BOREAS An international journal of Quaternary research

Rate of late Quaternary ice-cap thinning on King George Island, South Shetland Islands, West Antarctica defined by cosmogenic ^{36}Cl surface exposure dating

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Seong, Y. B., Owen, L. A., Lim, H. S., Yoon, H. I., Kim, Y., Lee, Y. I. & Caffee, M. W.: Rate of late Quaternary ice-cap thinning on King George Island, South Shetland Islands, West Antarctica defined by cosmogenic ^{36}Cl surface exposure dating. *Boreas*, Vol. 38, pp. 207–213. 10.1111/j.1502-3885.2008.00069.x. ISSN 0300-9483.

Glacial landforms on the Barton and Weaver peninsulas of King George Island in the South Shetland Islands, West Antarctica were mapped and dated using terrestrial cosmogenic ^{36}Cl methods to provide the first quantitative terrestrial record for late Quaternary deglaciation in the South Shetland Islands. ^{36}Cl ages on glacially eroded and striated bedrock surfaces range from 15.5±2.5 kyr to 1.0±0.7 kyr. The ^{36}Cl ages are younger with decreasing altitude, indicating progressive downwasting of the southwestern part of the Collins Ice Cap at a rate of ~12 mm yr^{-1} since 15.5±2.5 kyr ago, supporting the previously published marine records for the timing and estimate of the rate of deglaciation in this region.

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Understanding the past configurations and behavior of the Antarctic ice sheets is essential for predicting future responses in the cryosphere and for quantifying the magnitude and timing of the Antarctic contribution to postglacial eustatic sea level change (Bentley 1999). In particular, the West Antarctic Ice Sheet (WAIS), much of which is grounded below sea level and drained by fast-flowing ice streams, is one of the key sectors to monitor glacial responses to global warming (Mercer 1978; IPCC 2007). The WAIS of Saalian–Illinoian (MIS 6) age, for example, collapsed catastrophically during the Eemian–Sangamon interglacial (MIS 5) (Mercer 1968, 1978). This collapse caused a eustatic sea level rise of ~5 m above the present sea level ~120 kyr ago. Considerable debate surrounds the stability of the WAIS throughout the Cenozoic (Kennett 1982; Webb 1989; Barrett *et al.* 1992). The combination of previous WAIS instability during past warming periods, the seeming inevitability of near-term global warming, and the far-reaching consequences to the Earth's ecosystems of rapid sea-level change, motivate characterization of the dynamics of glaciers in West Antarctica. In this work, we investigate glacially scoured bedrock surfaces in the South Shetland Islands (SSIs) to determine how ice caps near the WAIS responded to regional/global warming after the Last Glacial Maximum. The region was mapped and samples were collected for terrestrial cosmogenic ^{36}Cl surface exposure dating.

Study area

The SSIs are on the southern flank of Drake Passage ~140 km from the Northern Antarctic Peninsula (Fig. 1). The SSIs consist of 11 major and hundreds of minor islands and shoals stretching northeastwards for ~230 km. The SSIs belong to part of a magmatic arc (Scotia Arc), which is closely linked to the formation of the Antarctic Peninsula (Smellie *et al.* 1984). King George Island, the largest of the SSIs, is located in the center of the archipelago. Most of the island is covered by the Collins Ice Cap, which is centered on the island and calves at sea level along most of its margin (Fig. 1C) (Hall 2007). The Collins Ice Cap has numerous outlet glaciers (Fig. 1C), including the Marian Cove Glacier that traverses the Barton and Weaver peninsulas (Fig. 2). The island has a cold oceanic climate, characteristic of maritime Antarctica, with frequent summer rains and moderate annual thermal amplitude (Turner *et al.* 1998). Recent measurements taken at meteorological stations on King George Island show a rapid rise in the mean annual temperature of between −1°C and −4°C since 1965 (Fig. 1B) (Lagun & Jagovkina 2004). The climate of the study area shows sharp seasonal contrasts. During winter, high pressure in the region of the Antarctic Peninsula is commonly associated with cold air temperatures on King George Island. In contrast, during summer, northerly and northwesterly advection provides moist warm air

DOI 10.1111/j.1502-3885.2008.00069.x

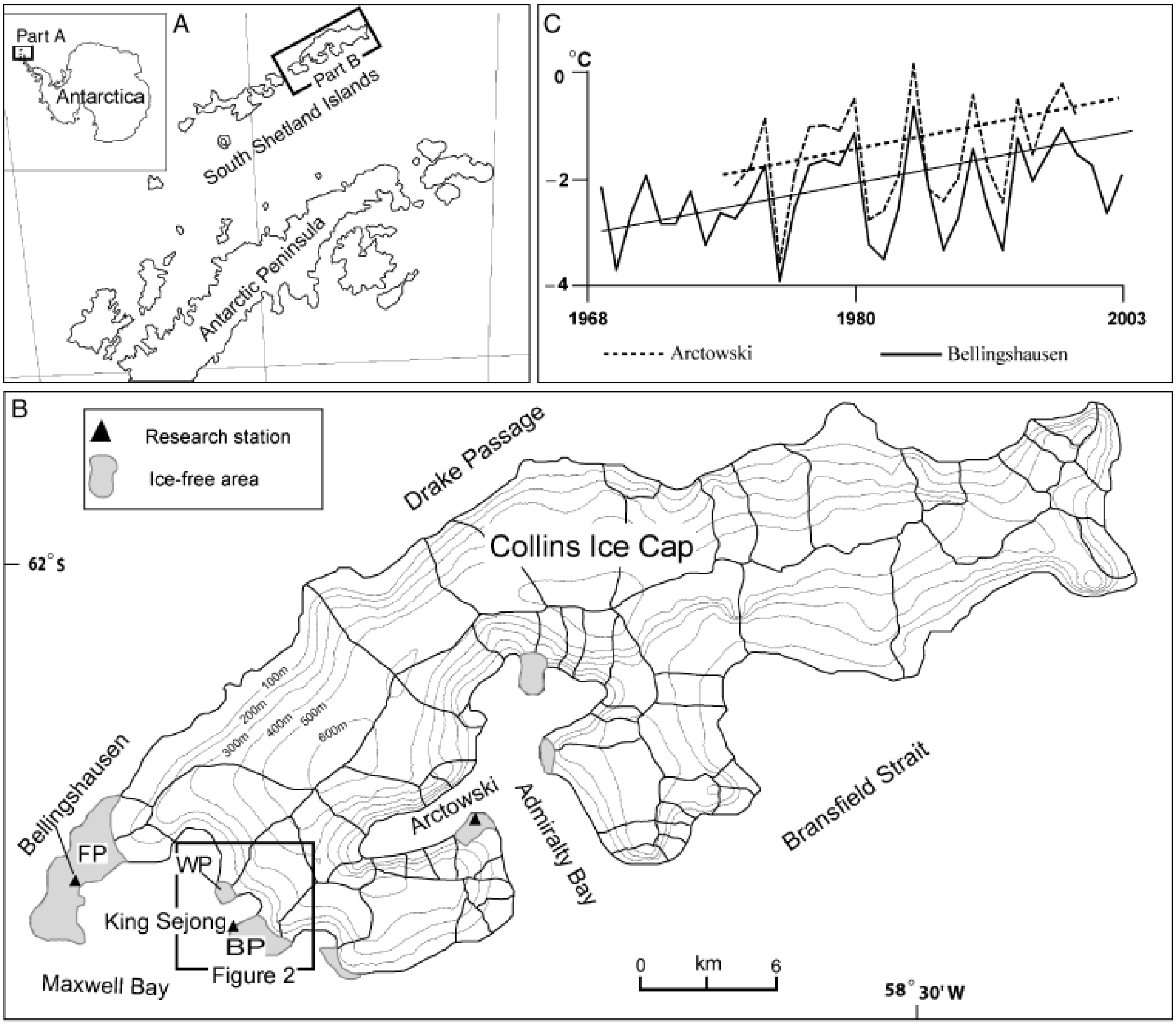

Figure 1. A. Location of the South Shetland Islands in Antarctica. B. The Collins Ice Cap centered on King George Island and its glacial drainage-basin divides (after Simoes *et al.* 1999). Contours, distribution of ice and outcropping rock and other geographic information are from RADARSAT. C. Observed temperature record from 1968 to 2003 in King George Island (Lagun & Jagovkina 2004).

masses to the SSIs (King & Turner 1997). Cyclonic activity becomes greater and more frequent in summer as a consequence of the shift in the circum-Antarctic low pressure trough, providing the archipelago with abundant precipitation (Turner *et al.* 2004).

The SSIs are extensively glaciated, with relatively few ice-free areas ($\sim$40 km^2). There have been few terrestrial glacial geologic studies within the SSIs because of their physical inaccessibility and the small number of ice-free areas. During the Quaternary, the SSIs experienced two major glaciations that resulted in a series of marine terraces, the erosional platforms and glacial landforms (Everett 1971; John & Sugden 1971; Birkenmajer 1981; Leventer *et al.* 1996; Hjort *et al.* 1998; Hall 2003). During the Last Glacial, the extensive ice cap located on the northern side of King George Island carved a deep trough, Maxwell Bay (John & Sugden 1971; Yoon *et al.* 1997). Since the LGM, the SSIs have experienced progressive postglacial warming, with a few minor limited cooling events resulting in glacier advances (Hall 2007). As a consequence of the postglacial warming, large glaciated areas became ice-free, exposing glacially striated erratics and bedrock landforms and till deposits, which record the former ice-cap configuration and the deglaciation history.

Ice-free areas, which are not covered by beaches or scree, are generally strewn with erratic blocks and till, reflecting former ice movement on King George Island (Fig. 1C). On the Barton and Weaver peninsulas (Fig. 2), erratics of fine-grained igneous rock are present on volcanic bedrock, and subglacially eroded bedforms such as roche moutonnée and striation are abundant. With the exception of the present outlet glacier margin, few moraine ridges are present below

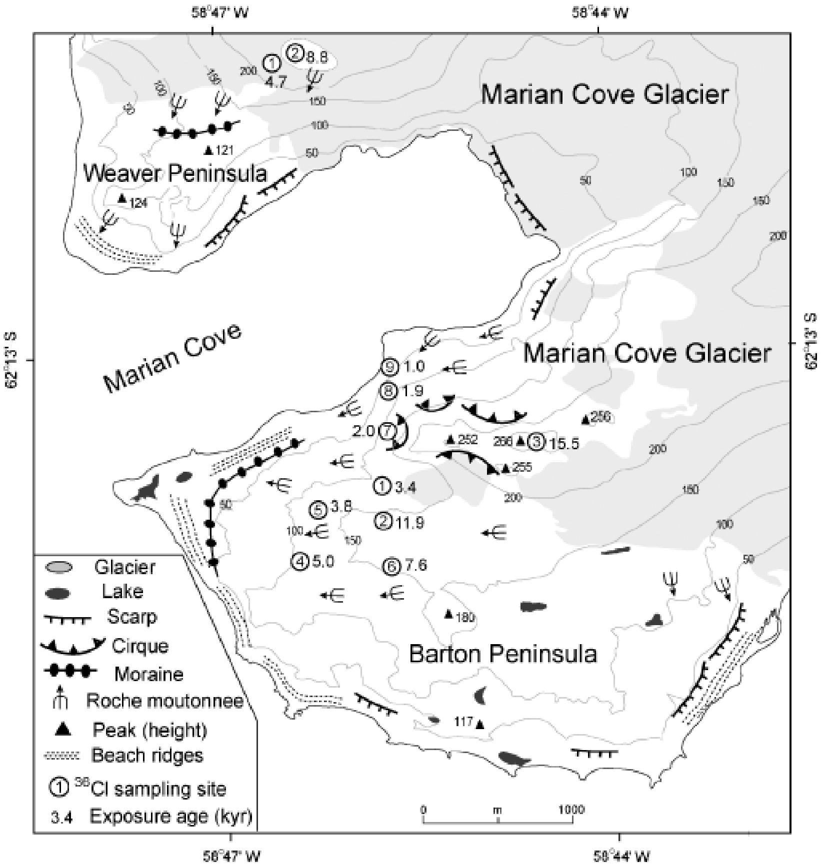

Figure 2. Locations of glacially polished surface sampled for cosmogenic ^{36}Cl exposure dating plotted on a modified version of the Lopez-Martinez *et al.* (2002) geomorphic map of the Barton and Weaver peninsulas.

the ice margin (Fig. 3). Several studies on lake sediments suggest various ages of initiation of deglaciation on the ice-free areas of King George Island, ranging from early to middle Holocene (Mäusbacher *et al.* 1989; Mäusbacher 1991) to middle to late Holocene (Björck *et al.* 1991, 1993, 1995). A recent study on the organic materials included in patterned ground suggests that deglaciation occurred during the middle Holocene on the Barton Peninsula (Jeong 2006). Given the ice-cap configuration and its downwasting style of melting, most of the deglacial ages are minimum. In this study, we obtain more robust ages for the deglaciation of the Barton and the Weaver peninsulas.

Methods

Sample collection and preparation

Eleven samples were collected from glacially polished and striated surfaces on the Barton and Weaver peninsulas (Fig. 2). The samples were collected from relatively flat-lying intrusions (~top 5 cm) within the bedrock to avoid possible cover/shielding by periglacial debris. All the samples were collected from locations where the angle to the skyline was $<20°$; there was little/no obstruction by high obstacles and the sampled areas were very flat in the middle of surfaces away from edge effects. Therefore no geometric corrections were required. All the samples were processed for whole-rock ^{36}Cl analysis as outlined by Stone *et al.* (1996). Samples were crushed and sieved to collect 250–500 μm particle size fraction. To remove potential meteoric ^{36}Cl contamination, crushed samples were leached thoroughly, first in 18 mΩ water and then in 10% HNO_3 for more than 12 h at room temperature. Major elements, including U and Th, before and after leaching, were determined by X-ray fluorescence, and B and Gd were detected by prompt-gamma-emission spectrometry. The samples were dissolved over 2 days in a 15 M HF and 2 M HNO_3 mixture at 60–70 °C. Approximately 1 mg of chloride spike (non-terrestrial ^{37}Cl/^{35}Cl) was added to each dissolved sample. Chloride was recovered from the sample solutions as AgCl.

^{36}Cl determinations

The ^{36}Cl/^{37}Cl and ^{35}Cl/^{37}Cl were measured using accelerator mass spectrometry (AMS) at the PRIME Laboratory of Purdue University. The concentration of cosmogenic ^{36}Cl atoms was used to calculate ages using

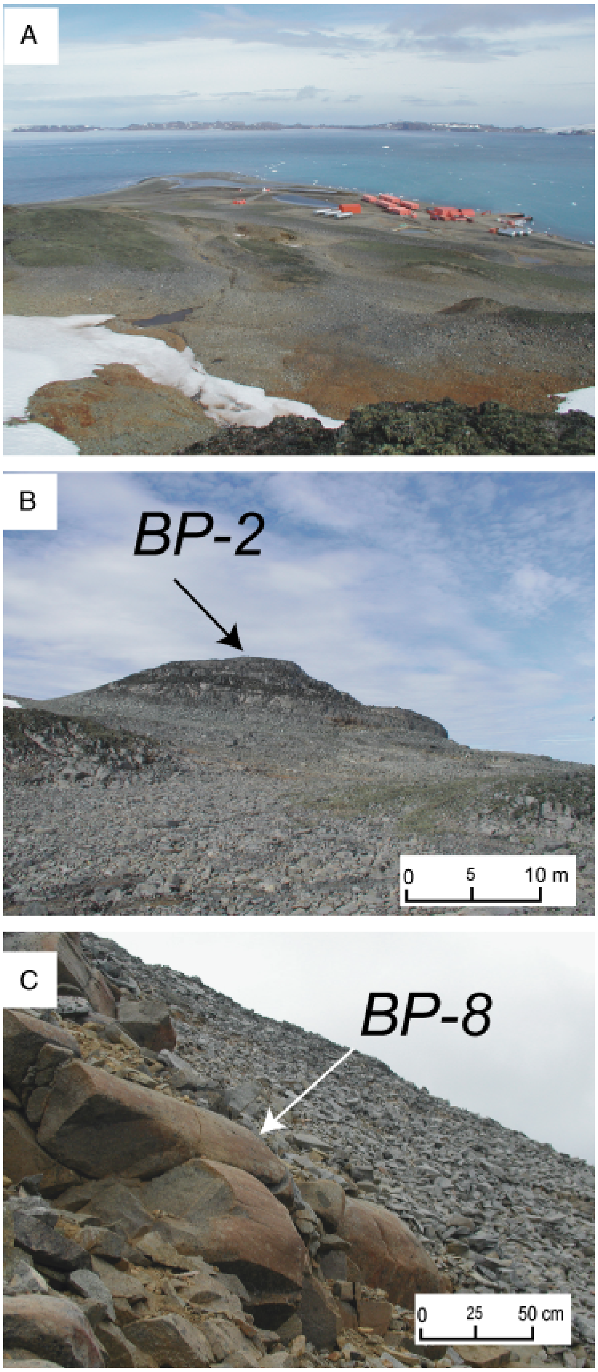

Figure 3. Typical glacial landforms within the study area. A. View looking southwest of glaciated landforms on Barton Peninsula with the King Sejong Research Station providing scale. A latero-frontal moraine and multiple lines of subglacially eroded hills are located behind the King Sejong Station. B. Roche moutonné subglacially eroded by glacier. The ice flowed from left to right. C. View of an outcrop (BP-8) with little weathered glacial striation on the surface. Ice flows from left to right.

the PRIME Laboratory program (http://www.physics.purdue.edu/primelab/for_users/rockage.html). Elevation-latitude scaling was based on Lal (1991) and Stone *et al*. (1996), and production by muon was based on Phillips *et al*. (2001). The assumed spallation production rates for ^{36}Cl from Ca and K are 66.8 and 154 atoms $g^{-1} yr^{-1}$, respectively (Phillips *et al*. 1996, 2001). All ages were calculated using a bulk density of 2.8 $g cm^{-3}$ and a neutron attenuation coefficient of 170 $g cm^{-2}$. The analytical uncertainty for ^{36}Cl ages is assumed to be $\leq$ 8% of the age (Phillips *et al*. 1997).

Results and discussion

The ^{36}Cl concentrations (Table 1) were used to calculate model surface exposure ages of the glacially scoured bedrock at varying elevations. These in turn are used to determine the downwasting rate of the Collins Ice Cap induced by postglacial warming since the LGM (Fig. 4). On the Barton Peninsula, the exposure ages range from 15.5±2.5 kyr at the highest location (BP-3, at 265 m a.s.l.) to 1.0±0.7 kyr at the lowest elevation (BP-9, at 41 m a.s.l.). In contrast, the exposure ages from the Weaver Peninsula are 8.8±1.1 kyr at 273 m a.s.l. (WP-2) and 4.7±0.9 kyr at 241 m a.s.l. (WP-1). Although the data set is relatively small, the exposure ages are systematically younger with decreasing altitude. We do not believe that the age differences between sampling sites at different altitudes can be explained by differential glacio-isostatic uplift, since the distance between sample positions is not great enough to produce this type of effect. Alternatively, if there was any isostatic rebound of the peninsula, the differential uplift of our sampling sites would be included in the spread of our exposure ages that were included in the linear downwasting calculation of ~12 mm yr^{-1}.

The ^{36}Cl surface exposure ages of the glacially scoured bedrock suggest that Marian Cove Glacier experienced progressive downwasting due to postglacial warming, since the LGM, at a rate of ~12 mm yr^{-1}. Given the present configuration of the glacier and the abundant evidence for extensive glaciation during the Last Glacial (John & Sugden 1971; Yoon *et al*. 1997; Hall 2003), it is most likely that the ice front was grounded below sea level at the time of initial deglaciation. Accordingly, it is hard to find the geologic evidence for initial deglaciation on land. The oldest exposure age (BP-3) from the study area should therefore be considered as the minimum age for deglaciation. Some of the marine sediments around King George Island were reported to be of glacial origin and occur at depths of as much as ~400 m below sea level (Griffiths & Anderson 1989; Lopez-Martinez *et al*. 1992; Yoon *et al*. 1997). The submerged moraines, however, have not yet been dated, but the veneered deglacial sediments lying on the basal glacial till were reported to be deposited at 17 kyr, based on extrapolation of sedimentation rate of dated deglacial sediments (Yoon *et al*. 1997). Since the terrestrial bedrock has the oldest deglaciation age in the study area, it is likely that there

Table 1. ^{36}Cl ages and chemical compositions of glacially striated bedrock samples in King George Island, Antarctica.

Sample ID	Latitude (±0.001°N)	Longitude (±0.001°E)	Altitude (m a.s.l.)	K_2O (%)	CaO (%)	Cl (ppm)	Spallation production (%)	$^{36}Cl/^{35}Cl$ (10^{-15})†	^{36}Cl exposure age (kyr)§
BP-1	62.227	58.771	0.123	0.21	10.7	316.00	75.46	36.8±4.0	3.4±0.7
BP-2	62.225	58.771	0.165	0.28	10.6	344.91	75.21	100.8±16.5	11.9±2.3
BP-3	62.224	58.748	0.265	0.27	10.7	238.58	76.66	142.3±20.6	15.5±2.5
BP-4	62.225	58.779	0.107	0.35	10.6	156.85	78.49	49.3±8.2	5.0±1.2
BP-5	62.225	58.771	0.124	0.19	10.8	856.41	72.93	37.8±4.8	3.8±0.9
BP-6	62.227	58.768	0.164	0.20	10.2	792.55	73.13	65.7±10.6	7.6±1.6
BP-7	62.223	58.764	0.120	0.22	10.6	392.13	74.75	26.2±6.5	2.0±1.0
BP-8	62.216	58.756	0.062	0.26	10.8	99.27	81.13	25.6±6.4	1.9±1.0
BP-9	62.214	58.744	0.041	0.21	10.8	54.31	85.21	20.5±4.8	1.0±0.7
WP-1	62.197	58.776	0.231	0.20	10.7	17.95	92.19	63.0±11.7	4.7±1.1
WP-2	62.197	58.777	0.273	0.21	10.7	13.65	93.56	106.8±9.1	8.8±0.9

†After subtraction of the radiogenic $^{36}Cl/^{35}Cl$.
§All ages assume no erosion.

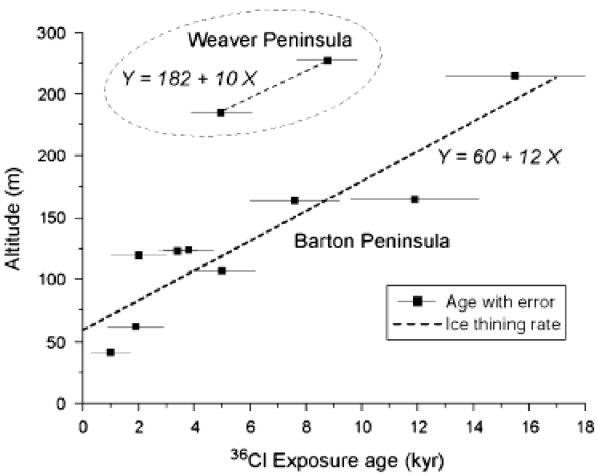

Figure 4. ^{36}Cl exposure ages of glacially striated surfaces plotted versus altitude. Nine samples (BP-1 through to BP-9) were analysed on the Barton Peninsula and two samples (WP-1 and WP-2) on the Weaver Peninsula. Exposure ages decrease consistently with decreasing altitude, implying that the ice began to melt after the global LGM and, since 15.5±2.5 kyr (BP-3), ice progressively downwasted over time. The apparent rate of ice downwasting is 12 mm yr^{-1} on the Barton Peninsula and 10 mm yr^{-1} on the Weaver Peninsula.

was a ~1.5 kyr time-lag after the initial deposition of the deglacial marine deposits.

All documented terrestrial records of deglaciation in the SSIs, most of which are from lakes, post-date the early Holocene (Mäusbacher *et al.* 1989; Mäusbacher 1991). The time gap between the terrestrial lake record and this study of deglaciation may reflect loss of the lake archives by a glacier advance/s. The glacially scoured peaks sampled in this study were likely exposed as nunataks during Lateglacial or Antarctic Cold Reversal (Blunier *et al.* 1997). Alternatively, because the lakes were formed only when the ice retreated from the position, the maximum age of lacustrine deposits should be younger than initial deglaciation except for the lakes that existed in the front of the ice or in elevated locations.

The ^{36}Cl ages in our study show that the Collins Ice Cap in the study area has progressively downwasted at a rate of 12 mm yr^{-1} since initial deglaciation 15.5±2.5 kyr ago. Nakada & Lambeck (1988) argue that the temporal pattern of deglaciation may explain the pattern of global sea level changes resulting from Antarctica meltwater input. Specifically, the WAIS and Antarctic Peninsula Ice Sheet are key sectors for watching the meltwater input into the ocean, because most of the glaciers on both areas are grounded below sea level and, thus, most susceptible to global warming and consequent sea level rising. Conway *et al.* (1999) and Stone *et al.* (2003) suggested that the WAIS experienced progressive thinning throughout the Holocene to the present. However, there is a contrasting suggestion on the deglaciation pattern of both sides of the Antarctic Peninsula only 140 km far away from the SSIs. Using cosmogenic surface exposure dating of glacial erratics, Bentley *et al.* (2006) suggested that ice thinning of the western side of the Antarctic Peninsula was almost complete to its present configuration by the early Holocene, while the thinning of ice on the eastern side was under way up to the late Holocene, i.e. like other WAIS areas. Given the data presented here, the study area is more like other WAIS areas and the eastern side of the Antarctic Peninsula in the temporal pattern of deglaciation which has been under the continuous thinning of ice until the present day.

The Marian Cove Glacier, which reaches into the sea (Fig. 2), has experienced a dramatic retreat of the ice front of ~1700 m over the past 50 years near the Marian Cove section (Lee *et al.* 2008). Although the present retreat rate is difficult to compare with the thinning rate of the past glacier, the observed recent retreating rate of ~33 m yr^{-1} is approximately three times higher than the long-term downwasting rate of the ice. This might reflect the accelerating effect of global warming in the study area. Moreover, this warming trend around the study area is well documented by observed temperature change over the past 50 years at the Bellingshausen Meteorological Station (Fig. 1B) (Lagun & Jagovkina 2004). Alternatively, the rapid retreat rate of the Marian Cove Glacier might reflect the sensitive response of a tidewater section of the glacier to rising sea level.

Conclusions

This study provides the first systematic constraints on the postglacial thinning rate of the Collins Ice Cap since the LGM on King George Island of the SSIs, West Antarctica. Determining the timing of deglaciation using geomorphic and terrestrial cosmogenic ^{36}Cl s urface exposure dating from the bedrock at varying elevations demonstrates that the ice has progressively melted down since the LGM. All the apparent cosmogenic ^{36}Cl abundances from the glacially striated bedrock surfaces yield post-LGM ages ranging from 15.5±2.5 kyr to 1.0±0.7 kyr, their model ^{36}Cl exposure ages becoming younger with decreasing altitude. The maximum terrestrial deglacial age of 15.5±2.5 kyr predates any ages of initial deglaciation from the terrestrial records and supports the previously reported deglacial age of 17 kyr from marine records. Our results suggest that glaciers on King George Island began to melt down no later than 15.5±2.5 kyr ago and have been progressively downwasted since the LGM up to the present at a long-term rate of $\sim$12 mm yr^{-1} on the Barton and the Weaver peninsulas.

Acknowledgements. – This work was supported by the Korea Research Foundation Grant funded by the Korean Government (KRF-2008-314-C00394), by the Korea Polar Research Institute Grant PE08010 and by the Ministry of the Environment as 'The Eco-technopia 21 project (PN08020)'. Thanks to Mike Bourgeois and Colby Smith for their generous help during chemical preparation of the ^{36}Cl samples at the PRIME Laboratory and at the University of Cincinnati. We are extremely grateful to J. Clark and J. van der Meer for their constructive reviews and to all the researchers who spent the 2005–2006 austral summer together at King Sejong Station, Antarctica.

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