Geology

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Geology 2010;38;635-638
doi: 10.1130/G30932.1

Notes

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ABSTRACT

Rapid warming and consequent ice-shelf collapse have focused attention on the glacial record of the Antarctic Peninsula. Here, we present the first record of terrestrial organic material exposed by recently retreating ice that bears on past glacier extent and climate in this sensitive region. Radiocarbon dates show that ice on Anvers Island was at or behind its present position at 700–970 cal. yr B.P., coincident with ice reduction elsewhere in the Southern Hemisphere. Moreover, the data indicate that present reduced ice extent on the western Antarctic Peninsula is not unprecedented and is similar to that experienced during at least three periods in the last 5600 yr.

INTRODUCTION

Rapid warming and consequent ice-shelf collapse have focused attention on the glacial record of the Antarctic Peninsula (i.e., Cook and Vaughan, 2009; Domack et al., 2005; Mercer, 1978) and the potential for rapid ice-sheet drawdown. Over the past 50 yr, the Antarctic Peninsula warmed ~2 °C (i.e., Vaughan et al., 2001). Although the cause of this warming is unclear, its expression is not. Rapid breakups have destroyed several small, thin ice shelves fringing the Antarctic Peninsula (i.e., Cook and Vaughan, 2009, and references therein). Removal of ice-shelf back pressure resulted in a marked increase in seaward flow of glaciers discharging into the now abandoned embayments (Cook and Vaughan, 2009; De Angelis and Skvarca, 2003; Rignot et al., 2004, 2005; Scambos et al., 2004a). Mercer (1978) was the first to propose climate control on the Antarctic Peninsula ice shelves and predicted their progressive southward disappearance with greenhouse warming. Increase in the intensity and length of the melt season is critical, with ice shelves becoming susceptible to breakup when January temperatures exceed –1.5 °C (Scambos et al., 2004b) or the mean annual temperature surpasses –9 °C (Morris and Vaughan, 2003), although geometry and pinning points are also important (Cook and Vaughan, 2009). One concern is that this present warming will continue to migrate southward, eventually causing collapse of the large Ross and Ronne-Filchner Ice Shelves that buttress the West Antarctic Ice Sheet (Mercer, 1978; Scambos et al., 2004b).

Is the recent warming of the Antarctic Peninsula unique in the Holocene? Existing evidence is mixed, but is critical for understanding the cause, expected duration, and effect of the present temperature changes. Both marine and lacustrine records indicate a mid-Holocene optimum (i.e., Ingólfsson et al., 2003, and references therein). Some ice shelves apparently collapsed in response to early and mid-Holocene warmth and re-formed later. For example, Pudsey and Evans (2001) showed from the presence of far-traveled ice-rafted detritus that Prince Gustav Channel Ice Shelf (Fig. 1) disappeared

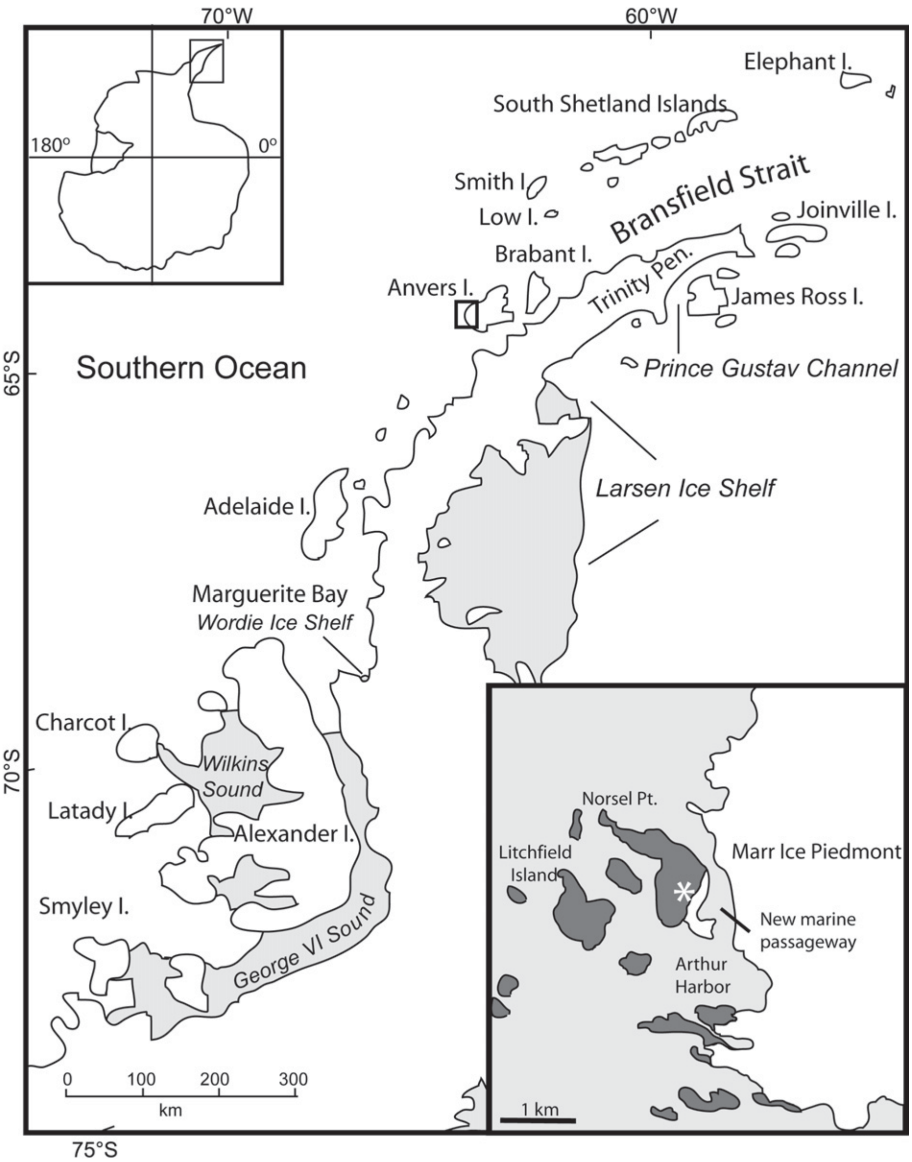

Figure 1. Index map of the Antarctic Peninsula. Small box indicates the approximate location of the field area, shown in greater detail in the inset. Star in the inset box indicates sampling site location.

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at 1900–6000 cal. yr B.P. (calendar years before present), whereas Brachfeld et al. (2003) suggested that the Larsen A Ice Shelf was absent at 1400–3800 cal. yr B.P. However, based on analysis of sediments from areas formerly beneath the ice shelf, Domack et al. (2005) showed that the adjacent Larsen B Ice Shelf was in existence throughout the Holocene, implying that its recent collapse is anomalous. In contrast, from analysis of epishelf lake sediments, Bentley et al. (2005) concluded that the George VI Sound Ice Shelf was absent at ca. 9600 cal. yr B.P., but re-formed by 7730 cal. yr B.P. and has been present ever since.

Although not as spectacular as the collapsing ice shelves, land-based glaciers also have retreated on the Antarctic Peninsula over the last half century and, presumably, are recording the same warming, without the nonlinear behavior characteristic of ice shelves. These glaciers have received comparatively little attention. The most comprehensive study is that of Cook et al. (2005), who examined a 50 yr record of photographs and satellite images. They concluded that over the time period studied, 87% of Antarctic Peninsula glaciers had retreated.

RESULTS AND INTERPRETATIONS

In order to put current ice recession in context, we examined organic-rich sediments exposed by recent retreat of the Marr Ice Piedmont on western Anvers Island near Norsel Point (Figs. 1 and 2). Glaciers on Anvers Island have been undergoing considerable retreat in response to the well-documented warming, and our sampling area was deglaciated in ~2004. Ice recession shortly thereafter allowed a narrow marine passageway to open between Norsel Point and Anvers Island, stranding a residual ice mass and leaving the main ice front ~400 m east of the sample sites.

Glacier retreat revealed stratified sands and silts, typical of ice-proximal meltwater fans and small ice-marginal ponds, interbedded with discontinuous layers of moss-rich peat. This was overlain by thin (<30 cm), stony till and water-laid glacial sediments (Fig. 3). The fans and pond sediments formed when ice extent was similar to present and then were overrun during the most recent glacier advance. The peat occurs both as contorted layers and as rip-up clasts. Upon subsequent ice retreat, meltwater dissection produced small sections, which we sampled for organic remains.

We obtained moss and reworked marine shells from natural sections within 26 m of the present ice front (Fig. 2). In addition, we obtained both peat and reworked shells from sediments exposed in a tunnel beneath the residual ice mass. The samples were dried thoroughly prior to shipment and kept in cool storage. We submitted eight samples for radiocarbon dating (the National Ocean Sciences Accelerator Mass Spectrometry Facility [NOSAMS] laboratory) and converted the results to calendar years using CALIB (Stuiver and Reimer, 1993) and the INTCAL09 data set (Reimer et al., 2009). We did not attempt a Southern Hemisphere correction. For the two marine samples, we used the Marine09 data set and a reservoir correction of 1130 yr, calculated from a compilation of published Antarctic reservoir data for use with the CALIB program (Reimer et al., 2004). All dates in the text are in calendar years with a 2σ error.

Peat from the overrun sediments dates between 707 ± 36 and 967 ± 47 cal. yr B.P. (Table 1), with all but one being 700–850 yr old. The reworked shells are ca. 3700 and ca. 5500 cal. yr B.P. and must have been derived upglacier from marine areas now or very recently occupied by ice. The Marr Ice Piedmont could not have covered the sample sites nor the source of the marine shells, when any of these organisms lived. Therefore, we conclude that ice was at or behind its present position at ca. 700–970 cal. yr B.P. and during at least two earlier times, represented by the dates of shells, in the mid-to-late Holocene. Thus, the present state of reduced ice on the western Antarctic Peninsula is not unprecedented.

Others have noted times when ice shelves on the Antarctic Peninsula were retracted, similar to today. However, most of these times are within the early and mid-Holocene climatic optimum. Of the ice shelves, only two apparently were absent during parts of the late Holocene (Brachfeld et al., 2003; Pudsey and Evans, 2001) and these re-formed prior to the growth of moss at Norsel Point. The late Holocene generally is considered a time of Neoglacial

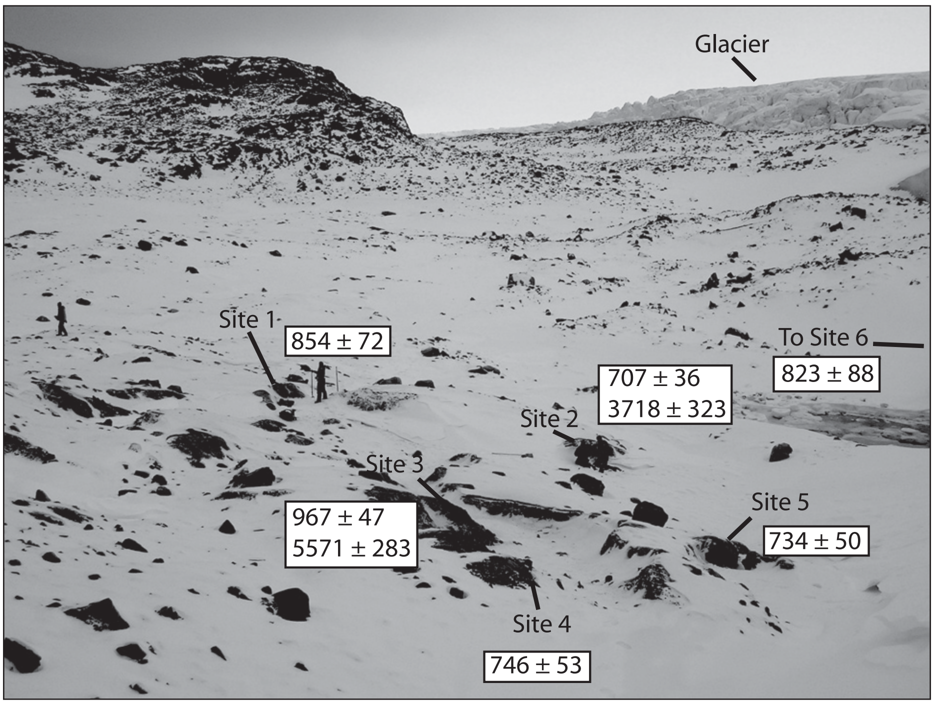

Figure 2. Photograph of sites along the residual ice mass near Norsel Point. The closest ice margin is just off the photograph to the right, 26 m from site 1. Ages are in calendar years, with the two older dates being of reworked shells.

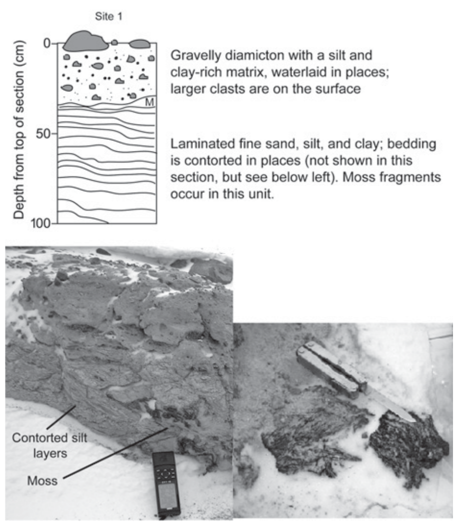

Figure 3. Upper part of figure shows a typical stratigraphic section, with diamicton overlying bedded silts and clays. "M" refers to moss. Lower left is a photograph of a different section, where laminated, moss-bearing sediments have been contorted, possibly during glacial advance. This area was ice-covered until 2004. Lower right photograph shows a moss sample.

TABLE 1. RADIOCARBON DATA FROM MOSS AND SHELLS RECENTLY UNCOVERED BY RETREATING ICE

Sample	Lab #	^{14}C age	1σ	Cal. age (cal. yr B.P.)	2σ (cal. yr B.P.)	Material	$\delta^{13}C$ (‰)
Site-1A	OS-57859	930	30	854	72	moss	–24.11
Site-2E	OS-57893	790	30	707	36	moss	–24.68
Site-2S	OS-57561	4540	35	3719	402	shell	2.20
Site-3D	OS-57773	1050	35	967	47	moss	–24.22
Site-3S	OS-57563	5970	40	5535	369	shell	2.21
Site-4A	OS-57860	860	30	746	53	moss	–23.55
Site-5C	OS-57894	820	30	734	50	moss	–21.08
Site-6	OS-57895	895	35	823	88	moss	–26.21

cooling on the Antarctic Peninsula (Björck et al., 1991a, 1991b; Domack et al., 2001; Jones et al., 2000). In contrast, our evidence points to a very recent episode (700–970 cal. yr B.P.) of reduced ice not highlighted in other records. In addition, the dates of reworked shells hint at other periods in the mid-to-late Holocene with reduced ice cover.

How widespread is the event at 700–970 cal. yr B.P.? Given that existing ice-shelf data do not record this warm period, could ice behavior on Anvers Island be anomalous and not reflect regional ice retreat? This question is difficult to answer with existing data. However, the Marr Ice Piedmont today is acting in a manner similar to most other Antarctic Peninsula glaciers, giving us some confidence that it may have responded in concert with regional climate in the past. In addition, some Antarctic Peninsula records do show warming at ca. 700–970 cal. yr B.P. For example, Khim et al. (2002) noted a pronounced high-productivity (warm) event between 500 and 1000 cal. yr B.P. in magnetic susceptibility records from Bransfield Basin. Moreover, dates of moss adjacent to the present ice front in the South Shetland Islands (Hall, 2007) indicate that ice there was no more extensive between ca. 650 and 825 cal. yr B.P. than it is now. Bentley et al. (2009) reported that evidence for warming at this time seems restricted to the western Antarctic Peninsula and is seen best in some (although not all) marine cores (i.e., Domack et al., 2003). They further noted that Holocene warm events tend to be expressed more strongly along the western Antarctic Peninsula than in the east (Bentley et al., 2009). In summary, the period of reduced ice at ca. 700–970 cal. yr B.P. does appear to have regional expression, at least in the western and northern Antarctic Peninsula area, and thus is not an anomalous event.

Holocene millennial-scale climate changes can have a number of possible causes, including changes in ocean and/or westerly wind circulation, greenhouse gases, and solar insolation (for a comprehensive review, see Bentley et al., 2009). Comparison of Antarctic Peninsula warm events to paleoclimate data elsewhere is instructive for understanding the origin of these changes. For example, our evidence for reduced ice extent at 700–970 cal. yr B.P. is consistent with tree-ring data from New Zealand that show a pronounced peak in summer temperatures (Cook et al., 2002). New Zealand glaciers were retracted at the same time (Schaefer et al., 2009). Moreover, our data are compatible with a record of glacier fluctuations from southern South America, the continental landmass closest to Antarctica (Strelin et al., 2008). The apparently synchronous climate behavior in our western Antarctic Peninsula data and New Zealand and South American records is uncharacteristic of recent, short-term climate variations, caused by El Niño–Southern Oscillation or the Interdecadal Pacific Oscillation (Fitzharris et al., 2007), suggesting that one may not be able to extrapolate short-term events to explain longer-term climate change in this region. Moreover, in contrast to our data, glacial records from Europe show that the first pulse of the Little Ice Age occurred at ca. 700–970 cal. yr B.P. (Fig. 4). If our interpretations of western Antarctic Peninsula data are correct, then this hints at asynchronous behavior between at least parts of the two hemispheres, a conclusion also reached by Schaefer et al. (2009) and Ljung and Björck (2007), among others. Such asynchrony, if borne out by additional data, would argue against hypotheses of millennial-scale climate change involving direct solar or greenhouse-gas forcing and favor instead mechanisms such as the bipolar seesaw (Broecker, 1998, 2001) or control by local insolation or wind patterns. Testing of this hypothesis of asynchrony will require additional, high-resolution records from the Antarctic Peninsula.

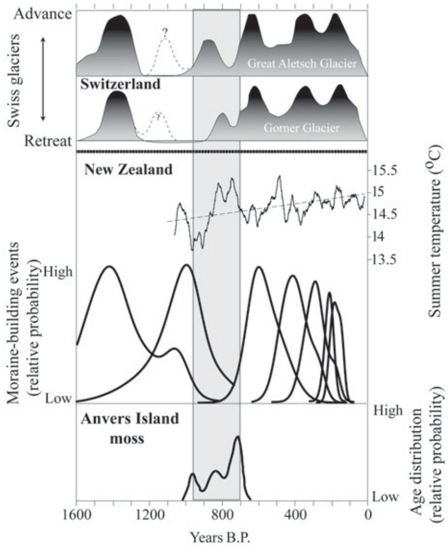

Figure 4. Comparison of moss dates with well-dated Northern and Southern Hemisphere records, modified from Schaefer et al. (2009). Top panels show glacier fluctuations in the Alps (Holzhauser et al., 2005), whereas the bottom displays New Zealand summer temperatures derived from tree rings (Cook et al., 2002), the timing of New Zealand moraine-building episodes dated with cosmogenic ^{10}Be (Schaefer et al., 2009, shown as probability, with high probability indicating the time of moraine formation), and a probability plot of the moss dates (this paper). Note that the inferred warm interval (represented by the moss dates and outlined in gray) on the western Antarctic Peninsula is coeval with similar warming and glacial retreat in New Zealand.

ACKNOWLEDGMENTS

This work was supported by the Office of Polar Programs of the National Science Foundation and by the Comer Science and Education Foundation. We especially wish to thank the 2006 Winter-Over crew at Palmer Station, who assisted in sample collection, and three reviewers who improved this paper greatly.

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Manuscript received 3 December 2009
Revised manuscript received 10 February 2010
Manuscript accepted 15 February 2010

Printed in USA