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Assessing Antarctic Ice Sheet-Sea Level Dynamics during the Holocene: The 'Meltwater Test'

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Volume changes in the Antarctic ice sheets and their impacts on sea-level rise during the last 10,000 years are poorly constrained. During periods of ice-sheet retreat, it is hypothesized that meltwater would have been introduced directly into the coastal zone around the continent (The 'Meltwater Test'). As an analog for interpreting the ecological signatures of these Holocene meltwater pulses, live Antarctic scallops (*Adamussium colbecki*) were collected adjacent to glacial streams which flow into West McMurdo Sound. Above 10 m depth, *Adamussium* smaller than 35 mm were absent as were other epizoic species on the larger adult scallops. Summer mark-and-recapture experiments also indicated that the growth rates of the adult scallops were significantly lower above 10 m depth. This depth variation in the *Adamussium* assemblage was paralleled by the trace element geochemistry of their calcitic shells. Holocene fossils of these scallops, which are well-preserved and abundant in emerged beaches adjacent to extant populations around the continent, provide a framework for extending these ecological interpretations over geological time scales.

Key words: benthic, ecology, meltwater, shell, geochemistry

INTRODUCTION

With ninety percent of the ice on the Earth, the Antarctic ice sheets have a dynamic connection with global sea level. However, during the last 10,000 years ("Holocene") the relationship between sea level and the Antarctic ice sheets is poorly constrained (Fairbanks, 1989). The purpose of this paper is to consider the development of a circumpolar dataset that could be used for empirically testing and resolving the role of the Antarctic ice sheets in Holocene sea-level rise.

Ice core records indicate that there was a "climatic optimum" in Antarctica between 10,000 and 6,000 years ago (Cias *et al.*, 1992) that may have influenced ice sheet melting. Isostatic models indeed suggest that the Antarctic ice sheets influenced an eustatic sea level rise up to 25 meters during the middle Holocene (Nakada and Lambeck, 1988; Tushingham and Peltier, 1991). Early-middle Holocene deglaciation also is suggested by sedimentary, glaciological and emerged species' records along the coasts of East Antarctica (Domack *et al.*, 1991a; Adamson and Colhoun, 1992; Goodwin, 1993) and West Antarctica (Clapperton and Sugden, 1983; Denton *et al.*, 1989).

In contrast to the suggestions of significant Antarctic glacial retreat, recent coastal geomorphology studies suggest that the Antarctic ice sheets influenced less than a 2.5 m sea level rise and remained virtually unchanged since the early Holocene (Colhoun *et al.*, 1992). Middle Holocene marine sedimentation in East Antarctica (Domack *et al.*, 1991b) and glacial stratigraphy in West Antarctica (Ingolfsson *et al.*, 1992) also appear to have been influenced by ice sheet advances, as has been suggested for warmer climates (Jacobs, 1992).

Contemporaneous raised beaches around the continent contain nearshore marine species which can be used for interpreting changes in the adjacent ice-sheet margins during the Holocene (Berkman, 1992). During periods of ice-sheet advance, coastal marine habitats along with any benthic species would be eliminated. During periods of ice-sheet retreat, benthic species in the coastal zone would be directly affected by meltwater runoff and isostatic processes that result in their emergence as fossils above sea level (Berkman *et al.*, 1992). However, if Antarctic fossil emergence during the Holocene was influenced by eustatic sea-level changes which originated elsewhere on the planet, then these fossils would not have been directly exposed to meltwater runoff. The paleoecology of these emerged fossils provides a test for interpreting the contribution of the Antarctic ice sheets to Holocene sea-level rise.

The critical assumption of the 'meltwater test' is that the Antarctic fossils can be used to interpret hydrochemical changes in coastal environments around the continent. Circumpolar species which are exposed to meltwater runoff today and which have analogous fossils in adjacent beaches will be used to assess the validity of this assumption.

MATERIALS AND METHODS

Along the coasts of West Antarctica (Stuiver *et al.*, 1981; Baroni and Orombelli, 1991) and East Antarctica (Pickard, 1985; Yoshida, 1983) there are abundant living populations of the Antarctic scallop, *Adamussium colbecki*, which are adjacent to dense fossil assemblages. In Explorers Cove (77°35′ S, 163°40′ E), which is at the base of the Transantarctic Mountains in the southern Ross Sea, scallop populations have been exposed to summer runoff from glacial meltwater streams since the middle Holocene (Elston and Bressler, 1981). Data from live *Adamussium*, which had been analyzed across a depth gradient in the vicinity of these streams (Berkman, 1990, 1991, 1994; Berkman *et al.*, 1992), will be compiled to assess whether the ecology of the scallops and their shell geochemistry were jointly impacted by the meltwater runoff.

RESULTS AND DISCUSSION

Prior to entering the marine environment at Explorers Cove, glacial meltwater streams from the Commonwealth and Wales Glaciers flow over rocks and sediments in the Lower Taylor Valley (*See* McGinnis, 1981). Afterward, trace elements solubilized by these meltwater streams are introduced into the marine environment in higher concentrations than in seawater (Boswell *et al.*, 1967). Mixing of the meltwater creates a buoyant lens of relatively low salinity water which can be visually distinguished from the underlying denser seawater (Berkman *et al.*, 1991). Given this vertical stratification, it can be predicted that meltwater impacts would be elevated in relatively shallow water.

Based on the observed salinity responses of comparable molluscan species (Carriker, 1951; Kautsky, 1982), low salinity impacts on the *Adamussium* population can be expected to cause higher mortality and slower growth. The absence of live or dead scallops less than 35 mm in shell height (Fig. 1a) indicates that juvenile survival was diminished above 10 m depth. Those scallops larger than 35 mm (Berkman, 1994), which could swim into these shallow water areas, also appear to have been impacted. Based on a mark-and-recapture experiment with similar size scallops at the same densities in the absence of predators (Berkman, 1990), it was observed that adult scallops grew slower above 10 m (Fig. 1b). Moreover, epizoic macrofauna with planktonic larvae that could be affected by low salinities (Long, 1972) were virtually absent above 10 m (Fig. 1c). The consistent ecological transitions above and below 10 meters depth strongly suggest that nearshore marine species at Explorers Cove were environmentally limited.

The carbonate shells of bivalve molluscs are known to reflect the hydrochemical conditions in which they are grown (Rosenberg, 1980). At Explorers Cove, relatively high trace element concentrations in shallow water would be a specific indicator of glacial meltwater input. The fact that iron, manganese, copper, zinc and chromium all had significantly higher concentrations in the shells of the shallowest scallops (Fig. 2) is evidence that this species was impacted by glacial meltwater.

Depth variation in shell geochemistry (Fig. 2) coincided with the observed ecological transitions (Figs 1a-1c) in which the most distinct changes occurred above and below 10 meters. These complementary datasets demonstrate that extant marine species in Antarctic coastal environments respond to glacial meltwater impacts. As analogs, living

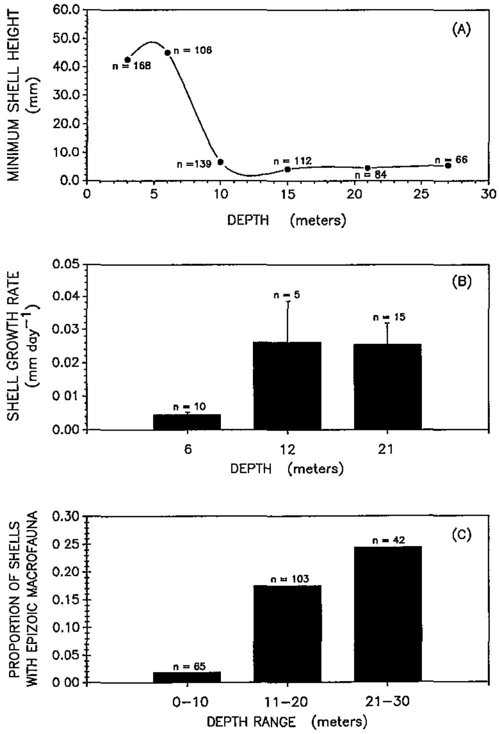

Fig. 1. Ecological variability in the nearshore marine environment at Explorers Cove, Antarctica, during the 1986-87 austral summer. (a) Variation in the minimum shell heights of *Adamussium colbecki* across a depth gradient from 3-27 m. (b) Summer shell growth rates of adult *Adamussium* which were released and recaptured at 6 m, 12 m and 21 m depth. (c) Proportion of *Adamussium* shells with attached epizoic macrofauna from 0-10 m, 11-20 m, and 21-30 m depth. Sample sizes (n) are shown. Based on data from Berkman (1990, 1991, 1994).

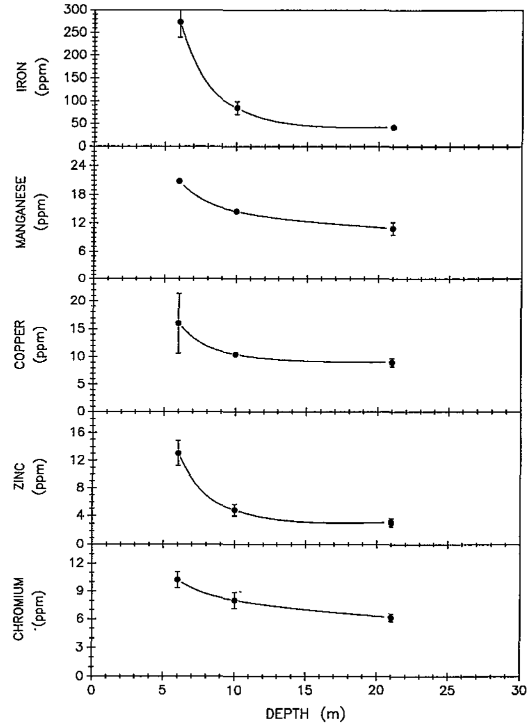

Fig. 2. Trace element variability in the upper valves of *Adamussium colbecki* shells (n = 3 for each depth) which were collected alive at 6 m, 10 m and 21 m depth at Explorers Cove, Antarctica, during the 1986-87 austral summer. Concentration differences were significant ($p < 0.05$) for each of the elements across this nearshore depth gradient. Based on data and statistical analyses from Berkman *et al.* (1992).

and fossil marine species in coastal areas around the continent can be used to interpret the relative magnitudes of meltwater pulses from Antarctica at different times in the Holocene. These data will help constrain the contribution of the Antarctic ice sheets to sea-level rise during the last 10,000 years.

FUTURE RESEARCH

Independent ecological and geochemical datasets indicate that nearshore marine species, such as *Adamussium colbecki*, can be analyzed to assess glacial meltwater impacts in Antarctic coastal areas. Paleoenvironmental interpretations, based on the emerged Holocene fossils around Antarctica (Berkman, 1992), will depend on well chosen geochemical criteria that can be controlled for diagenetic and vital effects (Raup and Stanley, 1971).

Given the importance of understanding Antarctica's role in global change (Weller, 1992), the 'meltwater test' provides a circumpolar research framework for evaluating alternative hypotheses regarding the dynamic relationship between the Antarctic ice sheets and Holocene sea level. Implementing this interdisciplinary research program will require the coordinated effort of scientists from different nations who are working together in coastal areas around the continent.

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REFERENCES

Adamson, D.A. and E.A. Colhoun. 1991. Late Quaternary glaciation and deglaciation of the Bunger Hills, Antarctica. *Antarct. Sci.* **4:** 435-446.

Baroni, C. and G. Orombelli. 1991. Holocene raised beaches at Terra Nova Bay, Victoria Land, Antarctica. *Quatern. Res.* **36:** 157-177.

Berkman, P.A. 1990. The population biology of the Antarctic scallop, *Adamussium colbecki* (Smith, 1902) at New Harbor, Ross Sea. *In*, Kerry, K.R. and G. Hempel (eds.). Antarctic Ecosystems: Ecological Change and Conservation. Springer-Verlag, Heidelberg. pp. 281-288.

Berkman, P.A., T.R. Waller and S.P. Alexander. 1991. Unprotected larval development in the Antarctic scallop, *Adamussium colbecki* (Mollusca: Bivalvia: Pectinidae). *Antarct. Sci.* **3:** 151-157.

Berkman, P.A. 1991. Holocene meltwater variations recorded in Antarctic coastal marine benthic assemblages. *In*, Weller, G., C.L. Wilson and B.A.B. Severin (eds.). Proceedings of the International Conference on the Role of the Polar Regions in Global Change. Univ. Alaska, Fairbanks. pp. 440-449.

Berkman, P.A. 1992. Circumpolar distribution of Holocene marine fossils in Antarctic beaches. *Quatern. Res.* **37:** 256-260.

Berkman, P.A., D.W. Foreman, J.C. Mitchell and R.J. Liptak. 1992. Scallop shell mineralogy and crystalline characteristics: Proxy records for interpreting Antarctic nearshore marine hydrochemical variability. *In*, Elliot, D.H. (ed.). Contributions to Antarctic Research III, Antarctic Research Series, Vol. 57. American Geophysical Union, Washington, D.C. pp. 27-38.

Berkman, P.A. 1994. Epizoic zonation on growing scallop shells in McMurdo Sound, Antarctica. *J. Exp. Mar. Biol. Ecol.* [in press].

Boswell, C.R., R.R. Brooks and T. Wilson. 1967. Some trace elements in lakes of McMurdo oasis, Antarctica. *Geochim. Cosmochim. Acta* **31:** 731-736.

Carriker, M.B. 1951. Ecological observation on the distribution of oyster larvae in New Jersey estuaries. *Ecol. Monogr.* **21:** 19-38.

Cias, P., J.R. Petit, J. Jouzel, C. Lorius, N.I. Barkov, V. Lipenkov and V. Nicolaiev. 1992. Evidence for an early Holocene climatic optimum in the Antarctic deep ice-core record. *Clim. Dynam.* **6:** 169-177.

Clapperton, C.M. and D.E. Sugden. 1982. Late Quaternary glacial history of George VI Sound area, West Antarctica. *Quatern. Res.* **18:** 243-267.

Colhoun, E.A., M.C.G. Mabin, D.A. Adamson and R.M. Kirk. 1992. Antarctic ice volume and contribution to sea-level fall at 20,000 yr BP from raised beaches. *Nature* **358:** 316-319.

Denton, G.H., J.G. Bockheim, S.C. Wilson and M. Stuiver. 1989. Late Wisconsin and Early Holocene glacial history, inner Ross Embayment, Antarctica. *Quatern. Res.* **31:** 151-182.

Domack, E.W., A.J.T. Jull and S. Nakao. 1991a. Advance of East Antarctic outlet glaciers during the Hypsithermal: Implications for the volume state of the Antarctic ice sheet under global warming. *Geology* **19:** 1059-1062.

Domack, E.W., A.J.T. Jull, J.B. Anderson and T.W. Linick. 1991b. Mid-Holocene ice sheet recession from the Wilkes Land continental shelf, East Antarctica. *In*, Thomson, M.R.A., J.A. Crame and J.W. Thomson (eds.). Geological Evolution of Antarctica. Cambridge Univ. Press, Cambridge. pp. 693-698.

Elston, D.P. and S.L. Bressler, 1981. Magnetic stratigraphy of DVDP drill cores and Late Cenozoic history of Taylor Valley, Transantarctic Mountains, Antarctica. *In*, McGinnis, L.D. (ed.). Dry Valley Drilling Project. Antarctic Research Series, Vol. 33, American Geophysical Union, Washington, D.C. pp. 413-426.

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* **342:** 637-642.

Goodwin, I.D. 1993. Holocene deglaciation, sea-level change, and the emergence of the Windmill Island, Budd Coast, Antarctica. *Quatern. Res.* **40:** 70-80.

Ingolfsson, O., C. Hjort, S. Bjorck and R.I. Lewis-Smith. 1992. Late Pleistocene and Holocene glacial history of James Ross Island, Antarctic Peninsula. *Boreas* **21:** 209-222.

Jacobs, S.S. 1992. Is the Antarctic ice sheet growing? *Nature* **360:** 29-33.

Kautsky, N. 1982. Growth and size structure in a Baltic *Mytilus edulis* population. *Mar. Biol.* **68:** 117-133.

Long, E.R. 1972. Studies of marine fouling and boring off Kodiak Island, Alaska. *Mar. Biol.* **14:** 52-57.

McGinnis, L.D. (ed.). 1981. Dry Valley Drilling Project. Antarctic Research Series, Vol. 33. American Geophysical Union, Washington, D.C.

Nakada, M. and K. Lambeck. 1988. The melting history of the Late Pleistocene Antarctic ice sheet. *Nature* **333:** 36-40.

Pickard, J. 1985. The Holocene fossil marine macrofauna of the Vestfold Hills, East Antarctica. *Boreas* **14:** 189-202.

Raup, D. and S. Stanley. 1971. The Principles of Paleontology. W.H. Freeman, San Francisco.

Rosenberg, G.D. 1980. An ontogenetic approach to the environmental significance of bivalve shell chemistry. *In*, Rhoads, D.C. and R.A. Lutz (eds.). Skeletal Growth of Aquatic Organisms. Plenum Press, New York. pp. 133-168.

Stuiver, M., G.H. Denton, T.J. Hughes and J.L. Fastook. 1981. History of the marine ice sheet in West Antarctica during the last glaciation: A working hypothesis. *In*, Denton, G.H. and T.J. Hughes (eds.). The Last Great Ice Sheets. Wiley, New York. pp. 319-436.

Tushingham, A.M. and W.R. Peltier. 1991. Ice-3G: A new global model of Late Pleistocene deglaciation based upon geophysical prediction of post-glacial relative sea level change. *J. Geophys. Res.* **96:** 4497-4523.

Weller, G. 1992. Antarctica and the detection of environmental change. *Trans. Roy. Soc. Lond. B* **338:** 201-208.

Yoshida, Y. 1983. Physiography of the Prince Olav and the Prince Harald Coasts, East Antarctica. *Mem. Natl. Inst. Polar Res. Ser. C* **13:**1-83.