Early Holocene retreat of the George VI Ice Shelf, Antarctic Peninsula

M.J. Bentley* Department of Geography, University of Durham, South Road, Durham DH1 3LE, UK
D.A. Hodgson* British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK
D.E. Sugden Institute of Geography, School of GeoSciences, University of Edinburgh, Drummond Street, Edinburgh EH8 9XP, UK
S.J. Roberts British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK
J.A. Smith Department of Geography, University of Durham, South Road, Durham DH1 3LE, UK, and British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK
M.J. Leng Natural Environment Research Council Isotope Geosciences Laboratory, British Geological Survey, Keyworth, Nottingham NG12 5GG, UK, and School of Geography, University of Nottingham, Nottingham NG7 2RD, UK
C. Bryant Natural Environment Research Council Radiocarbon Laboratory, Scottish Enterprise Technology Park, East Kilbride, Glasgow G75 OQF, UK

ABSTRACT

The recent collapse of several Antarctic Peninsula ice shelves has been linked to rapid regional atmospheric warming during the twentieth century. New high-resolution lake sediment records of Holocene ice-shelf behavior show that the George VI Ice Shelf was absent beginning ca. 9595 calibrated (cal.) yr B.P., but reformed by ca. 7945 cal. yr B.P. This retreat immediately followed a period of maximum Holocene warmth that is recorded in some ice cores and occurred at the same time as an influx of warmer ocean water onto the Antarctic Peninsula shelf. The absence of the ice shelf suggests that early Holocene ocean-atmosphere variability in the Antarctic Peninsula was greater than that measured in recent decades.

Keywords: ice shelves, Antarctic Peninsula, Holocene, paleoclimate, Circumpolar Deep Water.

INTRODUCTION

Recent decades have witnessed a retreat and collapse of some Antarctic Peninsula ice shelves (Fig. 1) that have been linked to rapid regional atmospheric warming (Vaughan and Doake, 1996). It has been suggested (Scambos et al., 2000) that the warming has led to ice-shelf collapse by the destabilizing effects of summer meltwater ponding on the ice-shelf surface, enhancing crevasse fracture. Collapse of individual ice shelves has been rapid, sometimes occurring in just a few weeks, due to a critical loss of structural stability (Doake et al., 1998). However, at least one part of the former Larsen Ice Shelf thinned progressively for ~9 yr prior to collapse, thought to be a result of sub–ice-shelf melting by warm ocean currents (Shepherd, 2003). Ice-shelf collapse is an important indicator of climatic warming and has potential impacts on the discharge of inland grounded ice and thus on global sea level (de Angelis and Skvarca, 2003).

It is not yet clear whether such ice-shelf collapses are unusual in the present interglacial or whether advance and retreat of ice shelves have occurred repeatedly in response to natural Holocene climate change. Some studies in the northern Antarctic Peninsula suggest ice-shelf collapse in the mid-Holocene (Pudsey and Evans, 2001). To date, ice shelves farther south (south of 70°S) have shown no catastrophic breakup, although some ice-shelf fronts are in retreat. This paper presents the first evidence of an early Holocene collapse of one of these more southern ice shelves.

*These authors contributed equally to this work.

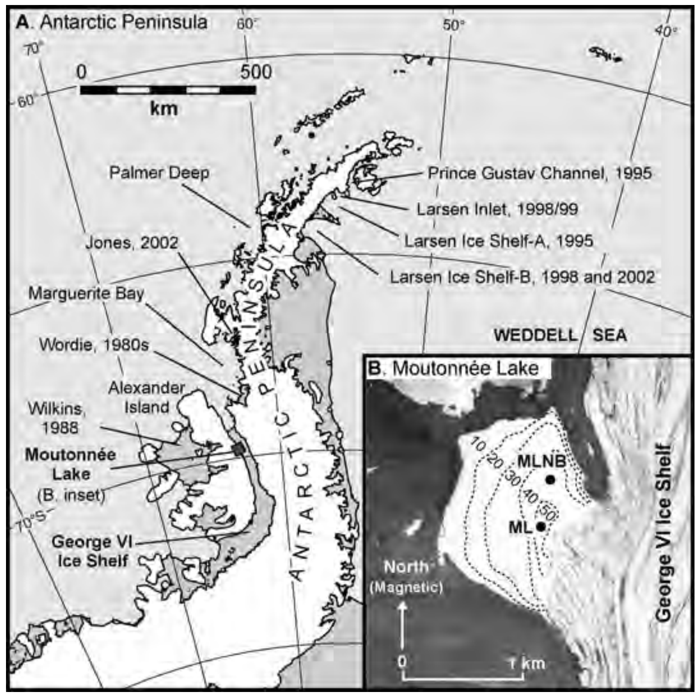

Figure 1. Location of field site. A: Map of Antarctic Peninsula. Ice shelves that have collapsed or retreated in late twentieth century are labeled with their dates of collapse. B: Vertical aerial photograph of Moutonnée Lake and western margin of George VI Ice Shelf (darker stripes are melt pools) where it abuts Alexander Island (source: British Antarctic Survey). Bathymetry of Moutonnée Lake superimposed (contours in meters) from Heywood (1977) with additional data. ML—Moutonnée Lake core site; MLNB—Moutonne´e Lake north basin core site.

The ~100–500-m-thick George VI Ice Shelf is situated between the Antarctic Peninsula and Alexander Island (Fig. 1). Most ice flows from the Antarctic Peninsula and across George VI Sound to where it abuts Alexander Island or eventually reaches one of its two calving fronts. The ice shelf has, so far, survived the regional warming, although it is predicted to be close to the limit of stability. Meltwater pools have appeared on the surface of the ice shelf each summer since at least the 1940s, accompanied by a slow retreat of the northern calving front (Vaughan and Doake, 1996) and some of the highest measured basal melt rates in Antarctica, linked to the intrusion of relatively

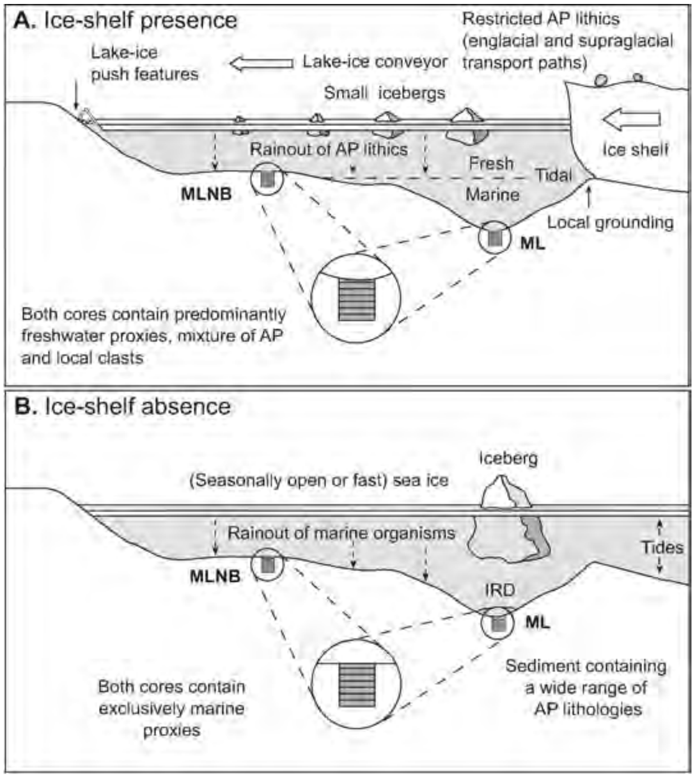

Figure 2. Conceptual model of how epishelf lake sediments can record ice-shelf presence and absence. A: Ice-shelf presence. Stratified water column produces freshwater and marine ecological signature, freshwater-derived isotopes from surface productivity, and restricted range of clasts from Antarctic Peninsula (AP). B: Ice-shelf absence. Lake is marine embayment with corresponding ecological and isotopic changes. Icebergs are free to deposit diverse range of clasts in basin. ML—Moutonne´e Lake core site; MLNB—Moutonnée Lake north basin core site; IRD—ice-rafted debris.

warm Circumpolar Deep Water onto the continental shelf (Potter and Paren, 1985).

On the east coast of Alexander Island, the ice shelf impounds two epishelf lakes: Moutonnée Lake (Fig. 1) and Ablation Lake. These are tidal, stratified water bodies, with a lower marine layer linked under the ice shelf to the ocean and an upper freshwater layer with a maximum thickness determined by the draught of the ice shelf (Heywood, 1977). A lake-ice conveyor (Hendy et al., 2000) has been observed at Moutonnée Lake, whereby lake ice transports clasts onshore toward a marginal moat. Measurements show that the lake ice moved 3.85 m WNW in 1 yr and several erratic (granitic) boulders lie along and above the present lake shoreline (Clapperton and Sugden, 1982), consistent with a lake-ice conveyor.

The lakes depend on the presence of the ice shelf: if the ice shelf disappears, they become marine embayments with changes in their ecology (Fig. 2) and changes in the composition of clasts reaching the sediments. The Antarctic Peninsula is composed primarily of plutonic and volcanic rocks, whereas Alexander Island is composed of sedimentary rocks (Crabtree et al., 1985). When the ice shelf is present, a restricted range of plutonic and volcanic clasts is transported along flow lines from the peninsula and deposited in the lake. With ice-shelf absence, a more diverse assemblage of clast lithologies would be deposited by debris-bearing icebergs derived from a wider area.

Our hypothesis is that lake sediment cores will record periods of ice-shelf presence (restricted range of clast lithologies, freshwater and marine ecology, and a carbon isotope signature of freshwater, or mixed, productivity) and ice-shelf absence (exclusively marine ecology, a wide range of clast lithologies, and a carbon isotope signature of marine productivity) (Fig. 2). We cored two sites in Moutonnée Lake with a cable-operated piston corer: the deepest point of the lake (ML) and a shallower northern basin (MLNB) (Fig. 1).

RESULTS

Multiproxy biological and lithologic analyses of the ML core reveal five stratigraphic zones (Fig. 3). Zone 1 (537–522 cm) sediments are similar to those deposited under epishelf lake conditions today. Zone 2 (522–490 cm) contains marine diatoms and foraminifera and diverse lithologies. Zone 3 (490–302 cm) is a zone of clast-rich unsorted ice-rafted debris (IRD). Zone 4 (302–236 cm) contains marine diatoms and foraminifera (similar to zone 2). Zone 5 (236–0 cm) reverts to sediments characteristic of epishelf lake conditions and persists to the present. The shallower water MLNB core replicates zones 4 (at 172–128 cm) and 5 (at 127–0 cm).

Several proxy records show near-simultaneous changes in the cores. The ML core has two marine zones (zones 2 and 4) with an assemblage of exclusively marine diatoms including benthic (*Cocconeis fasciolata*) and planktonic or sea-ice species (*Eucampia antarctica*, *Thalassiosira antarctica*) indicating (seasonally) open-marine conditions (Cremer et al., 2003). Planktonic diatoms and sea-ice diatoms (especially *Fragilariopsis curta*) dominate the lower part of zone 4. At ~272 cm (in ML) and ~152 cm (in MLNB), a marked decline in total diatom valves, a decrease in the planktonic diatom species and *Chaetoceros* spores, and an increase in benthic species imply decreased productivity presumably from increased perennial sea ice. The marine zones (2 and 4) also contain abundant foraminifera dominated (>99%) by benthic species such as *Globocassidulina* sp. and *Cibicides* sp. Above 268 cm, foraminifera concentrations decline, but three new species appear as minor components, including *Angulogerina earlandi* and *Stanforthia davisi*. The dominant species in the marine zones in both cores are epifaunal and typical of high-productivity, upwelling, continental shelf or slope environments (Murray, 1991). Carbon isotope measurements (Fig. 3) of bulk sediment in the marine zones (2 and 4) have high $\delta^{13}C_{organic}$ values, typical of organic sediment derived primarily from marine plants. Above and below the marine zones, the $\delta^{13}C_{organic}$ values are lower (characteristic of freshwater plants; Meyers, 1997) and similar to present isotope values. The shift from marine back to freshwater or mixed $\delta^{13}C_{organic}$ values occurs at ~260 cm depth (zone 4), similar to the decline in total foraminiferal abundance.

Detailed clast lithologic analysis throughout the ML core shows that the marine zones and the intervening IRD-rich zone (zone 3) contain a greater diversity of clast types than zones 5 and 1, which are characterized by a more restricted range of igneous clasts.

To date the marine zones, we obtained 10 radiocarbon dates on monospecific foraminifera (Fig. 3; also see Table DR1[1]). These macrofossils are not affected by reworking of old carbon, a common problem with bulk marine sediment dating in Antarctica. For calibration to calendar time scale we applied a commonly accepted Antarctic marine reservoir correction for marine carbonate (1300 yr, Berkman and Forman, 1996). Our cores provide the first well-dated paleoenvironmental record for the southern Antarctic Peninsula and the dates show four key features: (1) The dates are in stratigraphic sequence, within error. (2) The marine zones (2 and 4) date to the early Holocene (8170 ± 104 to 7300 ± 106 ^{14}C yr B.P.) (9595–7945 calibrated [cal.] yr B.P.). (3) The upper dates for zone 2 (7960 ± 149 and 8100 ± 108 ^{14}C yr B.P.) and the lower dates for zone 4 (8100 ± 105 ^{14}C yr B.P.) are statistically indistinguishable. (4) The dates for the top of zone 2 (7330 ± 104 ^{14}C yr B.P.) in the ML core and the top of zone 4 (7420 ± 105

[1]GSA Data Repository item 2005032, Table DR1, radiocarbon dates from the ML and MLNB cores, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

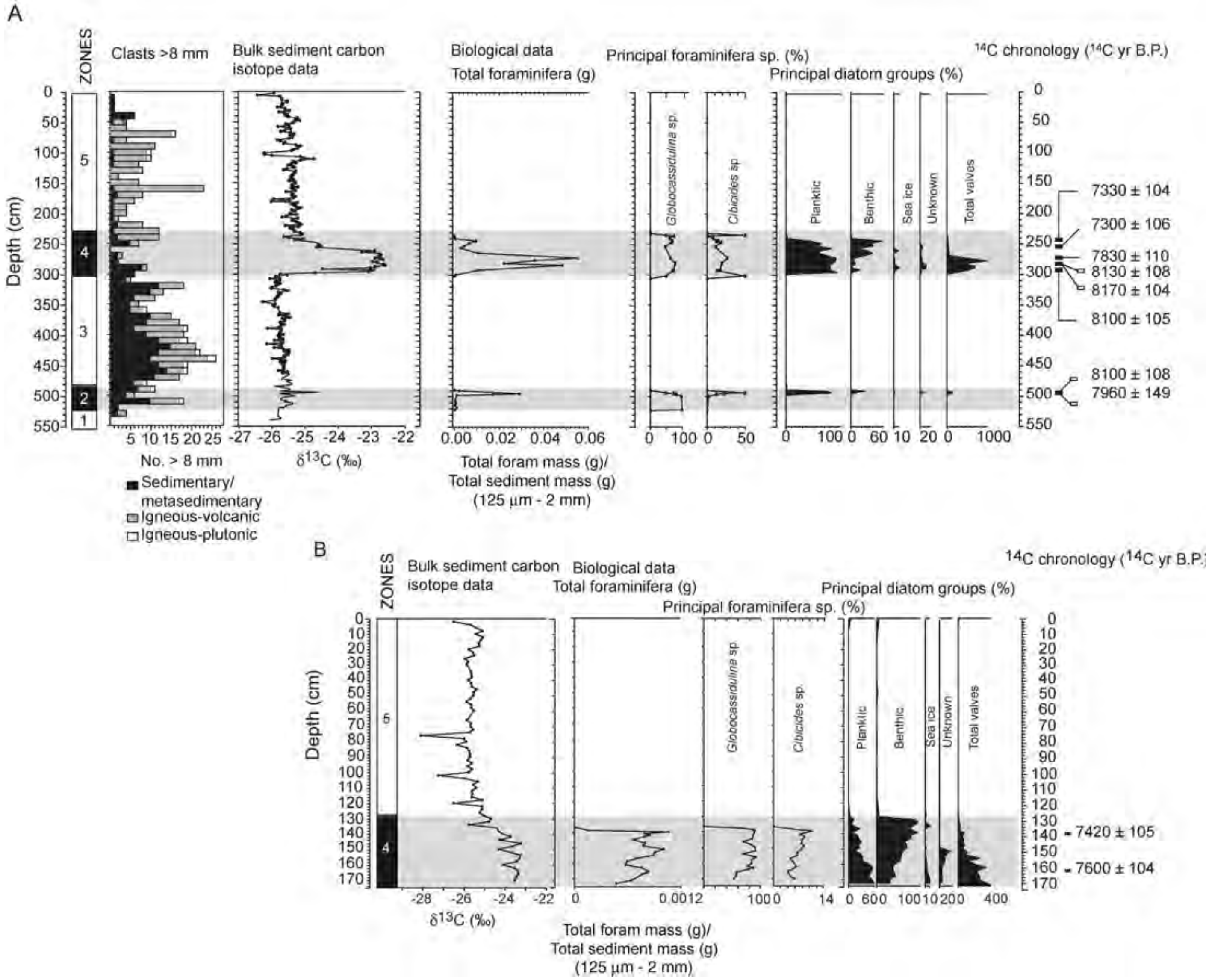

Figure 3. Multiproxy analysis of sediment cores (A) Moutonnée Lake core (ML) and (B) Moutonnée Lake north basin (MLNB). Proxies include $\delta^{13}C$ of organic matter in bulk sediment ($\delta^{13}C_{organic}$), diatom assemblages, foraminiferal assemblages, and clast lithologic analysis. Clasts were classified into 1 of 26 lithologic groups. $\delta^{13}C_{organic}$ values were calculated to Vienna Peedee belemnite scale by using within-run laboratory standard calibrated against NBS-19 and NBS-22. Diatom counts of total valves on each slide were made every 2 cm. Foraminiferal counts were made on 125 μm to 2 mm fraction every 4 cm (ML) or 2 cm (MLNB). Zones 1, 3, and 5 (ML) and zone 5 (MLNB) were devoid of both diatoms and foraminifera.

^{14}C yr B.P.) in the MLNB core are statistically indistinguishable, showing chronological consistency between the two cores.

DISCUSSION

The marine zones and the IRD zone in the two cores represent a period of past ice-shelf absence. Sediments deposited during this period carry a clear marine signature in the carbon isotopes, foraminifera, and diatoms of marine waters dominating the site with both sea-ice and open-water conditions. Moreover, a pronounced increase in lithologic diversity of clasts and clast abundance suggests that icebergs floated freely into the embayment.

The statistically indistinguishable dates for zones 2 and 4 imply that the intervening IRD was deposited rapidly. We think that the marine zones represent a single period of ice-shelf absence but that, soon after the ice shelf disappeared, icebergs rapidly dumped IRD into the lake. The main breakup of the George VI Ice Shelf would have been rapid and accompanied by widespread iceberg formation (Gilbert and Domack, 2003), consistent with other observations of Antarctic and Arctic ice-shelf breakup. Melting of these icebergs within the basin would account for the rapid deposition of IRD (zone 3) and the low relative abundance of marine and sea-ice indicator diatoms. We emphasize that, given the statistically indistinguishable ^{14}C dates immediately above and below this debris zone, the melt out and dumping of IRD during this period was rapid and short-lived.

Our core chronology shows that the George VI Ice Shelf disappeared in the early Holocene, with the onset of collapse by 8170 ^{14}C yr B.P. (9595 cal. yr B.P.) and complete reformation by 7300 ^{14}C yr B.P. (7945 cal. yr B.P.). This coincides with deglaciation in many Antarctic coastal areas (Ingólfsson et al., 1998), and follows deglaciation of the western Antarctic Peninsula shelf (Anderson, 1999). The record of the George VI Ice Shelf collapse immediately postdates ice-core evidence of a widespread, sustained early Holocene climatic optimum (Masson et al., 2000; Masson-Delmotte et al., 2004) ca. 11–9.5 ka (Fig. 4). The collapse is also coincident with the influx of Circumpolar Deep Water onto the Antarctic Peninsula continental shelf, as demonstrated in the Palmer Deep marine record (Domack et al., 2001; Fig. 4). Cir-

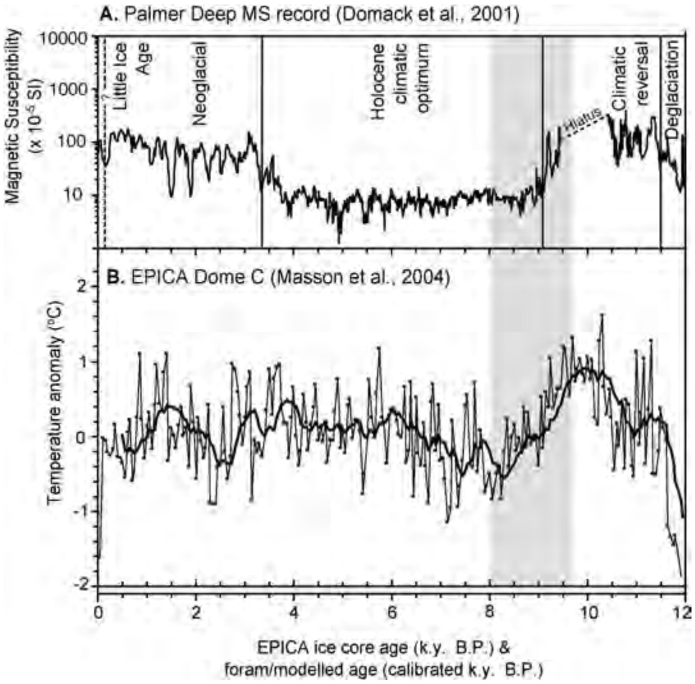

Figure 4. Ice-core and marine core records of Antarctic environmental change for past 12 k.y. Dome C ice-core record shows a ca. 11–9.5 ka climate optimum that is also seen in composite of Antarctic ice cores (Masson et al., 2000). Palmer Deep marine record shows abrupt warming in early Holocene. Timing of George VI Ice Shelf collapse is shown by vertical shaded bar.

cumpolar Deep Water is a relatively warm (>1 °C), intermediate-depth water mass that may be implicated in the thinning of other Antarctic ice shelves (Rignot, 2002). In the marine zones of ML and MLNB, the dominant foraminifera species are characteristic of a high-productivity, upwelling water mass and consistent with the suggestion that Circumpolar Deep Water contributed to the ice-shelf collapse. Thus, both atmospheric and oceanographic warming occurred immediately prior to, and coincident with, ice-shelf collapse. Finally, the timing of the ice-shelf collapse predates collapse at more northern Antarctic Peninsula sites (Pudsey and Evans, 2001), that has been linked to a mid-Holocene warm period (Jones et al., 2000; Hodgson et al., 2004).

We have three main conclusions: (1) High-resolution multiproxy sediment records show that the George VI Ice Shelf collapsed in the early Holocene. (2) The timing of collapse is consistent with both ice- and marine sediment–core evidence of early Holocene warmth. (3) The collapse of a currently extant ice shelf shows that early Holocene natural ocean-atmosphere variability in the Antarctic Peninsula was greater than the recent, potentially anthropogenically influenced changes.

ACKNOWLEDGMENTS

This work was jointly funded by the Natural Environment Research Council (NERC) Antarctic Funding Initiative (AFI2/69 and CGS00/06), and the NERC British Antarctic Survey (BAS) SAGES science program. We thank BAS field operations staff for excellent support in the field.

REFERENCES CITED

Anderson, J.B., 1999, Antarctic marine geology: Cambridge, Cambridge University Press, 297 p.

Berkman, P.A., and Forman, S.L., 1996, Pre-bomb radiocarbon and reservoir correction for calcareous marine species in the southern ocean: Geophysical Research Letters, v. 23, p. 363–366.

Clapperton, C.M., and Sugden, D.E., 1982, Late Quaternary glacial history of George VI Sound area, West Antarctica: Quaternary Research, v. 18, p. 243–267.

Crabtree, R.D., Storey, B.C., and Doake, C.S.M., 1985, The structural evolution of George VI Sound, Antarctic Peninsula: Tectonophysics, v. 114, p. 431–442.

Cremer, H., Roberts, D., McMinn, A., Gore, D., and Melles, M., 2003, The Holocene diatom flora of marine bays in the Windmill Islands, East Antarctica: Botanica Marina, v. 46, p. 82–106.

de Angelis, H., and Skvarca, P., 2003, Glacier surge after ice shelf collapse: Science, v. 299, p. 1560–1562.

Doake, C.S.M., Corr, H.F.J., Rott, H., Skvarca, P., and Young, N., 1998, Breakup and conditions for stability of the northern Larsen Ice Shelf, Antarctica: Nature, v. 391, p. 778–780.

Domack, E., Leventer, A., Dunbar, R., Taylor, F., Brachfeld, S., and Sjunneskog, C., 2001, Chronology of the Palmer Deep site, Antarctic Peninsula: A Holocene palaeoenvironmental reference for the circum-Antarctic: Holocene, v. 11, p. 1–9.

Gilbert, R., and Domack, E.W., 2003, Sedimentary record of disintegrating ice shelves in a warming climate, Antarctic Peninsula: Geochemistry, Geophysics, Geosystems, doi: 10.1029/2002GC000441.

Hendy, C.H., Sadler, A.J., Denton, G.H., and Hall, B.L., 2000, Proglacial lake-ice conveyors: A new mechanism for deposition of drift in polar environments: Geografiska Annaler, ser. A, v. 82, p. 249–270.

Heywood, R.B., 1977, A limnological survey of the Ablation Point area, Alexander Island, Antarctica: Royal Society of London Philosophical Transactions, ser. B, v. 279, p. 39–54.

Hodgson, D.A., Doran, P.T., Roberts, D., and McMinn, A., 2004, Palaeolimnological studies from the Antarctic and subantarctic islands, *in* Pienitz, R., et al., eds., Long-term environmental change in Arctic and Antarctic Lakes: Dordrecht, Netherlands, Kluwer, 500 p.

Ingólfsson, O., Hjort, C., Berkman, P.A., Björck, S., Colhoun, E., Goodwin, I.D., Hall, B., Hirakawa, K., Melles, M., Möller, P., and Prentice, M.L., 1998, Antarctic glacial history since the Last Glacial Maximum: An overview of the record on land: Antarctic Science, v. 10, p. 326–344.

Jones, V.J., Hodgson, D.A., and Chepstow-Lusty, A., 2000, Palaeolimnological evidence for marked Holocene environmental changes on Signy Island, Antarctica: Holocene, v. 10, p. 43–60.

Masson, V., Vimeux, F., Jouzel, J., Morgan, V., Delmotte, M., Ciais, P., Hammer, C., Johnsen, S., Lipenkov, V.Y., Mosley-Thompson, E., Petit, J.R., Steig, E.J., Stievenard, M., and Vaikmae, R., 2000, Holocene climate variability in Antarctica based on 11 ice-core isotopic records: Quaternary Research, v. 54, p. 348–358.

Masson-Delmotte, V., Stenni, B., and Jouzel, J., 2004, Common millennial-scale variability of Antarctic and Southern Ocean temperatures during the past 5000 years reconstructed from the EPICA Dome C ice core: The Holocene, v. 14, p. 145–151.

Meyers, P.A., 1997, Organic geochemical proxies of palaeoceanographic, palaeolimnologic, and palaeoclimate processes: Organic Geochemistry, v. 27, p. 213–250.

Murray, J.W., 1991, Ecology and distribution of benthic foraminifera, *in* Lee, J.J., and Anderson, O.R., eds., Biology of Foraminifera: London, Academic Press, p. 221–255.

Potter, J.R., and Paren, J.G., 1985, Interaction between ice shelf and ocean in George VI Sound, Antarctica, *in* Jacobs, S., ed., Oceanology of the Antarctic continental shelves: American Geophysical Union Antarctic Research Series, v. 43, p. 35–58.

Pudsey, C.J., and Evans, J., 2001, First survey of Antarctic sub–ice shelf sediments reveals mid-Holocene ice shelf retreat: Geology, v. 29, p. 787–790.

Rignot, E., 2002, Ice-shelf changes in Pine Island Bay, Antarctica, 1947–2000: Journal of Glaciology, v. 48, p. 247–256.

Scambos, T.A., Hulbe, C., Fahnestock, M., and Bohlander, J., 2000, The link between climate warming and break-up of ice shelves in the Antarctic Peninsula: Journal of Glaciology, v. 46, p. 516–530.

Shepherd, A., 2003, Larsen Ice Shelf has progressively thinned: Science, v. 302, p. 856–859.

Vaughan, D.G., and Doake, C.S.M., 1996, Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula: Nature, v. 379, p. 328–331.

Manuscript received 22 September 2004
Revised manuscript received 9 November 2004
Manuscript accepted 11 November 2004

Printed in USA