

Evidence from the Florida Straits for Younger Dryas ocean circulation changes

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[1] The waters passing through the Florida Straits today reflect both the western portion of the wind-driven subtropical gyre and the northward flow of the upper waters which cross the equator, compensating North Atlantic Deep Water export as part of the large-scale Atlantic meridional overturning circulation. It has been postulated from various lines of evidence that the overturning circulation was weaker during the Younger Dryas cold event of the last deglaciation. We show here that the contrast in the oxygen isotopic composition of benthic foraminiferal tests across the Florida Current is reduced during the Younger Dryas. This most likely reflects a decrease in the density gradient across the channel and a decrease in the vertical shear of the Florida Current. This reduced shear is consistent with the postulated reduction in the Atlantic meridional overturning circulation. We find that the onset of this change in density structure and flow at the start of the Younger Dryas is very abrupt, occurring in less than 70 years.

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1. Introduction

[2] Today deep water forms in the far North Atlantic, compensated by a northward flow of warm upper waters as part of the Atlantic meridional overturning circulation (AMOC). This overturning circulation acts to transport heat to the high northern latitudes. The Younger Dryas event, which is characterized by an abrupt cooling in Greenland and the North Atlantic, is thought to have been driven by an injection of freshwater into the far North Atlantic disrupting deep water production. This freshwater delivery resulted either from the sudden release of glacial water stored in proglacial lakes and/or the change in routing of glacial melt from the Mississippi drainage basin to the St. Lawrence [Broecker, 2006; Carlson *et al.*, 2007] or Arctic Ocean [Tarasov and Peltier, 2005]. It has also been suggested that the freshwater came from the release of very thick multiyear sea ice from the Arctic Ocean [Bradley and England, 2008].

[3] There is evidence that a reorganization of the deep water masses accompanied the Younger Dryas. Boyle and Keigwin [1987] demonstrated that the widespread surface cooling of the North Atlantic during the Younger Dryas was similar in both timing and duration to changes in the water mass properties in the deep North Atlantic. During the Younger Dryas, nutrient rich and radiocarbon poor waters,

presumably of a southern origin, replaced nutrient poor North Atlantic Deep Water in the North Atlantic below 2 km [Keigwin, 2004; Sarnthein *et al.*, 1994]. In addition, a shallower nutrient poor water mass fills the North Atlantic above 2 km during the Younger Dryas [Keigwin, 2004; Marchitto *et al.*, 1998]. This water mass configuration is similar to that of the last glacial maximum. However, these water mass changes alone cannot confirm or refute the hypothesis that meltwater caused a reduction in the strength of the AMOC and the related northward heat transport during the Younger Dryas. For this, we must turn to proxies that can tell us something about rates of flow.

[4] Reconstructions of atmospheric radiocarbon provide evidence for a reduction in North Atlantic Deep Water formation at the start of the Younger Dryas [Hughen *et al.*, 1998; Meissner, 2007]. Sediment grain size measurements also suggest a less vigorous overflow of waters from the polar seas into the deep North Atlantic [Manighetti and Mccave, 1995; Praetorius *et al.*, 2008]. The accumulation of the decay products of U (Pa and Th) in deep sea sediments can tell us about the residence time of deep waters in the Atlantic [Yu *et al.*, 1996]. McManus *et al.* [2004] infer a longer residence time for deep waters the North Atlantic during the Younger Dryas based on this technique. However, Gherardi *et al.* [2009] show that the ratios of Pa/Th in a series of sediment cores at various depths throughout the North Atlantic suggest a shallower, but vigorous AMOC during the Younger Dryas, presumably associated with the nutrient poor water mass above 2 km.

[5] The cross-equatorial flow of surface waters which compensate the export of deep waters from the North Atlantic forms an important component of the Florida Current (about 17 of 31 Sv [Schmitz and McCartney, 1993]). There is a pronounced contrast in the density of seawater from either

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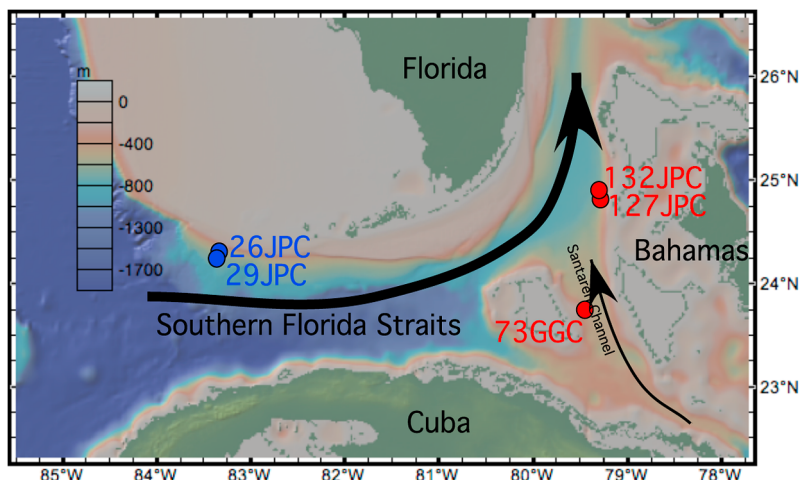


Figure 1. Bathymetry in the study area. Core locations are indicated with circles, and the approximate path of the Florida Current and Santaren Current are indicated with black arrows.

side of the channel, reflecting the vertical shear in this largely geostrophic current. This cross-straits density gradient is reflected as a contrast in the $\delta^{18}\text{O}$ of calcite tests of benthic foraminifera, which records the temperature of calcification and the $\delta^{18}\text{O}$ of seawater (related to salinity). We have taken advantage of this relationship to reconstruct the vertical density structure on both sides of the Straits and calculate the geostrophic transport for times in the past [Lund *et al.*, 2006; Lynch-Stieglitz *et al.*, 1999a, 2009]. Here we examine the contrast in $\delta^{18}\text{O}$ across the Straits at middepths during the Younger Dryas as a qualitative measure of changes in the flow through the Florida Straits during this time.

2. Materials and Methods

[6] On the Bahamas side of the Florida Current, we analyze cores from water depths of 542 m (KNR166-2-73GGC) within the Santaren Channel and at 631 m (KNR166-2-127JPC) and 739 m (KNR166-2-132JPC) on the flanks of the Great Bahama Bank (Figure 1 and Table 1). On the Florida side of the current we analyzed sediment cores recovered near the Florida Keys at depths of 546 m (KNR166-2-26JPC),

648 m (KNR166-2-29JPC) and 751 m (KNR166-2-31JPC). Results from KNR166-2-31JPC were previously reported by *Came et al.* [2007, 2008]. The flow through the Santaren Channel contributes an average of ~ 2 Sv to the Florida Current [Leaman *et al.*, 1995]. Modern measurements indicate that the largest velocity in the Santaren Channel is concentrated along the Great Bahama Banks side of the channel directed toward the Florida Current [Leaman *et al.*, 1995]. Thus, any measure of density contrast between the cores at 540 m water depths will not capture the shear associated with this contribution to the Florida Current.

[7] Age models for each core were constructed based on accelerator mass spectrometry ^{14}C dates on planktonic foraminifera converted to calendar age using Calib 5.0.2 (M. Stuiver *et al.*, Calib calibration program, version 5.0.2, 2005) using the standard marine reservoir correction [Hughen *et al.*, 2004] (Figure 2 and Table 2). Ages were linearly interpolated between control points. For core KNR166-2-26JPC, the radiocarbon dates between 344 and 408 cm were not used in the age model as indicated in Figure 2. These out of sequence radiocarbon dates are from the same section of the core where we find layers of coarse material

Table 1. Core Locations and Recent and Younger Dryas Isotope Averages

Core	Latitude	Longitude	Water Depth (m)	Recent $\delta^{18}\text{O}$ (‰ PDB)	SD	n	Younger Dryas $\delta^{18}\text{O}$ (‰ PDB)	SD	n	Species Analyzed
<i>Florida Profile</i>										
KNR166-2-26JPC	24°19.61'N	83°15.14'W	546	1.86	0.06	2	1.97	0.09	204	<i>C. pachyderma</i>
KNR166-2-29JPC	24°16.93'N	83°16.24'W	648	2.00	0.04	12	2.18	0.19	26	<i>C. pachyderma</i> , <i>P. ariminensis</i>
KNR166-2-31JPC	24°13.18'N	83°17.75'W	mixed layer	-1.62	0.10	30	-0.74	0.36	139	<i>G. ruber</i>
			751	2.17	0.08	10	2.38	0.16	10	<i>C. pachyderma</i> , <i>P. wuellerstorfi</i> , <i>C. sp.</i>
<i>Bahamas Profile</i>										
KNR166-2-73GGC	23°44.73'N	79°25.78'W	542	1.25	0.07	24	1.77	0.24	29	<i>C. pachyderma</i> , <i>P. ariminensis</i>
			mixed layer	-1.88	0.13	120	-0.74	0.29	80	<i>G. ruber</i>
KNR166-2-127JPC	24°45.83'N	79°15.94'W	631	1.34	0.08	62	1.90	0.15	27	<i>C. pachyderma</i> , <i>P. ariminensis</i>
KNR166-2-132JPC	24°50.90'N	79°16.88'W	739	1.67	0.22	43	1.99	0.14	8	<i>C. pachyderma</i> , <i>P. ariminensis</i> , <i>C. sp.</i>

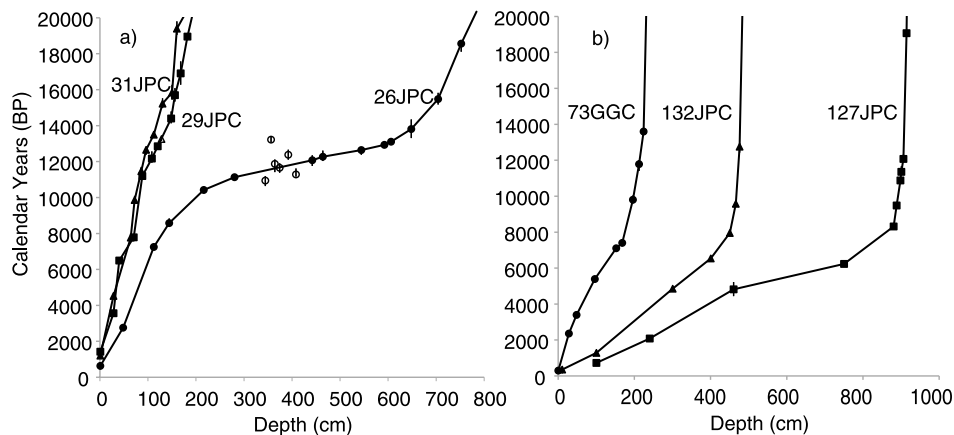


Figure 2. (a) Age model control points (solid symbols) and age models for cores on the Florida margin. Radiocarbon dates not used in the age models are indicated by open symbols. The 2-sigma range in possible calendar age is indicated by the vertical error bar. Where no error bar is visible, the 2-sigma range does not exceed ± 300 years from the most probable value. (b) Age model control points (solid symbols) and age models for cores on the Bahamas side of the Florida Current.

(352–418 cm) (Figure 3). These layers show no visual indication of grading in size, often do not extend across the entire core, and look like contourite lag deposits often found in sediments underlying the deep western boundary current. Although these layers were avoided for the radiocarbon dating, the presence of strong near bottom current could potentially transport older material laterally. We will consider the entire interval containing the coarse layers and anomalous radiocarbon dates (344–418 cm) as potentially disturbed or affected by lateral transport of material (Figure 3).

[8] Sedimentation rates in the Bahamas cores drop dramatically before 8 kyr B.P., probably due to decreased production of fine grained carbonates on the Bahama Banks during times of low sea level, which may compromise the ability of the deeper core to fully resolve the Younger Dryas event. The shallower core located on the Santaren Drift has sedimentation rates of 7–8 cm kyr^{-1} through the Younger Dryas, and the intermediate and deepest cores have sedimentation rates of 7 and 3 cm kyr^{-1} , respectively, going into the Younger Dryas. The cores on the Florida Margin show highest sedimentation rates between 14 and 10 kyr B.P. (10, 19 and 107 cm kyr^{-1} for the deepest to shallowest cores, respectively).

[9] Oxygen isotope ratios of benthic foraminifera (*Cibicides pachyderma* and *Planulina ariminensis*, $>250 \mu\text{m}$ size fraction) and planktonic foraminifera (*Globogerinoides ruber*, 250–350 μm , white variety) were measured using a GV Instruments Optima with Multiprep (LDEO), GV Instruments Isoprime mass spectrometer with Multiprep (Georgia Tech), and Finnigan MAT253 mass spectrometer with Kiel Device (WHOI and Georgia Tech). The oxygen isotope data are calibrated with NBS-19 and NBS-18 and in all labs internal precision met or exceeded 0.08‰ (1 sigma standard deviation of replicate analyses of NBS-19 or in-house standards).

[10] The benthic species we use here have been shown to accurately record seawater $\delta^{18}\text{O}$ and temperature of calci-

fication [e.g., Lynch-Stieglitz *et al.*, 1999b]. In addition to grouped measurements of 3 individuals, specimens were analyzed individually in order to assess the degree of mixing of individuals from different time periods on the deglaciation. All stable isotope data will be archived at the World Data Center for Paleoclimatology located at the U.S. National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) Paleoclimatology Program, Boulder, Colorado.

[11] Except as noted below, all benthic foraminiferal oxygen isotope measurements from intervals of the core between 0 and 2 kyr and between 11.5 and 12.5 kyr B.P. were averaged (weighted by number of individuals in each analysis) and the standard deviation computed (Table 1). For the Bahamas cores, sedimentation rates drop dramatically below the Holocene sections, and we must consider the possibility that the Younger Dryas dated interval contains individuals mixed in from other time intervals. Because both the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ in this region are much heavier before 15 kyr B.P. [Marchitto *et al.*, 1998] we can identify within the Younger Dryas age range individuals that clearly calcified at earlier times (Figure 4). For the shallowest core (KNR166-2-73GGC), 5 of the 34 individual benthic foraminifera in the Younger Dryas interval had LGM isotopic values ($\delta^{13}\text{C} > 1.6\text{‰}$ and $\delta^{18}\text{O} > 2.3\text{‰}$) and were not included in calculating the average values. For the intermediate depth core (KNR166-2-127JPC) all foraminifera appeared to be of Younger Dryas age, and for the deeper core (KNR166-2-132JPC) only one of eight foraminifera showed values indicating an earlier age and was excluded from the average.

[12] Mixed layer properties are reconstructed from oxygen isotope measurements on groups of the planktonic foraminifera *G. ruber* (250–350 μm , white variety) on one core from each profile (KNR166-2-29JPC and KNR166-2-73GGC). Time-slice averages were then calculated as for the benthic foraminifera. Additional measurements on *G. ruber* (250–350 μm , white variety) were made on our highest-resolution

Table 2. Radiocarbon Dates^a

Core	Depth in Core	Species	¹⁴ C Age	Error	Calendar Age
KNR166-2-26JPC	0.75	<i>G. sacculifer</i>	1070	70	634
	48.25	<i>G. sacculifer</i>	2990	30	2760
	112.25	<i>G. sacculifer</i>	6720	40	7251
	144.25	<i>G. sacculifer</i>	8100	80	8576
	216.25	<i>G. sacculifer</i>	9550	40	10418
	280.25	<i>G. sacculifer, G. ruber</i>	10100	45	11130
	344.25	<i>G. sacculifer</i>	10000	110	10944 ^b
	356.25	<i>G. sacculifer</i>	11750	95	13219 ^b
	364.25	<i>G. sacculifer, G. ruber</i>	10600	70	11873 ^b
	374.25	<i>G. sacculifer</i>	10500	50	11656 ^b
	392.25	<i>G. ruber</i>	10850	65	12380 ^b
	408.25	<i>G. sacculifer, G. ruber</i>	10300	60	11285 ^b
	442.25	<i>G. sacculifer, G. ruber</i>	10700	65	12078
	464.25	<i>G. sacculifer, G. ruber</i>	10800	55	12267
	544.25	<i>G. sacculifer, G. ruber</i>	11000	65	12644
	592.25	<i>G. ruber</i>	11400	65	12931
	606.25	<i>G. sacculifer</i>	11600	35	13104
	648.25	<i>G. sacculifer</i>	12350	200	13812
	704.25	<i>G. ruber</i>	13500	55	15481
	752.25	<i>G. ruber</i>	15550	70	18563
	848.25	<i>G. ruber</i>	20300	120	23841
952.25	<i>G. ruber</i>	26300	130	31124	
1014.25	<i>G. ruber</i>	28200	180	33155	
1032.25	<i>G. ruber</i>	28200	590	33152	
1074.25	<i>G. ruber</i>	29300	380	34305	
1118.25	<i>G. sacculifer</i>	30900	220	35874	
KNR166-2-29JPC	0.75	<i>G. sacculifer</i>	1880	25	1424
	28.25	<i>G. sacculifer</i>	3660	50	3566
	40.25	<i>G. sacculifer</i>	6070	45	6494
	88.25	<i>G. sacculifer</i>	10200	70	7783
	108.25	<i>G. ruber</i>	10750	60	11195
	120.25	<i>G. ruber</i>	11250	70	12172
	148.25	<i>G. ruber</i>	12800	50	12849
	156.25	<i>G. ruber</i>	13650	60	14399
	168.25	<i>G. sacculifer</i>	14550	180	15695
	182.25	<i>G. ruber</i>	16150	60	16905
	224.25	<i>G. sacculifer</i>	20300	160	18955
	288.25	<i>G. ruber</i>	26900	180	23832
	KNR166-2-31JPC	0.75	<i>G. sacculifer</i>	1640	40
28.25		<i>G. sacculifer</i>	4380	45	4526
64.25		<i>G. sacculifer</i>	7310	50	7773
72.25		<i>G. sacculifer</i>	9110	50	9860
86.25		<i>G. sacculifer</i>	10400	55	11468
96.25		<i>G. sacculifer</i>	11000	55	12655
112.25		<i>G. sacculifer</i>	12050	75	13500
128.25		<i>G. sacculifer</i>	11800	50	13259 ^b
130.25		<i>G. sacculifer</i>	13300	60	15227
150.25		<i>G. sacculifer, G. ruber</i>	13750	80	15842
160.25		<i>G. ruber</i>	16650	160	19397
200.25	<i>G. ruber</i>	18400	110	21300	
KNR166-2-73GGC	0.25	mixed planktonics	650	35	297
	28.25	mixed planktonics	2670	30	2357
	152.25	<i>G. sacculifer</i>	6580	40	7102
	48.25	<i>G. sacculifer</i>	3510	30	3394
	96.25	<i>G. sacculifer</i>	5040	40	5388
	168.25	<i>G. sacculifer</i>	6890	45	7404
	196.25	<i>G. sacculifer</i>	9080	50	9805
	212.25	<i>G. sacculifer</i>	10550	55	11782
	224.25	<i>G. sacculifer</i>	12150	70	13600
	232.25	<i>G. sacculifer</i>	18300	90	21143
	248.25	<i>G. sacculifer</i>	22900	130	27040
	280.25	<i>G. sacculifer</i>	31000	190	35969
	296.25	<i>G. sacculifer</i>	36800	350	41614
	KNR166-2-127JPC	100.50	<i>G. sacculifer</i>	1190	30
240.50		<i>G. sacculifer</i>	2440	50	2082
460.50		<i>G. sacculifer, G. ruber</i>	4600	140	4816
750.50		<i>G. sacculifer</i>	5810	45	6232
880.50		<i>G. sacculifer</i>	7850	55	8317
888.25		<i>G. sacculifer</i>	8820	40	9484

Table 2. (continued)

Core	Depth in Core	Species	¹⁴ C Age	Error	Calendar Age
KNR166-2-132JPC	898.25	<i>G. sacculifer</i>	9930	45	10879
	900.50	<i>G. sacculifer</i>	10350	60	11357
	906.25	<i>G. sacculifer</i>	10700	50	12074
	914.25	<i>G. sacculifer</i>	16300	60	19071
	918.25	<i>G. sacculifer</i>	21900	85	25842
	920.50	<i>G. sacculifer</i>	23300	190	27494
	950.50	<i>G. sacculifer</i>	48100	3100	
	10.50	<i>G. sacculifer</i>	715	90	357
	100.50	<i>G. sacculifer</i>	1730	35	1283
	300.50	<i>G. sacculifer</i>	4630	45	4853
	400.50	<i>G. sacculifer</i>	6110	35	6539
	450.50	<i>G. sacculifer</i>	7490	50	7951
	466.25	<i>G. sacculifer</i>	8920	45	9575
	476.25	<i>G. sacculifer</i>	11100	60	12758
	486.25	<i>G. sacculifer</i>	19700	95	22904
	494.25	<i>G. sacculifer</i>	27100	140	32413
	500.25	<i>G. sacculifer</i>	30400	190	35406

^aCalibrated using Calib 5.0.2 and Marine04 curve if younger than 26,000 years B.P.; otherwise, Fairbanks0107 with a 400 year surface reservoir age was used (<http://radiocarbon.ldeo.columbia.edu/research/radcarbcal.htm>).

^bNot used in age model.

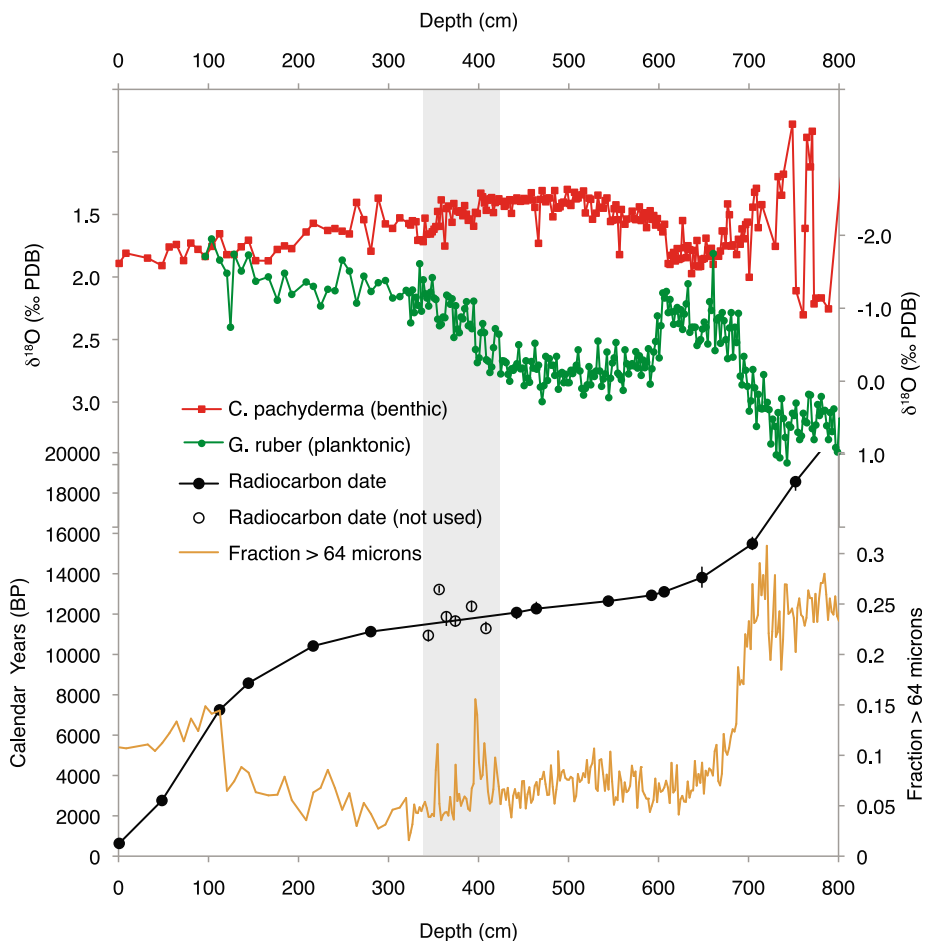


Figure 3. Downcore data for the high-resolution Florida margin core KNR166-2-26JPC. Benthic (*C. pachyderma*) and planktonic (*G. ruber*) foraminiferal δ¹⁸O measurements, radiocarbon dates, and fraction of the sediment by weight >64 microns for core KNR166-2-26JPC. Radiocarbon dates not used in the age model are indicated by open symbols. The gray shaded region encompasses the out of sequence radiocarbon dates and coarse layers and corresponds to the interval of the core for which the record should be interpreted with the caution that not all foraminifera are in situ.

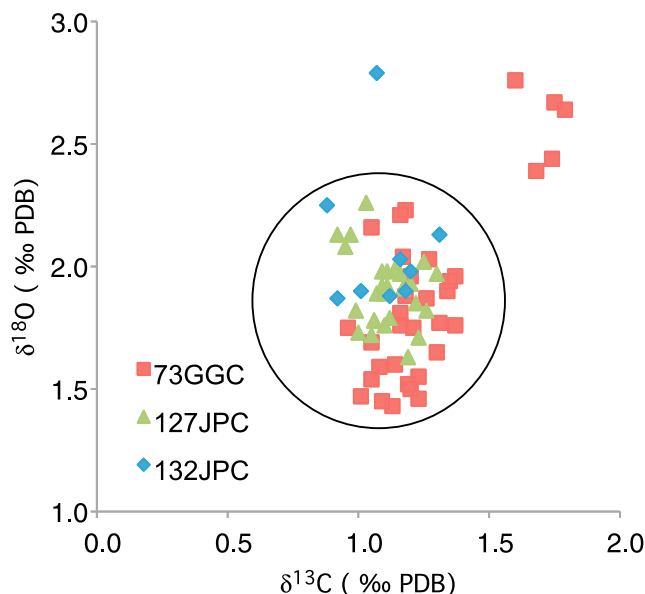


Figure 4. A small number of benthic foraminiferal $\delta^{18}\text{O}$ analyses from the Younger Dryas age interval of the Bahamas cores were not included in the Younger Dryas average (symbols that fall outside the circle) as their $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values clearly indicated a glacial age.

record (KNR166-2-26JPC) in order to compare the timing of surface and subsurface changes. For KNR166-2-29JPC and KNR166-2-26JPC, between 12–24 individual *G. ruber* were pooled for each reported oxygen isotope value, and for KNR166-2-73GGC 10 individual *G. ruber* were used.

3. Results and Discussion

3.1. Younger Dryas Cross Strait Gradients

[13] The contrast in the $\delta^{18}\text{O}$ of benthic foraminiferal tests across the deeper part of the Florida Straits was much smaller (about 0.3‰) during the Younger Dryas than during the late Holocene (about 0.6‰) (Figures 5 and 6). Today, the $\delta^{18}\text{O}$ of foraminiferal calcite is closely coupled to the density of the seawater in which it grew, with colder temperatures and saltier waters corresponding to higher values of both quantities. Today's contrast across the Florida Straits today is largely driven by the warmer temperature (about 4°C) on the Bahamas side of the Straits, which would account for a 0.9‰ lower $\delta^{18}\text{O}$ of calcite on the Bahamas side relative to the Florida margin. However, the saltier water on the Bahamas side has a higher $\delta^{18}\text{O}$ (by 0.25‰), offsetting slightly the gradient in $\delta^{18}\text{O}$ of calcite that would be expected from the temperature contrast alone. The relationship between temperature, salinity and $\delta^{18}\text{O}$ might vary in time due to changes in the relationship between salinity and seawater $\delta^{18}\text{O}$ in the thermocline of the North Atlantic.

[14] As an extreme scenario, we can consider the possibility that the fresh water $\delta^{18}\text{O}$ value that determines the S- $\delta^{18}\text{O}$ relationship [Craig and Gordon, 1965] was -28 per mil due to the introduction of glacial meltwater, instead of the modern value of -18 per mil. In this case, the slope of

the $\delta^{18}\text{O}$ -Salinity relationship would have increased by about 50%. All else being equal, this could increase the contrast in $\delta^{18}\text{O}$ of seawater across the Florida Straits at 550 m from 0.25 to 0.4‰. Assuming a similar temperature contrast as today, this could reduce the contrast in the $\delta^{18}\text{O}$ of the foraminiferal calcite by 0.15‰ without any corresponding change in the density contrast. It then seems reasonable to conclude that the larger observed Younger Dryas reduction in the contrast in the $\delta^{18}\text{O}$ of foraminiferal tests across the Straits was accompanied by a reduction in the density contrast.

[15] Paleotemperature estimates support the interpretation of the reduction in $\delta^{18}\text{O}$ contrast as a reduction in density contrast. *Came et al.* [2007] showed that in KNR166-2-31JPC, Mg/Ca in benthic foraminifera increased during the Younger Dryas relative to Holocene and LGM values, suggesting warmer temperatures on the Florida Margin. A deeper core (1000 m) near the Bahamas shows no change in temperature over Younger Dryas [Came et al., 2007]. These data suggest that the reduced $\delta^{18}\text{O}$ gradient across the straits we observe in our cores likely reflects a reduction in the temperature gradient that dominates the density contrast across the Straits today.

[16] A reduced density contrast would require a reduction in the vertical shear of the flow, similar to that observed for the Last Glacial Maximum [Lynch-Stieglitz et al., 1999a]. With information about the cross strait density gradient only in the deeper parts (450–700 m), we cannot quantify how the Florida Current transport might have changed during the Younger Dryas, and can only say that a change in some aspect of the upper ocean circulation is reflected in the reduced shear at this depth. It seems reasonable in the light of the other evidence discussed in section 1 that this reduction in shear may have reflected a weaker Florida Current due to the reduced surface branch of the AMOC which today supplies about 13 of the 32 Sv of flow through the Straits [Schmitz and McCartney, 1993]. However, we cannot rule out the possibility that the reduced shear resulted from less wind driven flow through the straits, or a more barotropic Florida current.

[17] While *Came et al.* [2007] discuss the changes in inferred temperature and salinity for two cores on either side of the Florida Current in terms of a warming of the western margin in response to reduced ocean heat transport by the AMOC and a cooling of the gyre during the Younger Dryas, we note that the changes they see (warmer and saltier waters on the Florida Margin relative to a deeper site in the gyre) are entirely consistent with a flattening of the isopycnals across the Straits. There is not necessarily a contradiction between the interpretations presented here and in the work by *Came et al.* [2007], as that paper discusses the heat and freshwater fluxes necessary to support the flatter isopycnals that are required to accompany the reduced shear we infer here.

3.2. Timing of Younger Dryas Hydrographic Changes

[18] The extremely high deglacial sedimentation rates (>100 cm kyr⁻¹) on the Florida margin allow us to look in more detail at the timing of the density changes. We generated high-resolution $\delta^{18}\text{O}$ data for both planktonic and benthic

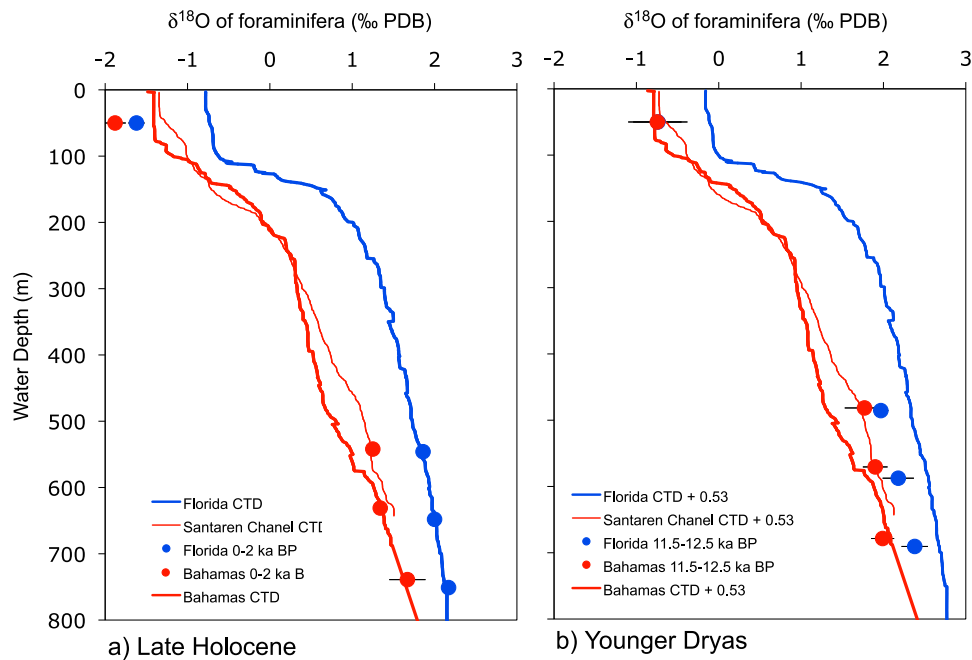
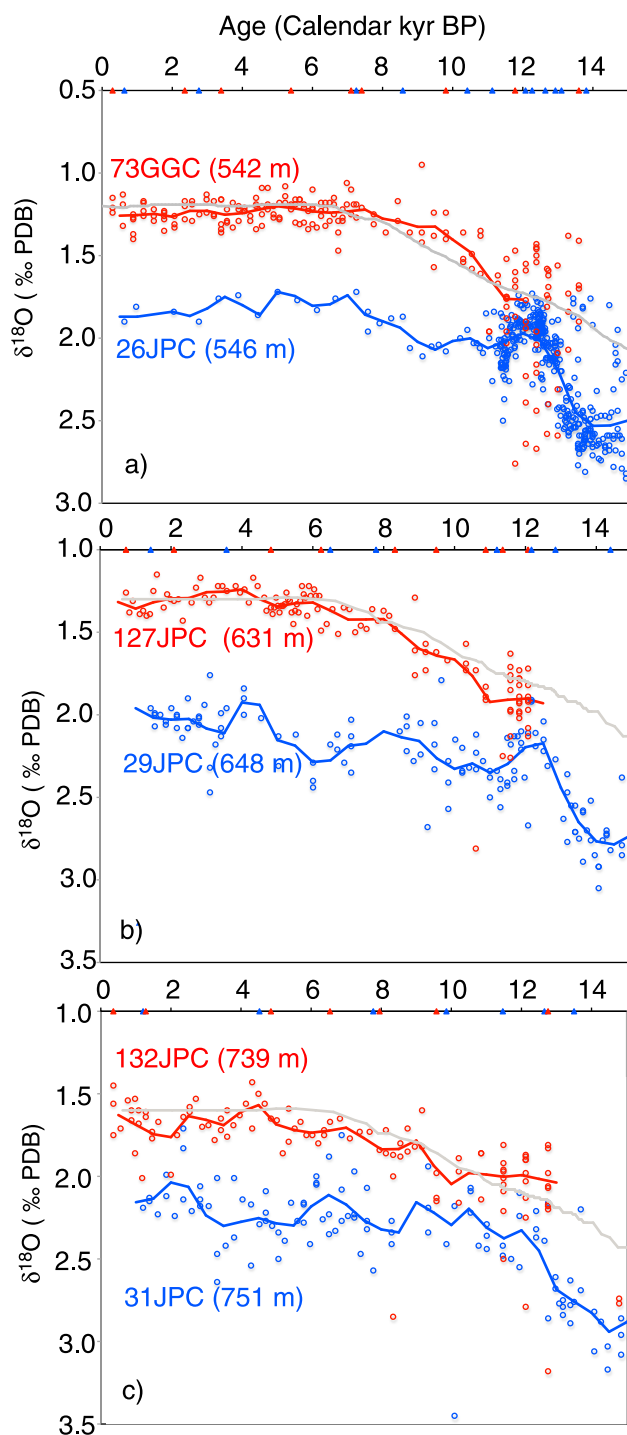


Figure 5. (a) Expected $\delta^{18}\text{O}$ of *Cibicidoides* and *Planulina* at the core sites from water column temperature and salinity (CTD) data using the relationship between *Cibicidoides* and *Planulina* $\delta^{18}\text{O}$ and temperature in the work by Lynch-Stieglitz *et al.* [1999b] and $\delta^{18}\text{O}$ of seawater and salinity from GEOSECS stations 29 and 37 (western subtropical North Atlantic). Florida margin water column data are indicated by a thick blue line, water column data at the Bahamas are indicated by a thick red line, and in the Santaren Channel data where the shallowest Bahamas core data are indicated by a thin red line. Also plotted (circles) are the most recent 2 kyr average foraminiferal $\delta^{18}\text{O}$ (Table 1). (b) Modern expected $\delta^{18}\text{O}$ shifted by +0.53 per mil, the expected whole ocean $\delta^{18}\text{O}$ change between the Younger Dryas and the present (lines same as in Figure 5a). The expected $\delta^{18}\text{O}$ shift is calculated using the sea level data in the work by Siddall *et al.* [2009], assuming a 120 glacial sea level drop corresponds to a 1.05‰ increase in seawater $\delta^{18}\text{O}$ [Schrag *et al.*, 2002]. Also plotted (circles) are the average foraminiferal $\delta^{18}\text{O}$ of for the 1 kyr interval that most closely coincides with the Younger Dryas (11.5–12.5 cal kyr B.P.). The depth of the core has been adjusted for the lower sea level during the Younger Dryas. Subsurface foraminiferal $\delta^{18}\text{O}$ are from benthic species *C. pachyderma* and *P. ariminensis*, and mixed layer values are from measurements on the planktonic species *G. ruber*.

foraminifera in the highest sedimentation rate core (KNR166-2-26JPC). The excursion toward higher *G. ruber* $\delta^{18}\text{O}$ values reflects either colder sea surface temperatures, higher sea surface salinity, or both during the Younger Dryas. The $\delta^{18}\text{O}$ record from benthic foraminifera (*C. pachyderma*), are used to assess circulation changes.

3.2.1. Timing of Surface Water Changes

[19] The $\delta^{18}\text{O}$ record from surface dwelling planktonic foraminifera (*G. ruber*) was corrected for whole ocean $\delta^{18}\text{O}$



changes in order to isolate the changes in surface water hydrography. We find that the onset of Younger Dryas conditions in surface waters was rapid (within 4–8 cm, 70–140 years) and occurred simultaneously with the change in climate conditions on Greenland, within the errors of the age model for our records and the ice core record (Figure 7). In the Greenland ice core (NGRIP) record, the abrupt transition into the Younger Dryas is dated between 12.896 cal kyr B.P. with a maximum counting error of 138 years, and the end of the Younger Dryas is dated at 11.703 cal kyr B.P. with a maximum counting error of 99 years [Rasmussen *et al.*, 2006]. The planktonic foraminifera (surface water) transition into the Younger Dryas occurs at 13.0 cal kyr B.P. with a possible range of 12.9–13.1 kyr B.P. based on uncertainties in the radiocarbon measurements and calibration data sets.

[20] The transition out of the Younger Dryas event occurs in the portion of the sediment core that displays out of sequence radiocarbon dates. However, the timing is constrained by the dates on either side of this interval to be between 11.1 and 12.1 kyr B.P., consistent with the age of the transition in the ice core record. Our age model puts the sharp transition in the planktonic data at 11.8 kyr B.P., again simultaneous with the ice core transition within the errors of the radiocarbon dates we used to develop the age model and the ice core counting. The fact that this sharp transition out of the Younger Dryas is seen in the planktonic record, and occurs at the same time as in the ice core record, gives us increased confidence both that our age model is appropriate and that the isotope record has not been terribly compromised by whatever process led to the coarse layers and scattered radiocarbon dates in this interval.

3.2.2. Timing of Subsurface (Circulation) Changes

[21] Because we have no comparably resolved benthic $\delta^{18}\text{O}$ record on the Bahamas side of the Florida Current to match with that of KNR166-2 26JPC from the Florida Margin, we will have to make some assumptions about conditions on the Bahamas side of the Florida Strait over the deglaciation. The long-term decrease in $\delta^{18}\text{O}$ at all sites reflects not only local oceanographic changes, but also the addition of isotopically light water to the oceans as the large ice sheets melt and sea level rises. The magnitude and timing of $\delta^{18}\text{O}$ changes recorded by the benthic foraminifera at the

Figure 6. Benthic foraminiferal $\delta^{18}\text{O}$ measurements (*C. pachyderma* and *P. ariminensis*) from (a) KNR166-2-73GGC (542 m, Bahamas, red circles) and KNR166-2-26JPC (546 m, Florida Keys, blue circles), (b) KNR166-2-127JPC (631 m, Bahamas, red circles) and KNR166-2-29JPC (648 m, Florida Keys, blue circles), and (c) KNR166-2-132JPC (739 m, Bahamas, red circles) and KNR166-2-31JPC (751 m, Florida Keys, blue circles). For all cores, 1 kyr average values are calculated, and those centered at 500 year intervals are shown in the solid red and blue lines. Also indicated with a gray line is the $\delta^{18}\text{O}$ change at the Bahamas that can be attributed to whole ocean changes due to the melting continental ice sheets. This curve is calculated using the sea level data by Siddall *et al.* [2009], assuming a 120 glacial sea level drop corresponds to a 1.05‰ increase in seawater $\delta^{18}\text{O}$ [Schrag *et al.*, 2002].

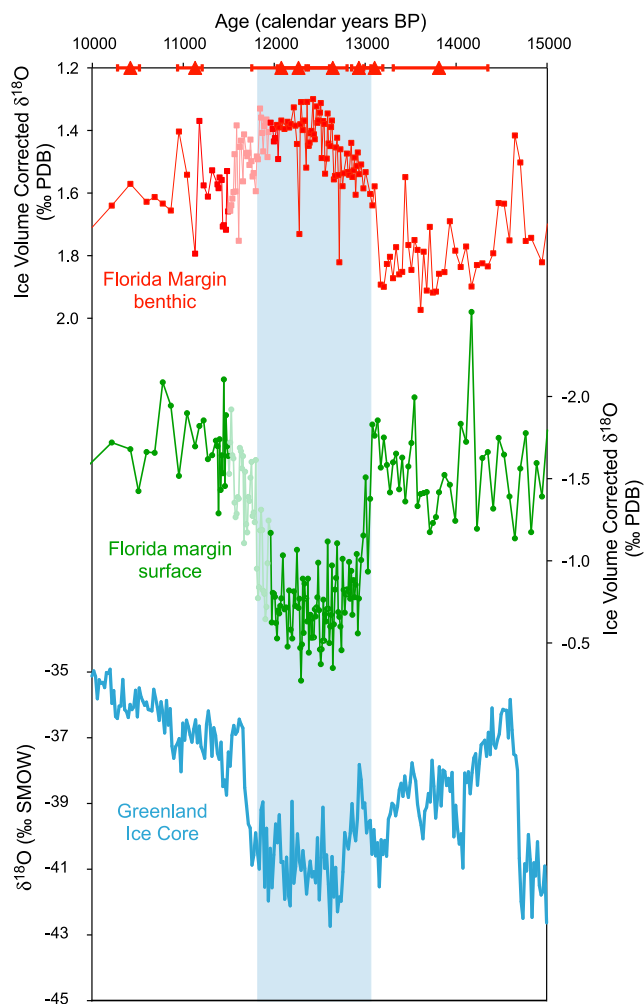


Figure 7. (top) Detail of the benthic (*C. pachyderma*) $\delta^{18}\text{O}$ from KNR166-2-26JPC (546 m, Florida Keys). The oxygen isotope values have been corrected for the expected whole ocean change due to the melting of the continental ice sheets using the sea level data by Siddall *et al.* [2009], assuming a 120 glacial sea level drop corresponds to a 1.05‰ increase in seawater $\delta^{18}\text{O}$ [Schrag *et al.*, 2002]. Since the changes in Bahamas benthic $\delta^{18}\text{O}$ values reflect largely these ice volume changes (Figure 6), low values of ice volume corrected $\delta^{18}\text{O}$ during the Younger Dryas are interpreted as a reduction in the cross-straits density gradient (low velocity shear associated with low flow through the straits). The data plotted in a lighter shade are from the interval of the core with the out of sequence radiocarbon dates and coarse layers (gray bar in Figure 3). (middle) Planktonic (*G. ruber*) $\delta^{18}\text{O}$ from the same sediment core, also corrected for whole ocean changes. High values during the Younger Dryas reflect colder and/or saltier water. (bottom) The Younger Dryas interval as expressed in the isotopic composition of snow accumulating on Greenland (low $\delta^{18}\text{O}$ during cold interval) [Andersen *et al.*, 2004; Rasmussen *et al.*, 2006].

Bahamas closely resemble whole ocean $\delta^{18}\text{O}$ changes due to continental ice volume variability at the time resolution of these records (see gray curves on Figure 6). Having no comparable highly resolved record on the Bahamas side, we assume that the oceanographic changes in this region follow the timing of ice volume changes, and subtract these whole ocean changes from the Florida margin $\delta^{18}\text{O}$ record in order to isolate the density changes on the Florida margin that are due to changes in the density gradient across the straits (Figure 7). We assume that the timing of the ice volume corrected $\delta^{18}\text{O}$ changes in our high-resolution Florida margin record reflect the timing of changes in cross strait density and flow.

[22] Taken at face value, it appears that the benthic (circulation related) change at the start of the Younger Dryas occurs 100 years before the changes in surface water properties as the sharp change occurs 6 cm lower in the sediment core. However, while *C. pachyderma* is considered epifaunal, it has been postulated that it may live in well irrigated burrows within the sediment [McCorkle *et al.*, 1997], potentially leading to burial several centimeters deeper than similar aged planktonic foraminiferal tests. We have not made any adjustment to the age model for the benthic foraminiferal record relative to the planktonic foraminiferal record to account for this offset, as it would be difficult to quantify but it is a source of error in the relative timing of these records. Given these age model uncertainties it is not possible to say whether the circulation change recorded by the benthic foraminifera occurred before or simultaneously with the atmospheric/surface ocean changes recorded by the planktonic foraminifera at the onset of the Younger Dryas.

[23] This transition in the benthic oxygen isotope record is sharp (within 4 cm = 70 years), implying a rapid change in ocean circulation near the start of the Younger Dryas. Mea-

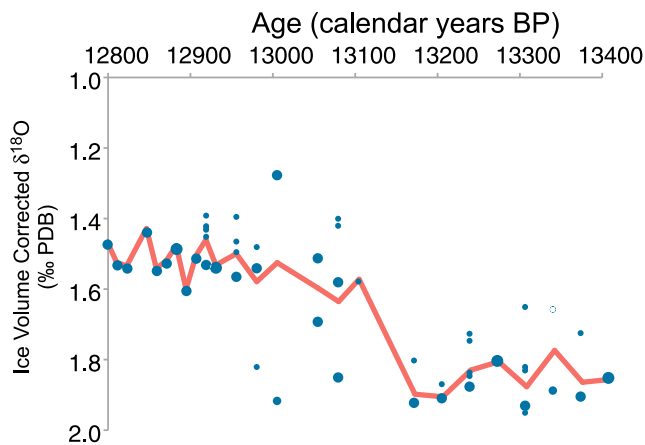


Figure 8. Individual analyses of *C. pachyderma* across transition into the Younger Dryas (blue dots). Analyses range from 1 to 4 individuals, and the size of the dot indicates the number of individuals in each analyses. The red line shows the average *C. pachyderma* value at each depth (weighted by number of individuals in each analysis) as plotted in Figure 7.

surements on individual and small groups of foraminifera suggest that while the average value of *C. pachyderma* shows a sharp transition, there is some mixing of individuals with pretransition and posttransition values in a 10 cm range, which is expected from both sediment mixing by burrowing organisms and a possible habitat within burrows for *C. pachyderma* (Figure 8). These sedimentary processes preclude a strong constraint on the abruptness of the transition from this data, but in general such processes will make the transition appear longer than it actually is. The abrupt transition implied by the average values is consistent with the idea that the AMOC responded abruptly to an injection of freshwater into the high-latitude North Atlantic, caused either by a switch in meltwater routing from the Gulf of Mexico to the North Atlantic [Broecker *et al.*, 1989; Flower *et al.*, 2004] or a sudden release of glacial meltwater stored in proglacial lakes at around 13,000 cal kyr B.P. [Broecker, 2006].

[24] However, in contrast to the surface water and ice core records which show a similarly abrupt transition at the end of the Younger Dryas, the $\delta^{18}\text{O}$ in the benthic record appears to recover more slowly over the course of several hundred years. This is consistent with model results that suggest that while the AMOC can shut down quickly, recovery can take from decades to centuries depending on the background state [Bitz *et al.*, 2007; Dahl *et al.*, 2005; Otto-Bliesner and Brady, 2010]. However, the inferred rate of the recovery is sensitive to the choices we made for the age model which are most

uncertain in the interval of the core containing the transition out of the Younger Dryas. The integrity of the record in this interval of the core could also be compromised by the same processes which lead to the scattered radiocarbon, so any inferences about the timing of changes at the end of the Younger Dryas are considered provisional.

4. Conclusions

[25] We have shown that the density gradient across the Florida Straits was likely diminished during the Younger Dryas relative to today. This is consistent with what we would expect to find, all else being equal, if the AMOC were weaker than today. Since there are other lines of evidence pointing toward a weaker AMOC during the Younger Dryas, we feel that this is the simplest explanation for this data set. If this indeed is the correct interpretation, our highly resolved record on the Florida margin shows the onset of this circulation change at the start of the Younger Dryas is very abrupt, occurring in less than 70 years.

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