (extrapolation dashed). Sedimentation rate based on adjacent long gravity core, blue line. The ^{137}Cs peak is marked by the 'X'. Foraminiferal ^{14}C dates – post bomb ages are marked by filled triangles and calibrated ages are marked with 1σ error bars. The '+' represents the marker for AD2000 based on foraminiferal assemblage from DA00–02 collected from the same location in 2000.

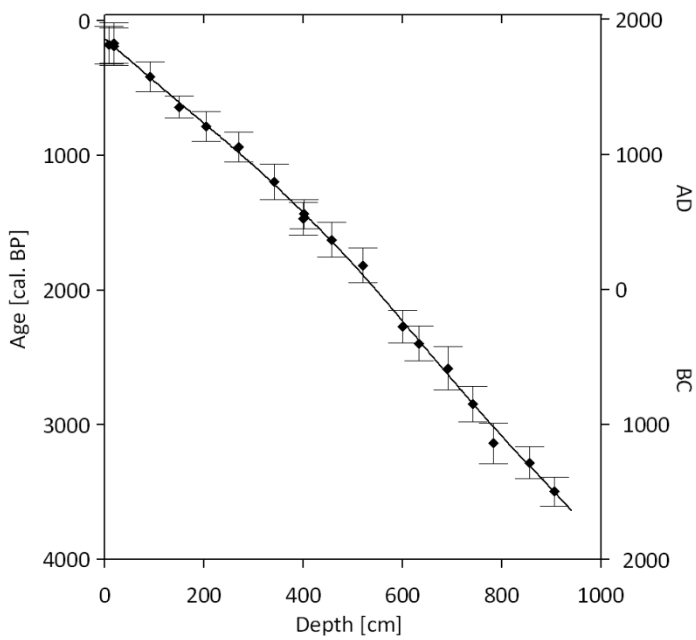

Figure DR4. Age model developed from ^{14}C radiocarbon dates from gravity core 343310 (see Table DR4 for details of individual ^{14}C dates).

Table DR4. Radiocarbon dates from gravity core 343310

depth (cm)	Lab. code	Material	Mass mgC	^{14}C date yrs BP (pMC)	Calibrated yrs BP 1950	Years (A.D./B.C.)
6 - 10	Poz-33417	mix benthic forams	NA	671 ± 29 (92 ± 0.4 pMC)	110 – 250	AD 1840 - 1710
18 - 20	Poz-33412	mix benthic forams	NA	659 ± 33 (92.1 ± 0.4 pMC)	90 – 240	AD 1860 - 1710
18 - 19	Poz-22357	Mollusc shell	NA	682 ± 32 (91.8 ± 0.4 pMC)	120 – 260	AD 1830 - 1690
90 - 92	Poz-33453	mix benthic forams	NA	909 ± 35 (89.3 ± 0.4 pMC)	360 – 470	AD 1590 - 1480
149 - 151	Poz-33411	mix benthic forams	NA	1216 ± 30 (86 ± 0.3 pMC)	600 – 680	AD 1350 - 1270
204 - 205	Poz-30969	Mollusc shell	NA	1384 ± 27 (84.2 ± 0.3 pMC)	730 – 840	AD 1220 - 1270
269 - 271	Poz-33413	mix benthic forams	NA	1526 ± 34 (82.7 ± 0.4 pMC)	880 - 990	AD 1070 - 960
340 - 342	Poz-33488	mix benthic forams	NA	1768 ± 46 (80.2 ± 0.5 pMC)	1130 - 1260	AD 820 - 690
400 - 401	Poz-33414	mix benthic forams	NA	2074 ± 29 (77.2 ± 0.3 pMC)	1410 - 1530	AD 540 – 420
401 - 402	Poz-22359	Mollusc shell	NA	2029 ± 28 (77.7 ± 0.3 pMC)	1380 - 1490	AD 570 - 460
457 - 458	Poz-30970	mix benthic forams	NA	2198 ± 31 (76.1 ± 0.3 pMC)	1560 - 1690	AD 390 - 260
519 - 521	Poz-33416	mix benthic forams	NA	2356 ± 35 (74.6 ± 0.3 pMC)	1750 - 1880	AD 200 - 70
600 - 601	Poz-30971	Mollusc shell	NA	2733 ± 30 (71.2 ± 0.3 pMC)	2210 - 2330	BC 260 - 380
633 - 634	AAR-1699	Mollusc shell	NA	2845 ± 37 (70.2 ± 0.3 pMC)	2330 - 2460	BC 380 - 510
691 - 692	Poz-30972	Mollusc shell	NA	2956 ± 30 (69.2 ± 0.3 pMC)	2500 - 2660	BC 550 - 710
740 - 742	Poz-33418	mix benthic forams	NA	3217 ± 34 (67 ± 0.3 pMC)	2780 - 2910	BC 830 - 960
782 - 783	Poz-30973	Mollusc shell	NA	3430 ± 33 (65.2 ± 0.3 pMC)	3060 - 3210	BC 1110 - 1260
856 - 857	Poz-30974	Mollusc shell	NA	3544 ± 32 (64.3 ± 0.3 pMC)	3220 - 3340	BC 1270 - 1390
855 - 857	Poz-33419	mix benthic forams	NA	3541 ± 36 (64.4 ± 0.4 pMC)	3220 - 3340	BC 1270 - 1390
905 - 906	Poz-30975	Mollusc shell	NA	3746 ± 26 (62.7 ± 0.2 pMC)	3440 - 3550	BC 1490 - 1600

2.3.2. Benthic foraminifera assemblage changes between 2000 and 2007

A short core collected in 2000 did not contain the peak in warm water taxa found at the top of the multicore collected from the same location in 2007 (Fig DR5, see section 3 below for definition and justification of warm water group). Box core DA00-02 was taken at the site of multicore 343320 in 2000 (Fig DR1) and contains 23% warm water fauna at the surface (Fig. DR5).

Multicore 343320 shows a rise in warm water fauna from 20% to > 80% at the top of the core. This supports an age model correlating the rise in warm water fauna in multicore 343320 with the similar rise in the other multicores.

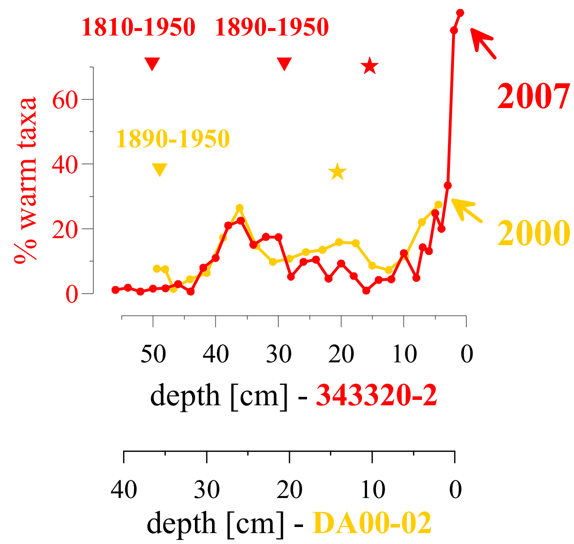

Figure DR5. Abundance of relatively warm water fauna (combined agglutinated and calcareous taxa) from multi-core 343320 collected in 2007 (red) and box core DA00-02 collected from a similar location in 2000 (yellow). Position (▼) and age of calibrated ^{14}C dates are shown; position of modern ^{14}C dates are also shown (*).

3. Preparation and analysis of foraminifera

A standard volume of sediment (8ml) was soaked overnight then sieved at 63 µm. All foraminifera were counted from the wet residue fraction coarser than 63 µm. Samples were counted wet to reduce any loss caused by drying of the more fragile arenaceaous species as advocated and used in previous studies (Scott and Vilks, 1991; Lloyd *et al.*, 2005).

The fauna from multicore 343310 has calcareous and agglutinated foraminifera throughout, but does show rather large changes in relative abundance of calcareous and agglutinated specimens. Therefore we have plotted the relative abundance of foraminifera separately for the calcareous and agglutinated fauna (Fig. DR6). The summary graphs of relatively warm (Atlantic Water) and relatively cold (Arctic Water) indicators shown in Fig. DR6 for calcareous and agglutinated specimens show the same trends. This supports our decision to combine calcareous and agglutinated specimens and plot total assemblages in our interpretation of oceanic conditions. As we present percentage data the graphs will be influenced by the 'closed array' issue (a rise in one variable will automatically force a fall in another variable). However, the trends identified are still significant.

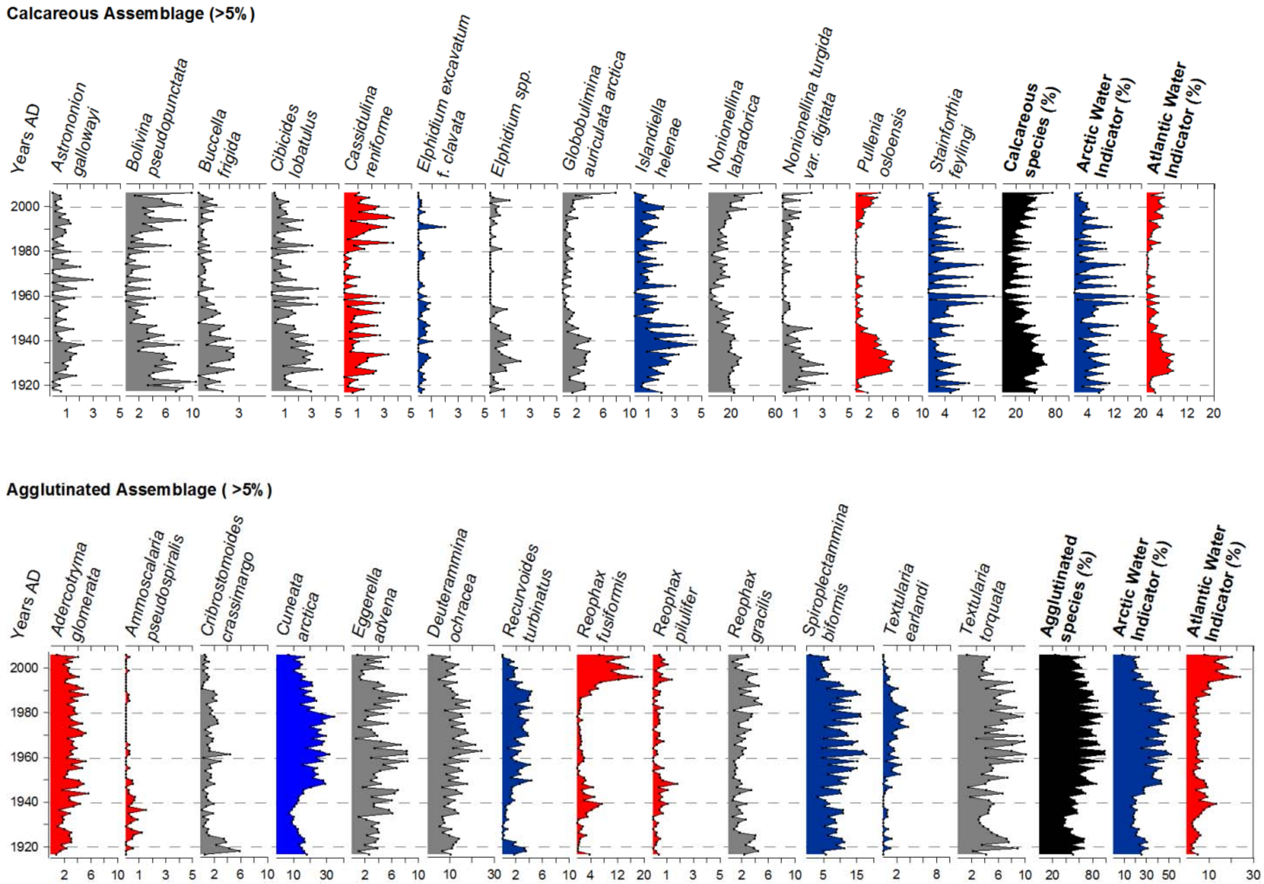

Figure DR6. Benthic foraminiferal assemblages from core 343310 split into calcareous only and agglutinated only groups. In these graphs percentage calculations are based on calcareous counts only for calcareous assemblage and agglutinated counts only for agglutinated assemblage. Summary curves on the right show percentage abundance of relatively cold water (Arctic Water) indicator species and relatively warm water (Atlantic Water) indicator species.

Benthic foraminifera are sensitive to a range of ecological parameters (Murray, 1991). In high northern latitudes certain species are particularly sensitive to water mass characteristics, such as temperature and salinity (e.g. Rytter *et al.*, 2002; Sejrup et al., 2004; Lloyd, 2006). These areas are strongly influenced by inflowing Atlantic sourced waters and, therefore, show a good correlation between temperature and salinity – a stronger Atlantic water influence brings more saline and warmer water, while a decrease leads to cooler and lower salinity water. There are certain benthic foraminifera species that are indicative of warmer more saline Atlantic water and others that are indicative of colder less saline Arctic water. We have used these characteristics to group species into a relatively warm water group (Atlantic water indicator species) and cold water group (Arctic water indicator species).
The ecological groupings used in this study are as follows;

Relatively warm water indicators: *Adercotryma glomerata*, *Ammoscalaria pseudospiralis*, *Reophax fusiformis, Reophax pilulifer, Saccammina difflugiformis, Cassidulina reniforme,* and *Pullenia osloensis*. The majority of these species are well documented as indicators of relatively warm water conditions in high latitude studies from fjords and shelf areas associated with Atlantic water influence (Vilks, 1980; Mudie *et al.*, 1984; Jennings and Helgadottir, 1994; Steinsund *et al.*, 1994; Hald and Steinsund, 1996; Hald and Korsun, 1997; Lloyd, 2006). We also include *Cassidulina reniforme,* which has been associated with chilled Atlantic water (Hald and Steinsund, 1996; Guilbault *et al.*, 1997) and *Pullenia osloensis* (associated with increased nutrient supply via the Atlantic water flux, Wollenburg *et al*., 2004). These species are, therefore, correlated with relatively warmer waters associated with a stronger Atlantic water influence in the WGC.

Relatively cold water indicators: *Cuneata arctica, Spiroplectammina biformis, Elphidium excavatum* f. *clavata* and *Islandiella hellenae*. These species have been identified in many studies of high latitude areas associated with relatively cold arctic waters or glaciomarine conditions (Vilks, 1964; Schafer and Cole, 1986; Jennings and Helgadottir, 1994; Korsun and Hald, 1998; Korsun and Hald, 2000; Lloyd, 2006). *Stainforthia feylingi* is also included in this group. This is predominantly an opportunistic species able to compete and bloom in environmental conditions with only episodic food supply, low oxygen levels, but also low salinity levels – conditions in which most species are unable to survive/ compete (Alve, 1994; Bernhard and Alve, 1996; Knudsen and Seidenkrantz, 1994). In this location *S. feylingi*, therefore, indicates conditions with reduced Atlantic water influence – hence colder waters.

The trends in foraminiferal assemblage from multi-core 343310 are supported by similar trends seen from the series of multi-cores studied (Fig. DR7). The actual percentage values vary due to differences in modern conditions produced by different sample site water depths. In particular all cores show a significant increase in warm water fauna towards the top of each core (shown by red arrows in Fig. DR7). Multi-cores 343310, 343320 and 343410 also show a similar reduced amplitude increase in warm water fauna lower down in each core (shown by red arrows in Fig. DR7).

Figure DR7. Location of additional multicores along with summary foraminiferal curves. Abundance of relatively warm (red) benthic foraminifera are shown from each core along with relatively cold fauna (blue) from multicore 343310. Red arrows on the graphs highlight the peaks in warm water fauna that can be correlated with the peaks identified from the main core (343310).

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