Iceberg scours along the southern U.S. Atlantic margin

Jenna C. Hill*
Paul T. Gayes
Coastal Carolina University, Burroughs and Chapin Center for Marine and Wetland Studies, Conway, South Carolina 29526, USA
Neal W. Driscoll
Elizabeth A. Johnstone
Scripps Institution of Oceanography, University of California–San Diego, La Jolla, California 92093, USA
George R. Sedberry
Gray's Reef National Marine Sanctuary, National Oceanic and Atmospheric Administration, Savannah, Georgia 31411, USA

ABSTRACT

Rapid climate fluctuations associated with ice-sheet oscillations have resulted in pulses of iceberg discharge that are recorded by iceberg scour marks along continental shelves and ice-rafted debris deposits across the North Atlantic. Iceberg transport is largely controlled by ocean surface currents; therefore, iceberg trajectories can serve as a proxy for paleocirculation studies. Records of iceberg transport from ice-rafted debris (i.e., Heinrich layers) in the North Atlantic suggest that most icebergs released during Quaternary glaciations were entrained in a cyclonic subpolar gyre restricted to polar and mid-latitudes; however, new data suggest that there may have been an additional southerly component of transport along the western Atlantic margin. Here, we present evidence of extensive iceberg scouring across the upper slope offshore of South Carolina, ~1000 km south of the proximal ice margin during Quaternary glacial maximums. The location and orientation of the keel marks suggest that icebergs were entrained in a southwestward-flowing coastal current. At present, warm waters of the rapid, northeastward-flowing Gulf Stream bathe the upper slope off the southeastern United States. An offshore shift in the Gulf Stream axis during sea-level lowstand may have allowed glacially fed coastal currents to penetrate farther south. This may be the first evidence of iceberg rafting to subtropical latitudes in the North Atlantic.

Keywords: iceberg scour, paleocirculation, multibeam bathymetry, Florida-Hatteras slope.

INTRODUCTION

The forcing mechanisms of ice-sheet oscillations and associated pulses of iceberg discharge remain poorly understood. Proxies for iceberg transport, such as iceberg keel marks and ice-rafted debris deposits, can provide insight into modes of ice-sheet collapse, freshwater inputs, and sea-surface temperatures, all of which strongly influence climatic and ocean circulation patterns. Here, we present new high-resolution bathymetric and side-scan sonar data that reveal extensive relict iceberg scours across the upper slope offshore of South Carolina, ~1000 km from the proximal ice margin during Quaternary glaciations. The orientation and morphology of the keel marks suggest iceberg entrainment in a southwestward-flowing coastal current derived from the retreating ice margin during deglaciation, and they highlight the influence of meltwater-driven coastal flows.

OBSERVATIONS AND RESULTS

High-resolution swath bathymetry data collected offshore of South Carolina aboard the National Oceanic and Atmospheric Administration (NOAA) ship *Nancy Foster* with a Kongsberg Simrad EM1002 (95 kHz) swath mapping system as part of the NOAA Ocean Exploration program in 2006 and 2007 reveal numerous kilometer-scale furrows along the upper slope (170–220 m water depth) (Fig. 1). The grooved features are typically 10–100 m wide and <10 m deep, and their lengths are >10 km, while some larger furrows are up to 400 m wide and 20 m deep. The furrows are oriented predominantly WSW subparallel to regional bathymetric contours; most azimuths are between 210° and 270° (Fig. 2). The furrows range from linear to arcuate, with crosscutting tracks. Many of the furrow troughs are flanked by lateral berms that are several meters high and that often terminate in semicircular pits ringed by several-meter-high ridges (Fig. 2). Video observations conducted along these berms, during NOAA Ocean Exploration submersible dives in 2002, show evidence of large upturned blocks and boulders. There are also numerous circular pits, 50–100 m in diameter and several meters deep, scattered across the region (Fig. 2).

The furrows were observed along an irregularly shaped platform that is elevated above the surrounding slope by ~10 m (Figs. 1 and 2). High backscatter across the platform suggests hardground material with very little sediment cover (Fig. 2I). Low backscatter was observed in both the deeper regions off the platform and the base of the furrows and pits (Fig. 2I). This interpretation was confirmed by bottom video, which showed an abundance of boulders interspersed with patchy sediment across the platform, whereas the deeper regions were sand covered.

DISCUSSION

While much of the shelf has been exposed and dissected by paleochannel networks during periods of lowered sea level, the slope has remained submerged throughout the Quaternary (Riggs and Belknap, 1988; Fairbanks, 1989; Baldwin et al., 2006). Multibeam bathymetry surveys conducted along the outer shelf and upper slope across the region as part of this project show no evidence of additional furrows upslope (<120 m) despite the presence of similar hardground areas, implying that these are not subaerial channel features. The upper-slope furrows trend subparallel to bathymetric contours and show no evidence of connection with regional downslope gullies that extend to abyssal depths across the lower slope (Tucholke, 1979). In addition, neither paleochannel drainage nor density-driven gravity flows appear

*E-mail: jchill@coastal.edu.

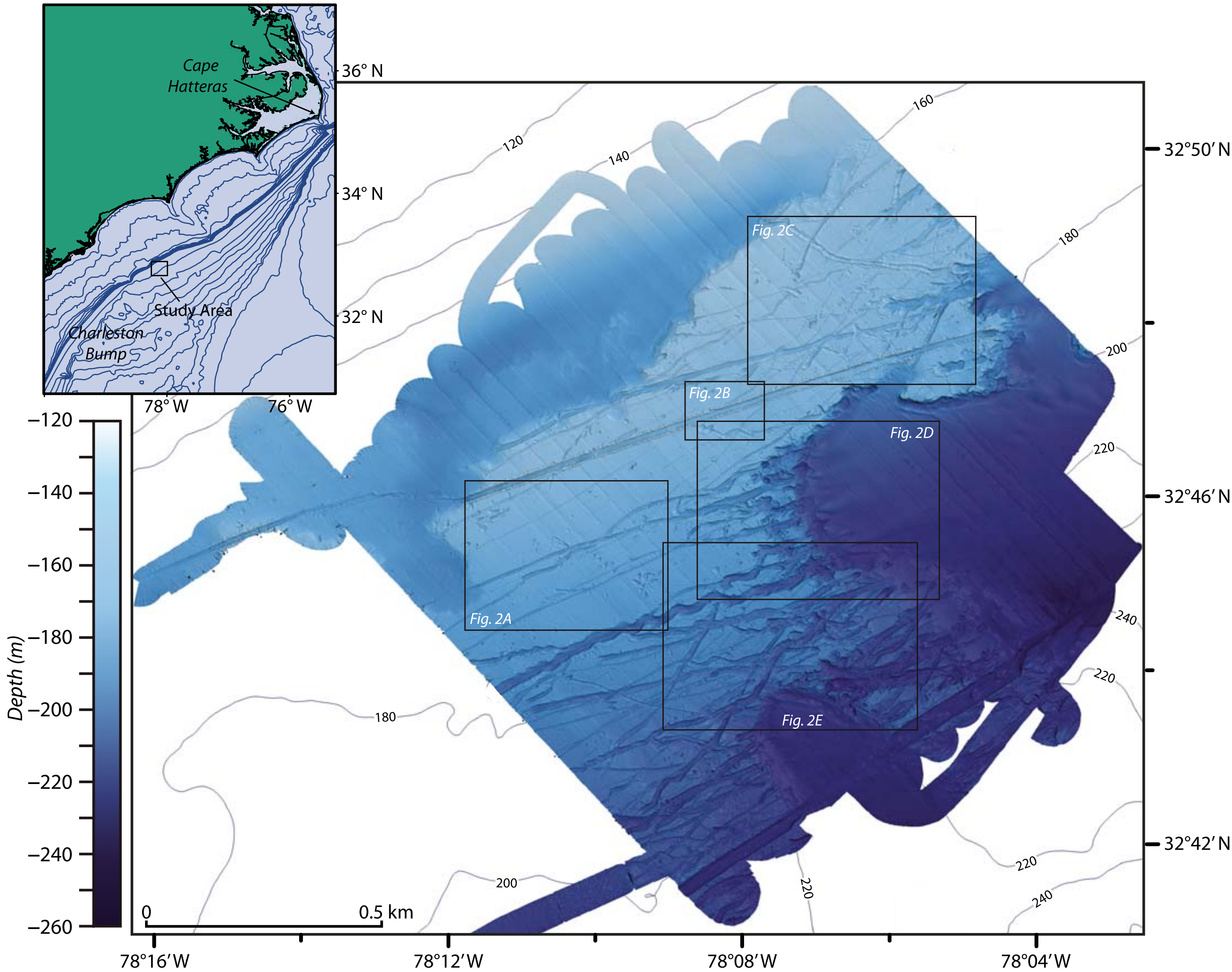

Figure 1. High-resolution bathymetry acquired along upper slope of Florida-Hatteras (5 m grid) imaged numerous iceberg scours along an irregularly shaped platform. Boxes indicate locations of detail images in Figure 2. Inset: Location map showing study area offshore of South Carolina.

to be sufficient to explain the presence of the lateral berms, push-up ridges, or circular pits observed in association with the furrows. First-order volume estimates indicate that the material along the lateral berms of furrows along the uppermost part of the slope is roughly equal to the amount of material removed from the adjacent furrows; this suggests that the berms were formed by material plowed out of the trough. Anthropogenic activities, such as bottom trawling and dredging, can create plow scars with a similar morphology (National Research Council, 2002); however, the furrows observed here are typically much larger, deeper, and more irregular than would be expected from bottom trawl scars. There are also no known trawl fisheries operating in this region. Likewise, these features are too large and linear to have been formed by biological activities such as tilefish burrowing (Able et al., 1982).

The furrows exhibit morphologies that are characteristic of iceberg scours documented along glaciated margins (Davies et al., 1997). In shallow water, iceberg keels will plow into the seafloor, creating the lateral berms observed along the furrow tracks (Fig. 2B), as well as building up piles of sediment around semicircular depressions at the end of the track (Woodworth-Lynas et al., 1991). These depressions are interpreted as terminal grounding pits, where an iceberg has come to rest on the seafloor (Fig. 2C). After a period of melting, grounded icebergs can become dislodged and will continue to move across the seafloor, creating smaller furrows that extend beyond the initial grounding pit (Dowdeswell et al., 1993; Syvitski et al., 2001). Strings and clusters of circular depressions interspersed among the scours (Fig. 2A) suggest that bobbing or semigrounded icebergs skipped across the seafloor (Bass and Woodworth-Lynas, 1988). The trajectory of iceberg transport can be determined from the orientation of the scour tracks and location of terminal grounding pits (Woodworth-Lynas et al., 1991). The general southwestward orientation of the scours and numerous terminal grounding pits found on the northeastern periphery of the platform suggest that the icebergs were transported southwest along the margin and became grounded as they plowed into the platform (Fig. 2).

While none of the relict keel marks is likely pristine, several lines of evidence suggest that many of the seaward furrows may have been enhanced and overprinted by bottom current

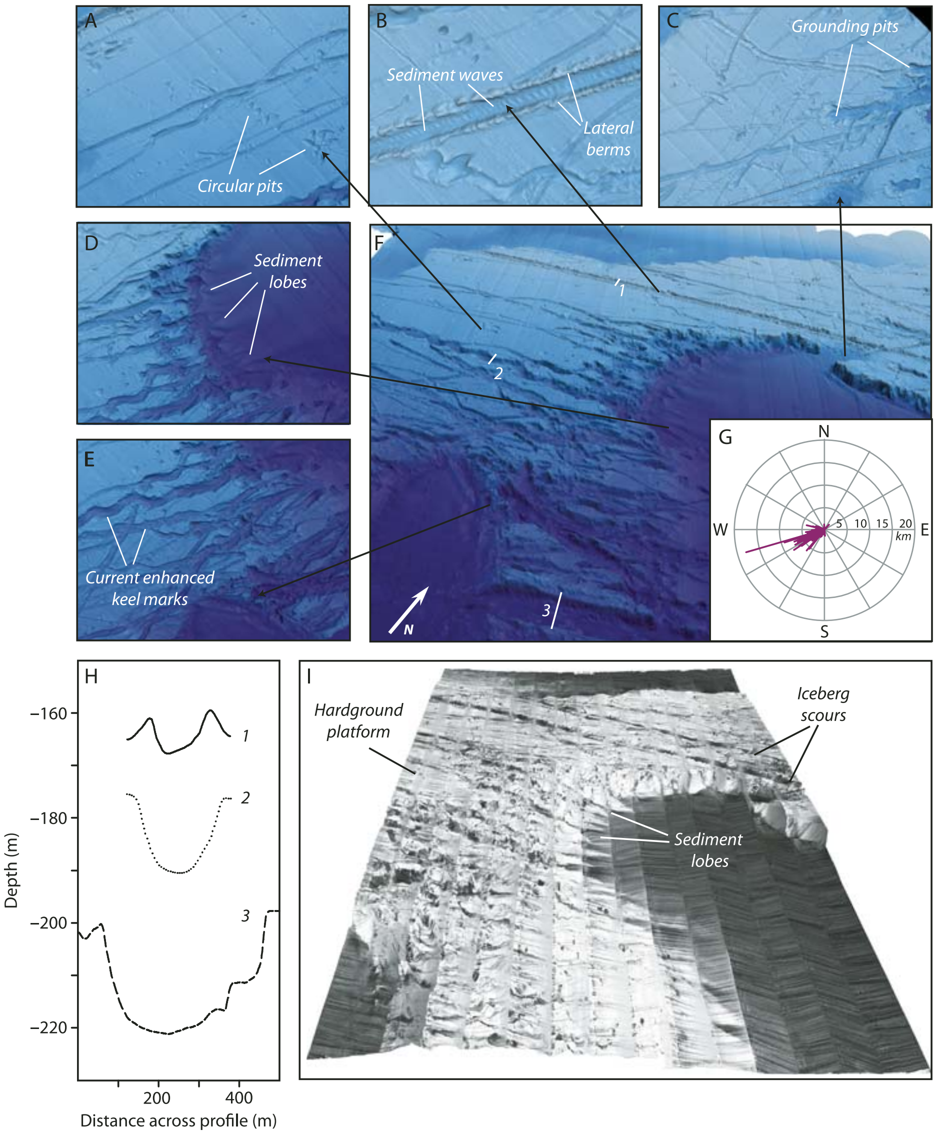

Figure 2. A: Strings and clusters of circular pits suggest iceberg keels skipping across seafloor. B: Lateral berms, interpreted as iceberg push-up ridges flank edges of scours, and sediment waves are observed in base of some scours. C: Terminal grounding pits flanked by push-up ridges indicate where icebergs have come to rest on seafloor. D: Small sediment lobes are built out off edge of platform. E: Seaward keel marks appear to have been enhanced and overprinted by bottom current erosion subsequent to their formation. F: Perspective view of iceberg scour region. G: Rose diagram showing measured azimuths and lengths of iceberg scours. H: Bathymetric profiles across three large iceberg scours. Scours appear to increase in width and depth farther offshore. I: Perspective view of side-scan sonar data draped over bathymetric data. Platform exhibits high backscatter due to increased roughness, indicative of hardground material; sediment cover appears to be restricted to base of scours and deeper regions off platform, and it exhibits lower backscatter.

erosion subsequent to their formation. The average width and depth of the scour troughs increase seaward (Fig. 2). Volume estimates suggest that the berms along the more landward scours are comparable to the material removed from the scour, whereas farther offshore, the scour troughs are much larger than the berm material would predict. Several of the larger scours also exhibit a tight meandering character indicative of flow through the trough. Bottom currents of 15–20 cm/s observed during the submersible dives in 2002 are consistent with the presence of sand waves in the base of the larger scours (Fig. 2B). The largest bed forms measured from the bathymetric data exhibit a wavelength of ~50 m and an amplitude of ~0.5 m. Smaller current ripples are also observed in the video records. Several small sediment lobes (3–4 m high) are built out in the large depression off the eastern edge of the platform (Fig. 2). The low-backscatter lobes appear to connect with sediment observed in the base of adjacent scours. Bottom currents appear to have eroded and reworked most of the sediment across the scoured platform, transforming the scour troughs into much larger features and redepositing sediment in the large bathymetric depressions adjacent to the platform (Fig. 2).

Circulation across the region is dominated by the western boundary current of the Gulf Stream, which flows northeastward along the Florida-Hatteras slope (100–800 m) before separating from the coast near Cape Hatteras (~36°N) (Bumpus, 1973). The inferred southwestward iceberg transport direction is roughly opposite of the modern bottom current flow of the Gulf Stream. This suggests that there has been a significant deflection of the circulation across the upper slope since the last deglaciation. Offshore of Cape Hatteras, there is a convergence point between the Gulf Stream and Mid-Atlantic Bight (MAB) shelf water, a buoyancy-driven coastal current that flows southwestward along the shelf and upper slope (Bumpus, 1973; Churchill and Berger, 1998). MAB shelf water is believed to be a downstream continuation of flow that originates along the southern coast of Greenland and feeds the Scotian Shelf Mean Flow (Chapman and Beardsley, 1989). The current is driven by freshwater inputs from Greenland glacial melt, as well as runoff entering through the Hudson Strait and along the Labrador coast (Chapman and Beardsley, 1989). During deglaciation, regional meltwater inputs would have been greatly increased, perhaps strengthening and invigorating the coastal flow. The observed scour orientation on the upper slope suggests that the icebergs were entrained in cold, southwestward-flowing current shoreward of the Gulf Stream system. Although the latitude of separation for the Gulf Stream appears to have remained relatively constant since the Last Glacial Maximum (LGM) (Matsumoto and Lynch-Stieglitz, 2003), well-documented shifts in the flow axis have occurred throughout the Cenozoic in response to sea-level fluctuations (Pinet et al., 1981; Pinet and Popenoe, 1982). The Gulf Stream has been repeatedly deflected offshore during sea-level lowstands by the Charleston Bump (~31.5°N), a prominent bathymetric high along the slope (Pinet et al., 1981; Pinet and Popenoe, 1982). With the Gulf Stream shifted seaward, MAB shelf water may have penetrated farther south, transporting icebergs from northern ice sheets to this portion of the margin. The warm waters of the Gulf Stream would provide an effective barrier to further iceberg transport such that the southern limit of iceberg transport was most likely north of the Charleston Bump.

In the absence of sediment samples or subbottom data, it is difficult to constrain the age of the iceberg discharge. The morphology of the scours is well preserved in the hardground material. These may be relatively recent features, perhaps derived from iceberg discharge from the Laurentide ice sheet during the LGM. Iceberg scours with similar size and orientation have been observed on Stellwagen Bank, offshore of eastern Massachusetts (Butman et al., 2004), and on the outer New Jersey margin (Duncan and Goff, 2001). Both of these scour fields are interpreted to record discharge and entrainment of icebergs in a southwestward-flowing coastal current following the LGM (Butman et al., 2004; Duncan and Goff, 2001). This iceberg trajectory is consistent with the scour orientation observed along the upper slope off the southeastern United States. This suggests that the southern scour field may represent a downstream continuation of the iceberg scouring recorded on the New Jersey margin, which has been tentatively correlated with pulses of Pleistocene iceberg discharge in the North Atlantic, specifically Heinrich events H2 (25.2 ka) and H1 (17.5 ka) (Duncan and Goff, 2001). Additional iceberg scour fields likely exist at similar water depths along the upper slope of the Mid-Atlantic Bight in between the New Jersey and South Carolina margins. While the ice-rafted debris deposits that typically define Heinrich events have been generally restricted to the polar and mid-latitudes of the North Atlantic (Heinrich, 1988; Ruddiman, 1977), the discovery of iceberg keel marks along the U.S. Atlantic margin at lower latitudes appears to be consistent with iceberg melt rates determined by Dowdeswell et al. (1995) and suggests that there may have been an additional southerly component of iceberg transport derived from these large outbursts of iceberg discharge.

CONCLUSIONS

Numerous iceberg scours found along the upper slope offshore of South Carolina have an overall orientation and morphology suggestive of iceberg entrainment in a southwestward-flowing coastal current. The icebergs were most likely derived from the retreating ice margin during the last deglaciation, possibly in concert with the most recent Heinrich iceberg discharge events. Iceberg transport to this low latitude implies that meltwater-driven coastal flows may have reached much farther south in the western North Atlantic than previously recognized. While iceberg scouring at the subtropical latitude of the South Atlantic Bight may represent an anomalous event, this occurrence of meltwater-driven coastal iceberg transport highlights the influence of freshwater input on paleocirculation patterns and places new constraints on deglaciation climate and circulation patterns for the region.

ACKNOWLEDGMENTS

We thank the captain and crew of the National Oceanic and Atmospheric Administration (NOAA) ship *Nancy Foster* and the R/V *Seward Johnson* for help with sonar and submersible surveys. This research was supported by NOAA Ocean Exploration grants NA16RP2697 and NA06OAR4600095 (G.R. Sedberry, Principal Investigator).

REFERENCES CITED

Able, K.W., Grimes, C.B., Cooper, R.A., and Uzmann, J.R., 1982, Burrow construction and behavior of tilefish, *Lopholatilus chamaeleonticeps*, in the Hudson Submarine Canyon: Environmental Biology of Fishes, v. 7, p. 199–205, doi: 10.1007/BF00002496.

Baldwin, W.E., Morton, R.A., Putney, T.R., Katuna, M.P., Harris, M.S., Gayes, P.T., Driscoll, N.W., Denny, J.F., and Schwab, W.C., 2006, Migration of the Pee Dee River system inferred from ancestral paleochannels underlying the South Carolina Grand Strand and Long Bay inner shelf: Geological Society of America Bulletin, v. 118, p. 533–548, doi: 10.1130/B25856.1.

Bass, D.W., and Woodworth-Lynas, C., 1988, Iceberg crater marks on the sea floor, Labrador shelf: Marine Geology, v. 79, p. 243–260, doi: 10.1016/0025–3227(88)90041–2.

Bond, G., Heinrich, H., Broeker, W., Labeyrie, L., McManus, J., Andrews, J., Huon, S., Jantschik, R., Clasen, S., Simet, C., Tedesco, K., Klas, M., Bonani, G., and Ivy, S., 1992, Evidence for massive discharges of icebergs into the North Atlantic ocean during the last glacial period: Nature, v. 360, p. 245–249, doi: 10.1038/360245a0.

Bumpus, D.F., 1973, A description of the circulation of the continental shelf of the east coast of the United States: Progress in Oceanography, v. 6, p. 111–157.

Butman, B., Valentine, P.C., Danforth, W.W., Hayes, L., Serrett, L.A., and Middleton, T.J., 2004, Shaded Relief, Sea Floor Topography, and Backscatter Intensity of Massachusetts Bay and the Stellwagen Bank Region Offshore of Boston, Massachusetts: U.S. Geological Survey Geologic Investigation Map I-2734, Scale 1:125,000.

Chapman, D.C., and Beardsley, R.C., 1989, On the origin of shelf water in the Middle Atlantic Bight: Journal of Physical Oceanography, v. 19, p. 384–391, doi: 10.1175/1520–0485(1989)019<0384:OTOOSW>2.0.CO;2.

Churchill, J.H., and Berger, T.J., 1998, Transport of Middle Atlantic Bight shelf water to the Gulf Stream near Cape Hatteras: Journal of Geophysical Research, v. 103, C13, p. 30,605–30,621.

Davies, T.A., Bell, T., Cooper, A.K., Josenhans, H., Polyak, L., Solheim, A., Stoker, M.S., and Stravers, J.A., eds., 1997, Glaciated Continental Margins: An Atlas of Acoustic Images: London, Chapman and Hall, 314 p.

Dowdeswell, J.A., Villinger, H., Whittington, R.J., and Marienfeld, P., 1993, Iceberg scouring in Scoresby Sund and on the East Greenland continental shelf: Marine Geology, v. 111, p. 37–53, doi: 10.1016/0025–3227(93)90187-Z.

Dowdeswell, J.A., Maslin, M.A., Andrews, J.T., and McCave, I.N., 1995, Iceberg production, debris rafting, and the extent and thickness of Heinrich layers (H-1, H-2) in North Atlantic sediments: Geology, v. 23, p. 301–304.

Duncan, C.S., and Goff, J.A., 2001, Relict iceberg keel marks on the New Jersey outer shelf, southern Hudson apron: Geology, v. 29, p. 411–414, doi: 10.1130/0091–7613(2001)029<0411:RIKMOT>2.0.CO;2.

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, doi: 10.1038/342637a0.

Heinrich, H., 1988, Origin and consequences of cyclic ice rafting in the northeast Atlantic Ocean during the past 130,000 years: Quaternary Research, v. 29, p. 142–152, doi: 10.1016/0033–5894(88)90057–9.

Matsumoto, K., and Lynch-Stieglitz, J., 2003, Persistence of Gulf Stream separation during the last glacial period: Implications for current separation theories: Journal of Geophysical Research, v. 108, doi: 10.1029/2001JC000861.

National Research Council, 2002, Effects of Trawling and Dredging on Seafloor Habitats: Washington, D.C., National Academy Press, 126 p.

Pinet, P.R., and Popenoe, P., 1982, Blake Plateau: Control of Miocene sedimentation patterns by large-scale shifts of the Gulf Stream axis: Geology, v. 10, p. 257–259, doi: 10.1130/0091–7613(1982)10<257:BPCOMS>2.0.CO;2.

Pinet, P.R., Popenoe, P., and Neligan, D.F., 1981, Gulf Stream: Reconstruction of Cenozoic flow patterns over the Blake Plateau: Geology, v. 9, p. 266–270, doi: 10.1130/0091–7613(1981)9<266:GSROCF>2.0.CO;2.

Riggs, S.R., and Belknap, D.F., 1988, Upper Cenozoic processes and environments of continental margin sedimentation: Eastern United States, *in* Sheridan, R.E., and Grow, J.A., eds., The Atlantic Continental Margin: U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. I-2, p. 131–176.

Robinson, S.G., Maslin, M.A., and McCave, I.N., 1995, Magnetic susceptibility variations in upper Pleistocene deep-sea sediments of the NE Atlantic: Implications for ice rafting and paleocirculation at the Last Glacial Maximum: Paleoceanography, v. 10, p. 221–250, doi: 10.1029/94PA02683.

Ruddiman, W.F., 1977, Late Quaternary deposition of ice-rafted sand in the subpolar North Atlantic (lat 40° to 65°N): Geological Society of America Bulletin, v. 88, p. 1813–1827, doi: 10.1130/0016–7606(1977)88<1813:LQDOIS>2.0.CO;2.

Syvitski, J.P.M., Stein, A.B., Andrews, J.T., and Milliman, J.D., 2001, Icebergs and the sea floor of the East Greenland (Kangerlussuaq) continental margin: Arctic, Antarctic, and Alpine Research, v. 33, p. 52–61, doi: 10.2307/1552277.

Tucholke, B.E., 1979, Furrows and focused echoes on the Blake Outer Ridge: Marine Geology, v. 31, p. M13–M20, doi: 10.1016/0025–3227(79)90048–3.

Watkins, S.J., Maher, B.A., and Bigg, G.R., 2007, Ocean circulation at the Last Glacial Maximum: A combined modeling and magnetic proxy-based study: Paleoceanography, v. 22, doi: 10.1029/2006PA001281.

Woodworth-Lynas, C.M.T., Josenhans, H.W., Barrie, J.V., Lewis, C.F.M., and Parrott, D.R., 1991, The physical processes of seabed disturbance during iceberg grounding and scouring: Continental Shelf Research, v. 11, p. 939–961, doi: 10.1016/0278–4343(91)90086-L.

Manuscript received 27 November 2007
Revised manuscript received 12 February 2008
Manuscript accepted 19 February 2008

Printed in USA