

Phasing of deglacial warming and Laurentide Ice Sheet meltwater in the Gulf of Mexico

Benjamin P. Flower College of Marine Science, University of South Florida, St. Petersburg, Florida 33701, USA

David W. Hastings Collegium of Natural Sciences, Eckerd College, St. Petersburg, Florida 33711, USA

Heather W. Hill

Terrence M. Quinn

College of Marine Science, University of South Florida, St. Petersburg, Florida 33701, USA

ABSTRACT

Evidence is emerging that the tropical climate system played a major role in global climate change during the last deglaciation. However, existing studies show that deglacial warming was asynchronous across the tropical band, complicating the identification of causal mechanisms. The Orca Basin in the northern Gulf of Mexico is ideally located to record subtropical Atlantic sea-surface temperature (SST) warming in relation to meltwater input from the Laurentide Ice Sheet. Paired $\delta^{18}\text{O}$ and Mg/Ca data on the planktonic foraminifer *Globigerinoides ruber* from core EN32-PC6 are used to separate deglacial changes in SST and $\delta^{18}\text{O}$ of seawater. SST as calculated from Mg/Ca data increased by $>3^\circ\text{C}$ from ca. 17.2 to 15.5 ka in association with Heinrich event 1 and was not in phase with Greenland air temperature. Subtracting temperature effects from $\delta^{18}\text{O}$ values in *G. ruber* reveals two excursions representing Laurentide meltwater input to the Gulf of Mexico, one of $>1.5\text{‰}$ from ca. 16.1 to 15.6 ka and a second major spike of $>2.5\text{‰}$ from ca. 15.2 to 13.0 ka that encompassed meltwater pulse 1A and peaked ca. 13.8 ka during the Bølling-Ållerød. Conversion to salinity through the use of a Laurentide meltwater end member of -25‰ indicates that near-surface salinity decreased by 2‰ – 4‰ during these spikes. These results suggest that Gulf of Mexico SST warming preceded peak Laurentide Ice Sheet decay and the Bølling-Ållerød interval by >2 k.y. and that heat was retained in the subtropical Atlantic during Heinrich event 1, consistent with modulation of deglacial climate by thermohaline circulation.

Keywords: Gulf of Mexico, Orca Basin, Laurentide Ice Sheet, deglaciation, meltwater floods, freshwater switching.

INTRODUCTION

Evidence is emerging that the low-latitude climate system may have been an important driver of deglacial climate change, through its influence on poleward heat and vapor transport (e.g., Cane and Clement, 1999). One key question is, did tropical sea-surface temperature (SST) warming lead or coincide with the onset of Bølling warming recorded in Greenland ice-core records? In the western tropical Atlantic (Fig. 1), the SST increase appears to have coincided with Bølling warming, on the basis of Cariaco Basin sediment records (Lea et al., 2003) and Barbados coral records (Guilderson et al., 2001). In contrast, the SST increase seems to have led Bølling warming in the Tobago Basin (Ruhlemann et al., 1999; Huls and Zahn, 2000). Indeed, SST may have been out of phase with Greenland air temperature throughout the deglaciation in this area. This relationship has been compared to the antiphasing of Greenland and Antarctic temperature (Blunier and Brook, 2001) and attributed to the “bipolar seesaw” model of deglacial climate change (Broecker, 1998). Therefore, substantial disagreement exists on the timing and possible causes of tropical Atlantic SST changes during deglaciation. Resolving the temporal and spatial pattern of deglacial SST variability has important implications for modulation of climate by thermohaline circulation and greenhouse gas levels.

The timing and magnitude of Laurentide meltwater input to the Gulf of Mexico and/or meltwater diversion to the North Atlantic via the St. Lawrence River and other eastern outlets may have influenced North Atlantic Deep Water (NADW) formation and hence regional to global climate. In particular, low-density meltwater may have inhibited deep convection in the North Atlantic and reduced northward heat transport, leading to regional cooling during the Younger Dryas ca. 12.8–11.2 ka (e.g., Broecker et al., 1989; Keigwin et al., 1991). This is a topic of renewed interest because of evidence linking eastward meltwater discharge to NADW reduction since ca. 22 ka (Licciardi et al., 1999; Clark et al., 2001). During the deglacial interval, meltwater flow may have switched rapidly between the Mississippi River drainage and the eastern drainage systems, triggering episodic cooling and warming in the North Atlantic region (Clark et al., 2001).

Orca Basin is a small (400 km²) anoxic basin located ~300 km south of Louisiana (Fig. 1) that is ideally located to record deglacial meltwater input through the Mississippi River system. A 200-m-thick hypersaline brine (salinity $>250\text{‰}$) limits oxygen mixing and diffusion and allows fine laminations to be preserved. Abundant aragonitic pteropods, planktonic foraminifera with intact spines, and fossil seaweed (*Sargassum*) with attached calcareous polychaetes attest to minimal carbonate dissolution. The entire Gulf of Mexico is within the Western Hemisphere Warm Pool (WHWP) of $>28.5^\circ\text{C}$ water that develops during the Northern Hemisphere late summer and that represents the warmest water in the low-latitude Atlantic and eastern North Pacific (Fig. 1; Wang and Enfield, 2001).

Oxygen isotope data on *Globigerinoides ruber* from Orca Basin sediment cores have previously been used to document Laurentide meltwater input during the last deglaciation (Leventer et al., 1982; Flower and Kennett, 1990). Attempts to separate Gulf of Mexico SSTs and $\delta^{18}\text{O}$ values of seawater ($\delta^{18}\text{O}_{\text{sw}}$) have been hampered by the lack of an independent SST record. Here we describe new Mg/Ca data generated on *G. ruber* (white variety predominantly) from core EN32-PC6 (26°56.8'N; 91°20.0'W) that provide such an SST record. The Mg/Ca and $\delta^{18}\text{O}$ data on *G. ruber* from the same samples (Fig. 2) as well as global $\delta^{18}\text{O}_{\text{sw}}$ constraints from sea-level records (Fairbanks, 1989; Bard et al., 1990) help document the phasing of SST and $\delta^{18}\text{O}_{\text{sw}}$ variations in the Gulf of Mexico.

METHODS

Picked planktonic foraminiferal specimens were cleaned for Mg/Ca analysis following established procedures (Barker et al., 2003; also see Appendix¹). Foraminiferal Mg and Ca were analyzed on a Perkin Elmer Optima 4300 dual view inductively coupled plasma–optical

¹GSA Data Repository item 2004095, Appendix, Table DR1 (radiocarbon dates for EN32-PC6), and Table DR2 (Mg/Ca and $\delta^{18}\text{O}$ data), is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA. Supporting data are also available electronically at World Data Center-A for Paleoclimatology, NOAA/NGDC, 325 Broadway, Boulder, CO 80305, USA, phone: (303) 457-6513; e-mail: paleo@mail.ngdc.noaa.gov; URL: <http://www.ngdc.noaa.gov/paleo>.

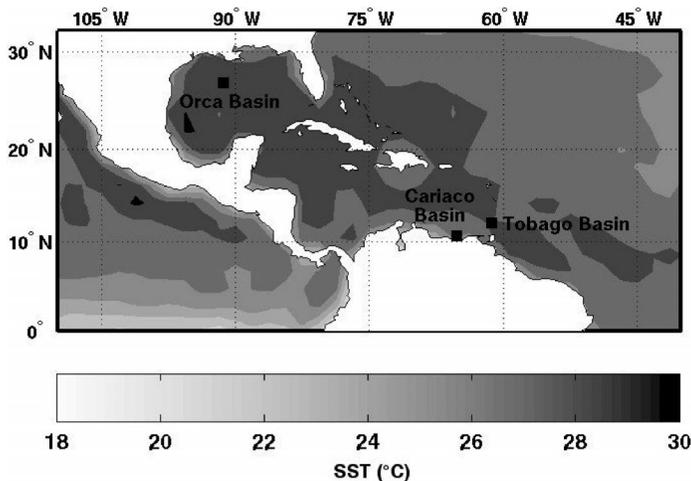


Figure 1. Map of western Atlantic Ocean showing present-day September sea-surface temperature (SST; in °C based on National Centers for Environmental Prediction reanalysis climatology) and location of core EN32-PC6 (26°56.8'N; 91°20.0'W at 2280 m) in Orca Basin, as well as Cariaco Basin and Tobago Basin. Darkest shade represents 28.5 °C contour of Western Hemisphere Warm Pool (Wang and Enfield, 2001).

emission spectrometer at the College of Marine Science, University of South Florida. Results indicate an analytical precision for Mg/Ca of $\leq 0.4\%$ root-mean standard deviation (1σ). A standard instrument-drift correction technique is routinely used. SST was calculated from Mg/Ca data by using a relationship obtained by core-top calibration of cores in the tropical Atlantic: $\text{Mg/Ca} = 0.38 \exp(0.090 \text{ SST})$, where the Mg/Ca concentration ratio in the foraminiferal tests is in mmol/mol and the SST is in °C (Dekens et al., 2002). This equation is nearly identical to a relationship obtained from South China Sea cores (Hastings et al., 2001). Also, a core-top Mg/Ca value of 4.5 ± 0.1 mmol/mol (27.5 ± 0.2 °C) matches summer-weighted mean annual SST (23–29 °C mean seasonal range). Average precision of all data based on duplicates or triplicates is ± 0.16 mmol/mol for Mg/Ca, which corresponds to $\sim \pm 0.4$ °C.

Age control is based on published and new accelerator mass spectrometry ^{14}C dates (Table DR1; see footnote 1). Radiocarbon ages were corrected by using a constant 400 yr reservoir age and converted to calendar years by using the CALIB 4.0 program (Stuiver et al., 1998). Depth in centimeters was converted to age by linear interpolation and yielded sedimentation rates of 45.4 ± 9.8 cm/k.y.

GULF OF MEXICO SEA-SURFACE TEMPERATURE

Comparison of our SST record based on Mg/Ca ratios to polar ice-core records (Fig. 3) reveals a gradual warming of >3 °C from ca. 17.2 to 15.5 ka, although the initiation point is uncertain because of sparse foraminifera in the 19.2–17.2 ka interval. This warming encompasses Heinrich event 1, which in contrast is marked by distinctly cool temperatures in the North Atlantic as well as in the Cariaco Basin (Lea et al., 2003). Orca Basin SSTs appear to have leveled off or slightly cooled during the Bølling-Ållerød, as also observed in the Tobago Basin (Ruhlemann et al., 1999). The Younger Dryas interval (ca. 12.9–11.6 ka based on Greenland ice core GISP2; Grootes et al., 1993) appears to be divided into a warm early phase and a phase that was ~ 1.5 °C cooler from ca. 12.2 to 11.5 ka, followed by SSTs reaching early Holocene values of 27.8 ± 0.4 °C by 11.3 ka. SST warming may reflect, in part, decreased influence of seasonally cold continental air masses at the Orca Basin location as the glacial shoreline retreated over the Louisiana shelf during deglaciation. This process may help

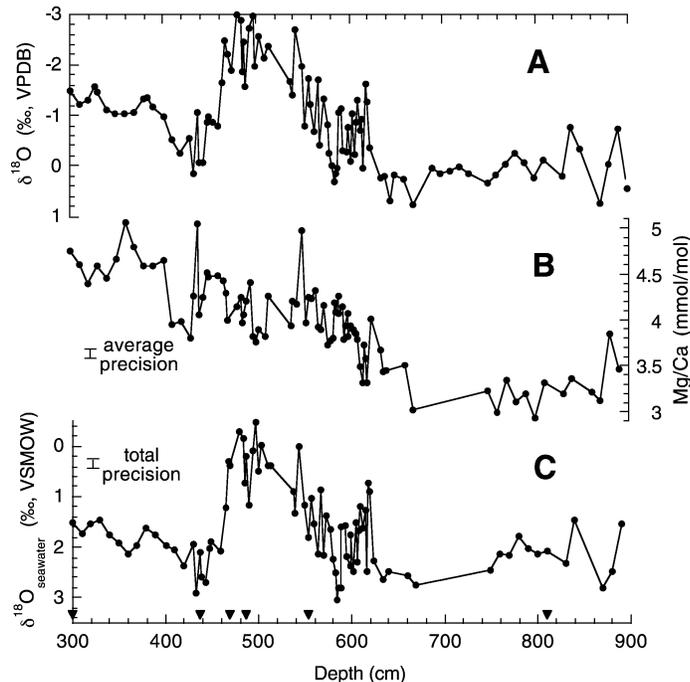


Figure 2. Paired (A) $\delta^{18}\text{O}$ (Leventer et al., 1982; this study) and (B) Mg/Ca data from Orca Basin core EN32-PC6 versus depth in core (Table DR2; see footnote 1). Sample spacing is generally 2–4 cm from 430 to 640 cm and 10 cm elsewhere, except for data gaps due to sparse foraminifera from 513 to 537 cm and from 670 to 750 cm. After subtracting temperature effect, $\delta^{18}\text{O}_{\text{sw}}$ was calculated by using equation appropriate for *G. ruber* (white) and converted to standard mean ocean water (SMOW) (see text). Also shown are depths of seven accelerator mass spectrometry ^{14}C dates (solid inverted triangles; Table DR1 [see footnote 1]) used in constructing age model. VPDB—Vienna Pee Dee belemnite.

explain the cool SSTs observed during the Last Glacial Maximum (23.6 ± 0.5 °C). However, the preference of *G. ruber* for the summer season probably limited the influence of cold winter air on our SST record. Furthermore, we note that the major warming phase from ca. 17.2 to 15.5 ka substantially preceded major global sea-level rise during meltwater pulse 1A, ca. 14.0 ka (Fairbanks, 1989), reducing the potential influence of sea-level changes on SST.

Overall, the Orca Basin SST exhibited early deglacial warming during Heinrich event 1 before the onset of the Bølling interval, as found in the Byrd ice core (Johnsen et al., 1972). The Orca Basin data do not appear to track Greenland air temperatures. Gulf of Mexico warming while the North Atlantic remained cold is consistent with weakened cross-equatorial heat transport (e.g., Manabe and Stouffer, 1997) and may indicate that thermohaline circulation modulated deglacial climate change on the millennial scale. Clearly, decreased NADW formation during Heinrich event 1 (Boyle and Keigwin, 1987) was associated with significant SST warming in the Gulf of Mexico. These observations need to be tested throughout the WHWP, including the northeastern tropical Pacific, which would not be influenced directly by Atlantic surface-ocean circulation (Fig. 1).

The SST data based on Mg/Ca ratios are consistent with foraminiferal assemblage data that indicate SST warming from ca. 17 to 15 ka (Kennett et al., 1985; Flower and Kennett, 1990, 1995). However, these studies also inferred a brief subsurface cooling near the beginning of the Younger Dryas ca. 13.0 ka based on reappearance of the glacial species *Globoconella inflata* (data not shown). This event is not recorded by the Mg/Ca ratios from *G. ruber*. Because *G. inflata* is a subsurface dweller in the Gulf of Mexico, we speculate that its brief

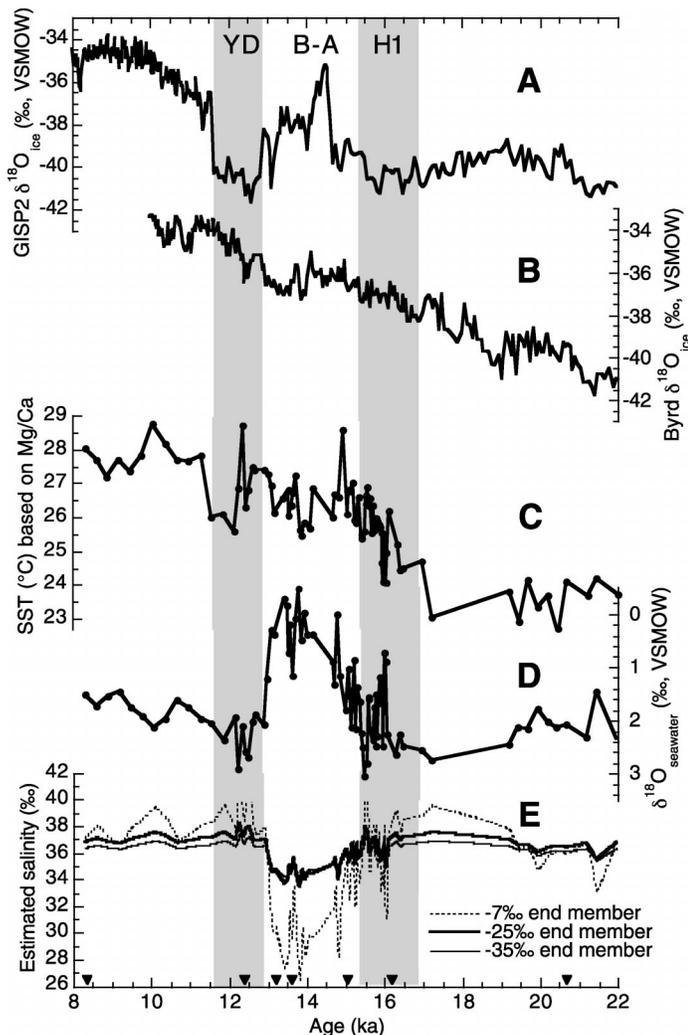


Figure 3. Deglacial proxy records during 22–8 ka interval. Shown is comparison of (A) Greenland air temperature based on Greenland Ice Sheet Project 2 (GISP2) $\delta^{18}\text{O}$ data (Grootes et al., 1993), (B) Antarctic air temperature based on Byrd $\delta^{18}\text{O}$ data (Johnsen et al., 1972; Blunier and Brook, 2001), (C) Orca Basin sea-surface temperatures (SSTs) based on Mg/Ca ratios from *G. ruber* in core EN32-PC6, (D) calculated $\delta^{18}\text{O}_{\text{sw}}$ values based on paired $\delta^{18}\text{O}$ values and Mg/Ca ratios, and (E) estimated salinity based on ice volume-corrected $\delta^{18}\text{O}_{\text{sw}}$ values and three possible end-member compositions for Laurentide meltwater (see text). Ages of seven accelerator mass spectrometry ^{14}C dates (Table DR1; see footnote 1) used in constructing age model are shown. Also indicated are Heinrich event 1 (H1) from 16.9 to 15.4 ka (shaded), Bølling-Ållerød warming (B-A) from 15.4 to 12.9 ka, and Younger Dryas cooling (YD) from 12.9 to 11.6 ka (shaded). VSMOW—Vienna standard mean ocean water.

reappearance reflects upper thermocline cooling linked to extratropical cooling within the Younger Dryas. This apparent discrepancy confirms the suggestion that the SST was decoupled from subsurface temperatures during the last deglaciation (Kennett et al., 1985) and raises the possibility that phasing of Gulf of Mexico temperatures relative to Greenland temperatures may differ on millennial and submillennial scales.

ISOLATING $\delta^{18}\text{O}$ VALUE OF SEAWATER

In order to isolate a $\delta^{18}\text{O}_{\text{sw}}$ record interpretable in terms of salinity, we first use SST data based on Mg/Ca to subtract the temperature component from the *G. ruber* $\delta^{18}\text{O}$ record. We use the *Orbulina universona* (high light) equation (equation 2 of Bemis et al., 1998), which is

also appropriate for *G. ruber* (Thunell et al., 1999): $T = 14.9 - 4.8 (\delta^{18}\text{O}_c - \delta^{18}\text{O}_{\text{sw}})$, where T is in $^{\circ}\text{C}$ and the c subscript indicates carbonate. Solving for $\delta^{18}\text{O}_{\text{sw}}$ and adding 0.27‰ yields a $\delta^{18}\text{O}_{\text{sw}}$ record on the Vienna standard mean ocean water (VSMOW) scale, which reflects a combination of ice volume-controlled $\delta^{18}\text{O}_{\text{sw}}$ changes and salinity variations (Fig. 3D). Total error is $\pm 0.2\%$ and includes analytical precision and errors in the Mg/Ca and $\delta^{18}\text{O}$ calibration equations. The middle Holocene mean (1.5‰) is somewhat higher than the present value of 1.2‰ (Fairbanks et al., 1992).

Isolating $\delta^{18}\text{O}_{\text{sw}}$ changes in this way reveals a brief negative excursion of $>1.5\%$ from ca. 16.1 to 15.6 ka and a major spike of $>2.5\%$ from ca. 15.2 to 13.0 ka; the lowest $\delta^{18}\text{O}_{\text{sw}}$ values were at 13.8 ka. Our findings are generally consistent with terrestrial data indicating meltwater input to the Gulf of Mexico from the southern Laurentide Ice Sheet margin throughout the early deglacial interval until ca. 13 ka (Licciardi et al., 1999; Rittentour et al., 2003). These meltwater floods coincided with the two largest events recorded independently in other cores from the Louisiana slope (Aharon, 2003). Moreover, documentation of the earlier flood ca. 16.1–15.6 ka does not support a simple model of meltwater routing in which diversion to eastern outlets inhibited NADW formation and caused regional to global cooling, whereas southward flow led to regional to global warming (Clark et al., 2001), because this flooding episode occurred during Heinrich event 1.

Furthermore, these 1‰–3‰ spikes may not translate to substantial salinity changes because the end-member Laurentide meltwater composition was probably -25% to -35% (Fairbanks, 1989; Schrag et al., 2002). In order to quantify salinity from $\delta^{18}\text{O}_{\text{sw}}$ data, we first subtract global $\delta^{18}\text{O}_{\text{sw}}$ changes based on sea-level history for the last deglaciation (Fairbanks, 1989; Bard et al., 1990). We smooth the sea-level data by 25% to reduce the high-frequency fluctuations, scale to $\delta^{18}\text{O}_{\text{sw}}$ as 0.083‰ per 10 m sea-level change (Schrag et al., 2002), and subtract from our $\delta^{18}\text{O}_{\text{sw}}$ record to yield a Gulf of Mexico $\delta^{18}\text{O}_{\text{sw}}$ residual. We derive a $\delta^{18}\text{O}_{\text{sw}}$ versus salinity relationship for Gulf of Mexico surface waters based on paired $\delta^{18}\text{O}_{\text{sw}}$ and salinity data (Fairbanks et al., 1992) and Laurentide meltwater end-member compositions of -25% to -35% . Our estimated salinity data (Fig. 3E) show reductions of $\sim 2\%$ – 4% from ca. 16.1 to 15.6 ka and from ca. 15.2 to 13.0 ka. These reductions are far less than those estimated by using a -7% end member appropriate for the modern Gulf of Mexico (Ortner et al., 1995). With the caveat that *G. ruber* may sink to subsurface waters to avoid the lowest salinities (Spero and Williams, 1991), these results indicate only modest salinity changes even during peak meltwater inflow. Consequently, models that invoke a direct influence of Laurentide meltwater input to the Gulf of Mexico on the basis of NADW variations should take into account only modest changes in density.

CONCLUSIONS

Paired $\delta^{18}\text{O}$ and Mg/Ca data on planktonic foraminifera (*G. ruber*) from Orca Basin core EN32-PC6 are used to separate deglacial changes in SSTs and $\delta^{18}\text{O}_{\text{sw}}$ values. SSTs based on Mg/Ca ratios increased from Last Glacial Maximum values of 23.6 ± 0.5 $^{\circ}\text{C}$ to early Holocene values of 27.8 ± 0.4 $^{\circ}\text{C}$ beginning between ca. 17.2 and 15.2 ka. SST warming of >3 $^{\circ}\text{C}$ spans Heinrich event 1 and clearly precedes peak meltwater input ca. 13.8 ka by >2 k.y. These results are consistent with the observation that western tropical Atlantic SSTs were not in phase with Greenland climate (Ruhlemann et al., 1999). If confined to this region and parts of the South Atlantic, this finding may indicate that thermohaline circulation modulated Atlantic climate on the millennial scale.

SST data based on Mg/Ca ratios and global $\delta^{18}\text{O}_{\text{sw}}$ changes are

subtracted from *G. ruber* $\delta^{18}\text{O}$ values to isolate local $\delta^{18}\text{O}_{\text{sw}}$, which allows us to determine meltwater variability with a precision impossible without independent SST data. Our $\delta^{18}\text{O}_{\text{sw}}$ data indicate a major spike of $>2.5\text{‰}$ attributable to meltwater input from ca. 15.2 to 13.0 ka during the Bølling-Ållerød and a precursor event of $>1.5\text{‰}$ from ca. 16.1 to 15.6 ka during Heinrich event 1. The earlier flooding episode does not support a simple model in which southward routing of Laurentide meltwater allowed a resumption of NADW formation and led to regional to global warming. Conversion of $\delta^{18}\text{O}_{\text{sw}}$ to salinity by using reasonable end-member compositions for Laurentide meltwater (-25‰ to -35‰) indicates only modest salinity decreases of 2%–4% during these intervals, which must be considered when evaluating a direct influence on NADW variability of Laurentide meltwater input to the Gulf of Mexico.

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REFERENCES CITED

- Aharon, P., 2003, Meltwater flooding events in the Gulf of Mexico revisited: Implications for rapid climate changes during the last deglaciation: *Paleoceanography*, v. 18, 1079, doi: 10.1029/2002PA000840.
- Bard, E., Hamelin, B., Fairbanks, R.G., and Zindler, A., 1990, Calibration of the ^{14}C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals: *Nature*, v. 345, p. 405–410.
- Barker, S., Greaves, M., and Elderfield, H., 2003, A study of cleaning procedures used for foraminiferal Mg/Ca paleothermometry: *Geochemistry, Geophysics, Geosystems*, v. 4, doi: 10.1029/2003GC000559.
- Bemis, B.E., Spero, H.J., Bijma, J., and Lea, D.W., 1998, Reevaluation of the oxygen isotopic composition of planktonic foraminifera: Experimental results and revised paleotemperature equations: *Paleoceanography*, v. 13, p. 150–160.
- Blunier, T., and Brook, E.J., 2001, Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period: *Science*, v. 291, p. 109–112.
- Boyle, E.A., and Keigwin, L.D., 1987, North Atlantic thermohaline circulation during the past 20,000 years linked to high-latitude surface temperature: *Nature*, v. 330, p. 35–40.
- Broecker, W.S., 1998, Paleocan circulation during the last deglaciation: A bipolar seesaw?: *Paleoceanography*, v. 13, p. 119–121.
- Broecker, W.S., Kennett, J.P., Flower, B.P., Teller, J.T., Trumbore, S., Bonani, G., and Wolff, W., 1989, The routing of meltwater from the Laurentide Ice Sheet during the Younger Dryas cold episode: *Nature*, v. 341, p. 318–321.
- Cane, M., and Clement, A., 1999, A role for the tropical Pacific coupled ocean-atmosphere system on Milankovitch and millennial timescales: Part II. Global impacts, in Clark, P.U., et al., *Mechanisms of global climate change at millennial time scales*: American Geophysical Union Geophysical Monograph 112, p. 373–383.
- Clark, P.U., Marshall, S.J., Clarke, G.K.C., Hostetler, S.W., Licciardi, J.M., and Teller, J.T., 2001, Freshwater forcing of abrupt climate change during the last glaciation: *Science*, v. 293, p. 283–287.
- Dekens, P.S., Lea, D.W., Pak, D.K., and Spero, H.J., 2002, Core top calibration of Mg/Ca in tropical foraminifera: Refining paleotemperature estimation: *Geochemistry, Geophysics, Geosystems*, v. 3, doi: 10.1029/2001GC00200.
- Fairbanks, R.G., 1989, A 17,000-year glacio-eustatic sea level record: Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation: *Nature*, v. 342, p. 637–642.
- Fairbanks, R.G., Charles, C.D., and Wright, J.D., 1992, Origin of global meltwater pulses, in Taylor, R.E., et al., eds., *Radiocarbon after four decades*: New York, Springer-Verlag, p. 473–500.
- Flower, B.P., and Kennett, J.P., 1990, The Younger Dryas cool episode in the Gulf of Mexico: *Paleoceanography*, v. 5, p. 949–961.
- Flower, B.P., and Kennett, J.P., 1995, Biotic responses to temperature and salinity changes during the last deglaciation, Gulf of Mexico, in Stanley, S.M., ed., *Effects of past global change on life*: Washington, D.C., National Academy Press, National Research Council Studies in Geophysics, p. 209–220.
- Groote, P.M., Stuiver, M., White, J.M.C., Johnsen, S.J., and Jouzel, J., 1993, Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores: *Nature*, v. 366, p. 552–554.
- Guilderson, T.P., Fairbanks, R.G., and Rubenstone, J.L., 2001, Tropical Atlantic coral oxygen isotopes: Glacial-interglacial temperatures and climate change: *Marine Geology*, v. 172, p. 75–89.
- Hastings, D.W., Whitko, A., Kienast, M., and Steinke, S., 2001, A comparison of three independent paleotemperature estimates from a high resolution record of deglacial SST records in the tropical South China Sea: *Eos (Transactions, American Geophysical Union)*, v. 82, abs. PP12B-10.
- Huls, M., and Zahn, R., 2000, Millennial-scale sea surface temperature variability in the western tropical North Atlantic from planktonic foraminiferal census counts: *Paleoceanography*, v. 15, p. 659–678.
- Johnsen, S.J., Dansgaard, W., Clausen, H.B., and Langway, C.C., Jr., 1972, Oxygen isotope profiles through the Antarctic and Greenland ice sheet: *Nature*, v. 235, p. 429–434.
- Keigwin, L.D., Jones, G.A., and Lehman, S.J., 1991, Deglacial meltwater discharge, North Atlantic deep circulation, and abrupt climate change: *Journal of Geophysical Research*, v. 96, p. 16,811–16,826.
- Kennett, J.P., Elmstrom, K., and Penrose, N., 1985, The last deglaciation in Orca Basin, Gulf of Mexico: High-resolution planktonic foraminiferal changes: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 50, p. 189–216.
- Lea, D.W., Pak, D.K., Peterson, L.C., and Hughen, K.A., 2003, Synchronicity of tropical and high-latitude Atlantic temperatures over the last glacial termination: *Science*, v. 301, p. 1361–1364.
- Leventer, A., Williams, D.F., and Kennett, J.P., 1982, Dynamics of the Laurentide Ice Sheet during the last deglaciation: Evidence from the Gulf of Mexico: *Earth and Planetary Science Letters*, v. 59, p. 11–17.
- Licciardi, J.M., Teller, J.T., and Clark, P.U., 1999, Freshwater routing by the Laurentide Ice Sheet during the last deglaciation, in Clark, P.U., et al., eds., *Mechanisms of global climate change at millennial time scales*: American Geophysical Union Geophysical Monograph 112, p. 177–201.
- Manabe, S., and Stouffer, R.J., 1997, Coupled ocean-atmosphere model response to freshwater input: Comparison to Younger Dryas event: *Paleoceanography*, v. 12, p. 321–336.
- Ortner, P.B., Lee, T.N., Milne, P.J., Zika, R.G., Clarke, M.E., Podesta, G.P., Swart, P.K., Tester, P.A., Atkinson, L.P., and Johnson, W.R., 1995, Mississippi River flood waters that reached the Gulf Stream: *Journal of Geophysical Research*, v. 100, p. 13,595–13,601.
- Rittentour, T.M., Goble, R.J., and Blum, M.D., 2003, An optical age chronology of late Pleistocene fluvial deposits in the northern lower Mississippi River valley: *Quaternary Science Reviews*, v. 22, p. 1105–1110.
- Ruhlemann, C., Mulitza, S., Muller, P.J., Wefer, G., and Zahn, R., 1999, Warming of the tropical Atlantic Ocean and slowdown of thermohaline circulation during the last deglaciation: *Nature*, v. 402, p. 511–514.
- Schrag, D.P., Adkins, J.F., McIntyre, K., Alexander, J.L., Hodell, D.A., Charles, C.D., and McManus, J.F., 2002, The oxygen isotopic composition of seawater during the Last Glacial Maximum: *Quaternary Science Reviews*, v. 21, p. 331–342.
- Spero, H.J., and Williams, D.F., 1991, Evidence for seasonal low-salinity surface waters in the Gulf of Mexico over the last 16,000 years: *Paleoceanography*, v. 5, p. 963–975.
- Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., Van Der Plicht, J., and Spurk, M., 1998, INT-CAL98 radiocarbon age calibration 24,000–0 cal BP: *Radiocarbon*, v. 40, p. 1041–1083.
- Thunell, R., Tappa, E., Pride, C., and Kincaid, E., 1999, Sea-surface temperature anomalies associated with the 1997–1998 El Niño recorded in the oxygen isotope composition of planktonic foraminifera: *Geology*, v. 27, p. 843–846.
- Wang, C., and Enfield, D.B., 2001, The tropical Western Hemisphere Warm Pool: *Geophysical Research Letters*, v. 28, p. 1635–1638.

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