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ABSTRACT

The history of meltwater flow from the Laurentide Ice Sheet to the Gulf of Mexico during the last deglaciation, which holds possible implications for the cause of the Younger Dryas cold episode, is not well understood. We propose a new chronology based on using the percentage of reworked calcareous nannofossils in Orca Basin sediments as a proxy for erosion. The period of greatest meltwater flow to the gulf was between 12.7 and 12.1 ka (during the Bølling warm interval), and flow remained high until the beginning of the Younger Dryas cold episode at 11.3 ka; this corresponds to meltwater pulse IA. A sharp meltwater decrease at 12.2 ka may represent the Older Dryas glacial readvance. Little or no meltwater is inferred to have flowed to the gulf from ~10 to 9 ka, which is the time of the second major meltwater pulse, IB. Therefore, meltwater must have been permanently diverted away from the Gulf of Mexico at the beginning of the Younger Dryas.

INTRODUCTION

Much discussion about Laurentide Ice Sheet meltwater has revolved around sediment cores in the Gulf of Mexico (Kennett and Shackleton, 1975; Emiliani et al., 1975) and especially in the Orca Basin, an anoxic depression ~290 km southwest of the Mississippi Delta (e.g., Leventer et al., 1982, 1983; Kennett et al., 1985; Broecker et al., 1988, 1989; Flower and Kennett, 1990). High sedimentation rates, excellent microfossil preservation, lack of bioturbation, and proximity to the Mississippi River make this site ideal for high-resolution meltwater studies. To elucidate the nature of meltwater flow to the gulf (Fig. 1A), Broecker et al. (1989) presented the $\delta^{18}O$ record of planktonic foraminifera in the Orca Basin between ~16 and 17 ka (^{14}C ages). They identified a negative $\delta^{18}O$ anomaly between 12.7 and 11.3 ka as representing a large influx of fresh, isotopically negative meltwater from the decaying Laurentide Ice Sheet. This event had been previously identified in other Gulf of Mexico cores (Kennett and Shackleton, 1975; Emiliani et al., 1975, 1978; Leventer et al., 1982, 1983; Kennett et al., 1985). The shift was too large to be explained by warming alone, as its $\delta^{18}O$ values were significantly more negative than those of the early Holocene (post–10.1 ka). Kennett and Shackleton (1975) and Broecker et al. (1989) attributed the sharp increase in $\delta^{18}O$ at 11.3 ka to a temporary diversion of meltwater away from the Gulf of Mexico to the St. Lawrence River. As first proposed by Rooth (1982), this diversion supposedly inhibited North Atlantic deep-water (NADW) formation and shut down the Atlantic's conveyor circulation system. The result was the Younger Dryas cold episode, which increased ocean $\delta^{18}O$, making the shift in the Orca Basin core even more positive. The $\delta^{18}O$ decrease at 10.1 ka was identified as the end of the Younger Dryas, accompanied by the return of meltwater to the gulf (Broecker et al., 1989).

Fairbanks (1989) disagreed with Broecker et al.'s (1989) evidence for a meltwater diversion. He calculated a global meltwater curve from sea-level data from the reef-crest coral *Acropora palmata* in Barbados (Fig. 2). It shows two distinct meltwater pulses (mwp), mwp-IA and mwp-IB, centered at ~12 and 9.5 ka, respectively. Mwp-IA, which corresponds to the prominent negative $\delta^{18}O$ anomaly in the Orca Basin, began shortly after 13 ka and reached maximum discharge at ~12 ka. Discharge was at a minimum at 11 ka and remained low until ~10.5 ka, when mwp-IB began. Thus, the apparent absence of meltwater in the Gulf of Mexico during the Younger Dryas could be explained by greatly reduced melting rather than a temporary diversion. Broecker (1990) maintained that NADW formation could have been reduced by a large, brief burst of meltwater at the beginning of the diversion, before melting decreased. Broecker et al. (1990a) further proposed that a salt oscillator operated in the glacial northern Atlantic. By this mechanism, the Atlantic's conveyor circulation is primarily controlled by vapor loss and heat flux, and the meltwater diversion merely acted as a trigger to cripple an already weakened conveyor. Several authors have presented independent paleogeochemical evidence that NADW formation was decreased during the Younger Dryas (Boyle and Keigwin, 1987; Keigwin et al., 1991; Lehman and Keigwin, 1992), although others suggest that NADW formation was strong at this time (Jansen and Veum, 1990; Veum et al., 1992).

The actual history of meltwater flow to the Gulf of Mexico during the Wisconsin deglaciation is not discernible from the $\delta^{18}O$ record alone, because $\delta^{18}O$ reflects temperature and global ice volume as well as freshwater input. In search of another proxy for meltwater flow, we turned to sediment erosion, as evidenced by reworked calcareous nannofossils. These are mainly coccoliths, the remains of unicellular marine algae of the family Coccolithophoridae (size range ~1–15 μm). Constans and Parker (1986) showed that the ratio of reworked (extinct) nannofossils to indigenous (extant) nannofossils in the Gulf of Mexico sediments is an index of erosion on a glacial-interglacial scale. During glacial lowstands of sea level, increased erosion led to greater input of Cretaceous and Tertiary coccoliths into the gulf, from continental and Mississippi Delta fan deposits. Increased meltwater flow to the Gulf of Mexico

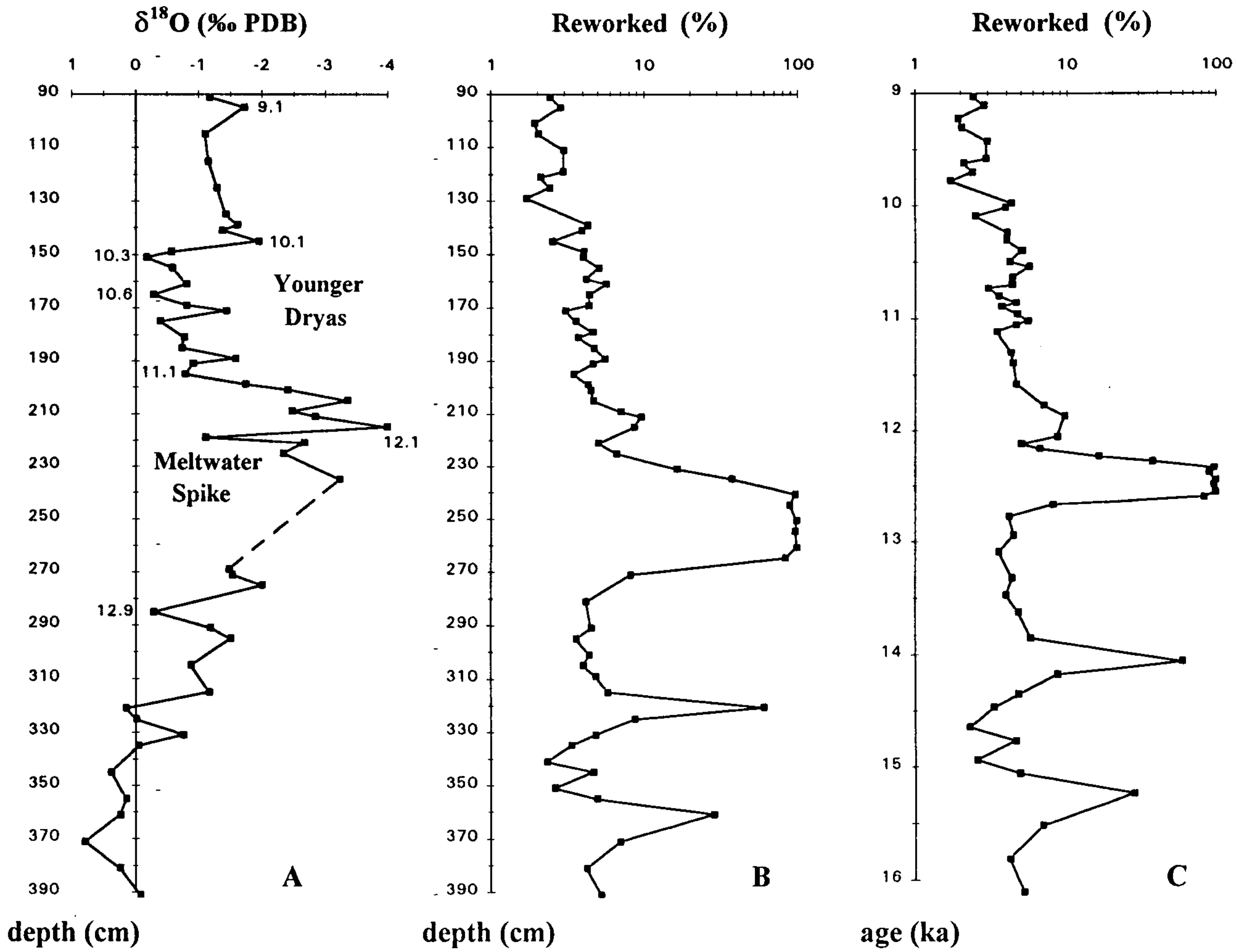

Figure 1. A: Oxygen isotope values (PDB = Peedee belemnite) for *Globigerinoides ruber* (white variety) from Orca Basin core EN32-PC4, plotted vs. depth (Broecker et al., 1989). Also shown are seven accelerator mass spectrometer (AMS) radiocarbon ages in ka (Broecker et al., 1989, 1990b). Prominent meltwater spike occurs between 12.7 and 11.3 ka, and Younger Dryas cold episode occurs between 11.3 and 10.1 ka. B: Percentages of reworked calcareous nannofossils for EN32-PC4, plotted on log scale vs. depth. C: Same plot as in B, but vs. age (dates revised by Flower and Kennett, 1990).

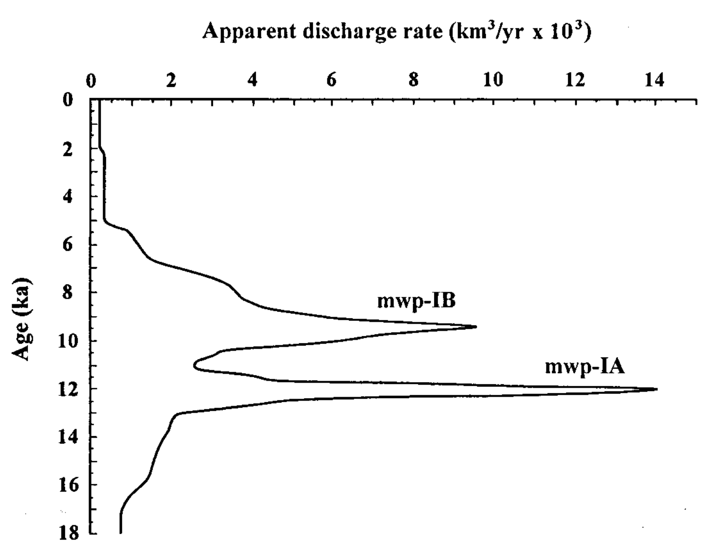

Figure 2. Global meltwater discharge rate calculated from coral-derived sea-level curve, plotted vs. radiocarbon age (Fairbanks, 1989). Meltwater pulses (mwp) IA and IB are centered at 12 and 9.5 ka, respectively, and are separated by Younger Dryas cold episode.

should further enhance erosion in the Mississippi watershed, increasing the input of reworked calcareous nannofossils into the gulf.

METHODS

Slides were prepared for light-microscope study from raw (unsieved) gray-brown sediment from Orca Basin piston core EN32-PC4. For most of the core, two to three samples were analyzed per 10 cm for a total of 67 samples between 90 and 392 cm depth. Slides were viewed at 1250× on a Zeiss Axioscope, primarily under cross-polarized light. At least 750 nannofossils were identified (by species) and counted per sample; the only exceptions were samples in which nannofossils were scarce (~250 fossils counted for four samples) or rare (~50 counted for seven samples). For each sample, the abundance of reworked nannofossils was calculated as a percentage of total (reworked plus extant) nannofossils. Only extinct species were identified as reworked.

CHRONOLOGY AND ISOTOPES

Orca Basin core EN32-PC4 is the same core studied by Broecker et al. (1989). They obtained seven accelerator mass spectrometer (AMS) radiocarbon ages from mixed planktonic foraminifera, which were revised by Broecker et al. (1990b) (Fig. 1A).

These ages provide an excellent chronology between 12.86 and 9.11 ka. This chronology was extended for sediments older than 12.86 ka by Flower and Kennett (1990), who correlated $\delta^{18}O$ oscillations at 13.97 and 17.86 ka in the planktonic foraminifer *Globigerinoides ruber* (white variety) with those dated by Broecker et al. (1988) in nearby core EN32-PC6. Flower and Kennett (1990) determined ages for the top of the core by extrapolating the sedimentation rate of the interval between the two youngest AMS dates. On the basis of the above chronology, the section examined in this study ranges from 16.1 (early deglacial) to 9 ka (early Holocene).

The $\delta^{18}O$ record of EN32-PC4, from the planktonic foraminifer *Gs. ruber* (white variety), was determined by Broecker et al. (1989) (Fig. 1A). This curve shows maximum $\delta^{18}O$ values between the base of the interval and ~12.7 ka, and between ~11.3 and 10.1 ka; these correspond to the late Wisconsin glacial period and the Younger Dryas cold episode, respectively. Lower $\delta^{18}O$ values occur from 12.7 to 11.3 ka and from 10.1 ka to the top of the section; these have been identified as a prominent meltwater spike (paired with warm, interglacial conditions) and the Holocene Epoch, respectively (Broecker et al., 1989; Flower and Kennett, 1990).

RESULTS AND DISCUSSION

Reworked nannofossils compose <10% of total specimens for most of the core length (percentage of reworked specimens vs. depth and vs. age, Fig. 1, B and C, respectively). Three exceptions are found at ~15.2, 14.1, and 12.7 to 12.2 ka. The first two peaks, each of which have only one data point above 10%, do not correlate with any low $\delta^{18}O$ excursions. They probably represent isolated turbidity currents associated with low sea levels, rather than major meltwater pulses. The largest peak of percentage of reworked specimens, between 12.7 and 12.2 ka, contains eight values above 10% to a maximum of 98%; it corresponds well to the first half of the meltwater spike. This interval appears to be the time of maximum meltwater flow to the Gulf of Mexico and also correlates with the first half of pulse mwp-IA of Fairbanks (1989). It should also be noted that $\delta^{18}O$ data are lacking from this period owing to the rarity of foraminifera; we might expect the missing values to be even lower than during the 12.1 ka minimum.

The period between ~13 and 11 ka corresponds to the Bølling-Allerød warm interval. This interval was separated by a minor glacial readvance (~12.1–11.9 ka), the Older Dryas (e.g., Dansgaard et al., 1971; Berger, 1990). The main peak in reworked nannofossils decreases to ~5% at 12.1 ka, the same time as the high $\delta^{18}O$ event that separates the two halves of the meltwater spike. Thus these two events correspond to the Older Dryas cold episode. Decreases in several extant coccolithophore species (*Gephyrocapsa oceanica, G.* [small spp.], and *Umbilicosphaera sibogae*) also indicate cooling in the gulf at 12.1 ka. The low percentage of reworked nannofossils suggests that meltwater flow decreased significantly during this brief glacial readvance. Flow into the gulf may not have fully recovered during the subsequent Allerød warm interval (12.1–11.3 ka), perhaps because it was partially diverted to another outlet. The negative $\delta^{18}O$ anomaly during the Allerød suggests that flow was still considerable, however, as the values are too low to have been caused by warm temperatures alone. Another factor that probably contributed to the relatively low abundances of reworked nannofossils during this interval is a lack of loose, erodable sediment, because much of the sediment was likely removed in the early stages of meltwater erosion. Thus, meltwater flow into the gulf was probably substantial until ~11.3 ka, when $\delta^{18}O$ values increase sharply.

Evidence for mwp-IB is clearly missing from the Orca Basin sequence. This absence is contrary to the hypothesis of Broecker et al. (1989), who suggested that meltwater returned to the Gulf of Mexico following the Younger Dryas. If major flow did return to the gulf, we would expect evidence for another high-erosion peak at ~9.5 ka, as the discharge of mwp-IB was inferred by Fairbanks (1989) to be more than two-thirds that of mwp-IA. In fact, the interval between 10 and 9 ka exhibits the lowest concentrations of reworked nannofossils in the core. There is also no negative $\delta^{18}O$ anomaly (meltwater spike) during this period; the $\delta^{18}O$ difference between the Younger Dryas and early Holocene (~1‰) may be explained by warming and ice-volume reduction alone. The absence of mwp-IB indicates that major meltwater flow was *permanently* diverted away from the Gulf of Mexico at ~11.3 ka. The general decrease in reworked-specimen percentages between 11.3 and 9 ka was probably caused by rising sea levels, which covered previously exposed fan sediments and decreased the gradient of the Mississippi. Although one might argue that this sea-level rise is the reason that mwp-IB and the second half of mwp-IA do not appear in the data on percentage of reworked specimens, we see at least two reasons to disagree. First, the drop in percentage of reworked specimens at 12.1 ka is too rapid to be explained by rising seas. Second, even with high sea levels, we would expect to see *some* increase in erosion centered around 9.5 ka if mwp-IB were present. The relative constancy of $\delta^{18}O$ in the pink form of *Gs. ruber* after 11.3 ka offers further confirmation that major meltwater flow did not return to the gulf (Broecker et al., 1989; Flower and Kennett, 1990).

Numerous authors have shown that meltwater was diverted away from the Mississippi River at ~11 ka (e.g., Prest, 1970; Ashworth et al., 1972; Clayton and Moran, 1982; Teller and Clayton, 1983; Teller, 1985, 1987; Broecker et al., 1989). Their terrestrial evidence indicates that the retreat of the Laurentide Ice Sheet allowed meltwater passing through proglacial Lake Agassiz to flow eastward to the St. Lawrence River. These authors further argued that meltwater returned to the Mississippi at ~10 ka, but this conclusion has recently been challenged. Smith and Fisher (1993) concluded that meltwater flowed from Lake Agassiz northward to the Arctic Ocean at ~10 ka, rather than southward to the Gulf of Mexico. Porter and Guccione (1994) attributed the Charleston alluvial fan, the youngest product of deglacial flooding in the lower Mississippi Valley, to the pre–11 ka flow (mwp-IA). These two studies indicate that there was no major meltwater flow down the Mississippi at ~10 ka, in agreement with our results. Our data are thus consistent with a diversion of meltwater to the St. Lawrence River at ~11.3 ka and a subsequent rerouting to the Arctic at ~10 ka, when Lake Agassiz's eastern outlets were blocked. A meltwater trigger for the Younger Dryas cold episode, via the St. Lawrence, cannot be ruled out.

CONCLUSIONS

The abundance of reworked calcareous nannofossils in Orca Basin sediments serves as a proxy for sediment erosion into the Gulf of Mexico during the last deglaciation. Combined with oxygen isotope data from planktonic foraminifera, this proxy records the history of meltwater flow down the Mississippi River. Flow was greatest during the Bølling warm interval (12.7–12.2 ka) and remained high until the beginning of the Younger Dryas cold episode (11.3 ka), corresponding to meltwater pulse IA. There was no return of meltwater to the Gulf of Mexico at the end of the Younger Dryas (~10 ka), the age of meltwater pulse IB. Flow was thus permanently diverted away from the Mississippi at the beginning of the Younger Dryas cold episode.

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