Glacial history of the Antarctic Peninsula since the Last Glacial Maximum—a synthesis

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The extent of ice, thickness and dynamics of the Last Glacial Maximum (LGM) ice sheets in the Antarctic Peninsula region, as well as the pattern of subsequent deglaciation and climate development, are not well constrained in time and space. During the LGM, ice thickened considerably and expanded towards the middle–outer submarine shelves around the Antarctic Peninsula. Deglaciation was slow, occurring mainly between >14 Ky BP (^{14}C kilo years before present) and ca. 6 Ky BP, when interglacial climate was established in the region. After a climate optimum, peaking ca. 4 - 3 Ky BP, a cooling trend started, with expanding glaciers and ice shelves. Rapid warming during the past 50 years may be causing instability to some Antarctic Peninsula ice shelves.

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The Antarctic Peninsula (Fig. 1) encompasses one of the most dynamic climate systems on Earth, where the natural systems respond rapidly to climatic changes (Smith et al. 1999; Domack et al. 2001a). Signs of accelerating retreat of ice shelves, in combination with rapid warming (>2 °C) over the past 50 years, have raised concerns as to the future stability of the glacial system (Doake et al. 1998; Skvarca et al. 1999). Knowledge of past ice extent and the history of climatic fluctuations are essential for understanding what controls the patterns of glacial fluctuations. This paper briefly reviews the most important types of data used for interpreting the glacial and climatic history of the Antarctic Peninsula region since the Last Glacial Maximum (LGM,) 20 - 18 Ky BP. Radiocarbon dates of marine samples used for chronological constrains are in this paper reported as reservoir corrected (-1300 years), but not calibrated, regardless of how the dates were reported in the original publication.

Onshore evidence for the LGM ice extent

Evidence of more extensive ice cover than today is present on ice-free lowland areas along the Antarctic Peninsula and its surrounding islands, primarily in the form of glacial drift, erratics and striations (Sugden & Clapperton 1977, 1980; Curl 1980). The erratics and glacial striae on the lowlands mostly confirm with ice flow constrained by local topography, from land onto the submarine shelf areas. Chronological control in the form of ^{14}C dates from organic material in glacial drift and overlying sediments dates this latest major glacial event as Late Wisconsinan–early Holocene (Sugden & John 1973; Ingólfsson et al. 1998).

Evidence of ice thickness at the glacial maximum includes ice-abraded ridge crests, striations, erratics and glacial drift on nunataks and coastal

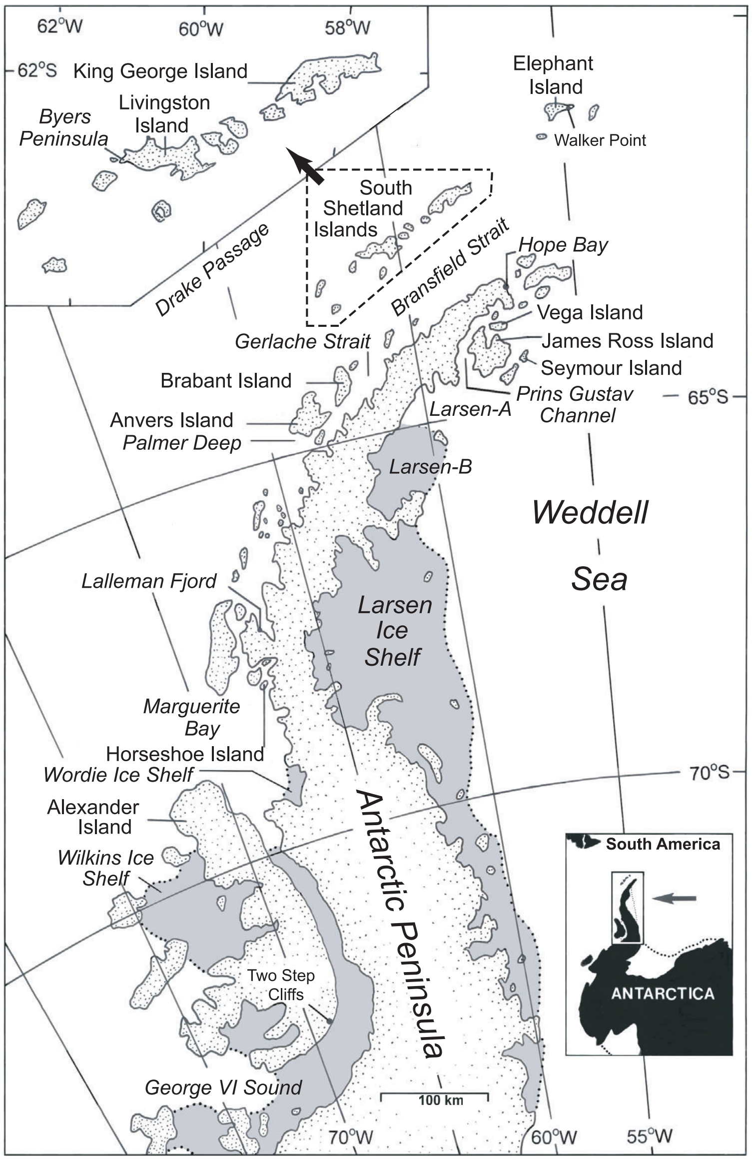

Fig. 1. The Antarctic Peninsula.

mountains. Ancient glacial trimlines are rarely recognized. Attempts to map altitudinal evidence of LGM ice thickness led Carrara (1981) and Waitt (1983) to conclude that the southern Antarctic Peninsula had at some time in the past been overridden by an ice sheet which was at least 500 m thicker than today. Bentley & Anderson (1998) concurred with that when reconstructing the LGM configuration of an Antarctic Peninsula ice sheet, with an ice divide stretching north–south along the axis of the peninsula. Hjort et al. (1997) suggested that LGM ice flow off the peninsula towards the submarine shelf in the north-western Weddell Sea was channelled through straits and troughs among the offshore islands, and did not attain much greater thickness there than ca 150 m a.s.l.

Raised beaches on the Antarctic Peninsula, which post-date the last major glaciation and provide isostatic fingerprinting of earlier expanded ice volumes, have been described from most ice-free areas on the peninsula and nearby islands (e.g. John & Sugden 1971; Curl 1980; Hjort et al. 1997). In the northern part of the region the marine limit (ML) often lies at 15 - 20 m a.s.l., with the highest ML found on northern James Ross Island at 30 m a.s.l. and dated to ca. 7.4 Ky BP (Hjort et al. 1997). The ML rises towards the south. It is highest on Horseshoe Island in Marguerite Bay, at ca. 55 m a.s.l. (Hjort & Ingólfsson 1990). Its age is constrained by minimum ages for the deglaciation of Marguerite Bay as being older than 7 - 6 Ky BP (Kennedy & Anderson 1989; Harden et al. 1992; Pope & Anderson 1992; Emslie 2001; Anderson et al. 2002). The north–south gradient in ML altitude agrees with the concept of greater LGM ice volumes in the central and southern part of the region.

Offshore evidence for the LGM ice extent

Marine geological evidence for former ice extent include shelf bathymetry (troughs, submarine valleys, moraine ridges, flutes), which delineate drainage of glaciers and show that the shelf areas have been shaped by erosion and deposition below and in front of moving outlet glaciers and ice streams. Seismic records reveal glacial unconformities and sediment cover, and illustrate the extent of glacial erosion and deposition on the shelf. Sediment cores, which penetrate glaciomarine sediments into underlying tills, provide data on former ice extent. Radiocarbon dates from glaciomarine sediments provide minimum dates for deglaciation of the submarine shelves.

The data indicate that grounded ice sheets, ice streams and outlet glaciers extended onto the Antarctic Peninsula shelves during the LGM. Canals et al. (2000) suggested that during the LGM, a major ice stream from the northwestern Antarctic Peninsula had drained into the Gerlache Strait and flowed northwards into the Bransfield basin. Banfield & Anderson (1995) recognized a widespread glacial unconformity extending to the shelf break off Bransfield Strait, with prominent ridges occurring above the unconformity within troughs on the middle shelf. Bentley & Anderson (1998) and Anderson et al. (2002) suggested that these ridges were moraines, marking the LGM grounding line, but their origin is still circumstantial. Larter & Vanneste (1995) described relict subglacial till-deltas on the outer Antarctic Peninsula shelf, off Anvers Island, interpreted as products of progradation at former ice stream grounding lines. Minimum ages for the till-deltas, 12.2 - 11.3 Ky BP, were provided by ^{14}C dates from stratigraphically overlying glacial marine sediments on the shelf (Pudsey et al. 1994; Domack et al. 2001a). Bentley & Anderson (1998) concluded that LGM glaciers flowing west from the Antarctic Peninsula had grounded on the outer shelf, at water depths of ca. 400 m, and that ice shelves extending over the submarine shelf break fringed them. This reconstruction was not well constrained, but Anderson et al. (2002) added new swath bathymetric data that supports the LGM grounding of an ice stream close to the shelf edge off Marguerite Bay.

Bathymetric data from the western Weddell Sea indicate submarine troughs, which have drained large outlet glaciers from the Antarctic Peninsula into the Weddell Sea (Sloan et al. 1995). Multibeam records from the inner shelf show flutes and other lineations that indicate ice overriding (Domack et al. 2001b). Seismic profiles and sediment cores suggest a widespread erosional unconformity extending to the shelf break (Anderson et al. 1992), and Anderson et al. (2002) described a prominent grounding zone wedge above this unconformity on the mid-shelf. Bentley & Anderson (1998) and Anderson et al. (2002) suggested that the unconformity marked the extension of LGM Antarctic Peninsula ice sheet, and suggested that it grounded on the outer shelf, some 200 km east of the peninsula. Anderson et al. (2002), however, point out that the age of the unconformity is uncertain. Thus, the LGM ice may have grounded closer to the peninsula, and been fringed by an ice shelf extending to the shelf edge.

The marine geological data can be interpreted to suggest that the LGM Antarctic Peninsula ice sheet was composed of a number of confluencing, localized domes and ice stream systems, rather than a concentric and dynamically coherent ice sheet.

Deglaciation of the submarine shelves

The oldest ^{14}C dates, constraining ice retreat from the outer and middle continental shelf west of the Antarctic Peninsula come from the Bransfield Strait (Banfield & Anderson 1995), and from areas west of Anvers Island (Pope & Anderson 1992; Pudsey et al. 1994), and indicate ice retreat by 14 - 13 Ky BP and 12 - 11 Ky BP, respectively. Domack et al. (2001a) date the onset of deglaciation of the Palmer Deep to ca. 11 Ky BP. Most dates from the inner submarine shelves, fjords and bays constrain deglaciation there to 8 - 6 Ky BP: Harden et al. (1992) and Shevenell et al. (1996) provided 8 Ky BP as a minimum date for onset of glaciomarine sedimentation in the central Gerlache Strait and in Lalleman Fjord, respectively. The inner shelves around Anvers Island and in Marguerite Bay were ice-free at 7 - 6 Ky BP (Kennedy & Anderson 1989; Harden et al. 1992; Pope & Anderson 1992; Pudsey et al. 1994).

There is no conclusive evidence that ice retreat from the LGM positions and the subsequent deglaciation of the submarine shelves were controlled by regional warming. Hence, the ice retreat was probably controlled by the global sea level rise due to meltwater input from melting Northern Hemisphere glaciers (see Hollin 1962; Ingólfsson & Hjort 1999).

Deglaciation of the presently ice-free coastal areas

The deglaciation of the coastal areas is constrained by minimum ages obtained from ^{14}C dating of subfossil mollusc shells from raised marine deposits, penguin remains from coastal rookeries, peat deposits in moss banks on the islands off the Antarctic Peninsula and bulk-organics, microbial mats, aquatic mosses and algal flakes from lake sediments.

The oldest ^{14}C dates give a minimum age for initial deglaciation on King George Island at 9 - 8 Ky BP (Sugden & John 1973; Mäusbacher 1991). A stratigraphic record from northern James Ross Island dates deglaciation there to before 7.4 Ky BP (Hjort et al. 1997). In the southern part of the peninsula, ^{14}C dated shell fragments from ice shelf moraines at Two Step Cliffs on Alexander Island provide minimum ages for deglaciation and ice shelf retreat in George VI Sound of 6.5 - 5.7 Ky BP (Clapperton & Sugden 1982; Hjort et al. 2001). Data on initial penguin colonization of coastal rookeries in Marguerite Bay suggest ice-free conditions there by 6.5 - 5.5 Ky BP (Emslie 2001), which fits very well with the marine geological data cited above.

A number of studies, exploring lake sediment archives and moss bank peats, suggest that once the glaciers were inside the present coastline, glacial retreat and ice disintegration was slow (Barsch & Mäusbacher 1986; Mäusbacher et al. 1989; Ingólfsson et al. 1992; Björck et al. 1993; Björck et al. 1996a; Björck et al. 1996b; Hjort et al. 1997): on King George Island, glaciers were at or within their present limits by ca. 6 Ky BP (Martinez-Macchiavello et al. 1996), on northern James Ross Island prior to 4.7 Ky BP (Hjort et al. 1997), and parts of Byers Peninsula on Livingston Island deglaciated as late as 5 - 3 Ky BP (Björck et al. 1996b). Minimum date for deglaciation on Elephant Island is provided by the onset of moss bank formation on the steep slopes at Walker Point by 5.5 Ky BP (Björck et al. 1991).

The transition from glacial to interglacial conditions in the Antarctic Peninsula region was broadly completed by 6 Ky BP. By then, ice configuration was similar to or less than the present, penguins were occupying coastal rookeries along the peninsula, lake sediments had started to accumulate in ice-free basins and moss banks began to grow on islands off the peninsula.

Mid Holocene glacial readvances

There are indications from a number of sites of mid Holocene glacial expansions: Mäusbacher (1991) found evidence of increased glacial activity between 5 - 4 Ky BP on King George Island, confirming with Sugden & John (1973) who suggested glacial expansion there after 6 Ky BP. Hansom & Flint (1989) documented a glacial readvance on Brabant Island some time after 5.3 Ky BP, and the post 5.7 Ky BP expansion of the George VI Sound ice shelf is well documented (Clapperton & Sugden 1982; Hjort et al. 2001). A mid Holocene glacial readvance on northern James Ross Island (Rabassa 1983) culminated around 4.6 Ky BP (Hjort et al. 1997), and Zale (1994) described moraines in Hope Bay, at the northern tip of the Antarctic Peninsula, suggested to mark a glacial oscillation at 4.7 Ky BP. The cause of the glacial advances is not well understood (Ingólfsson et al. 1992).

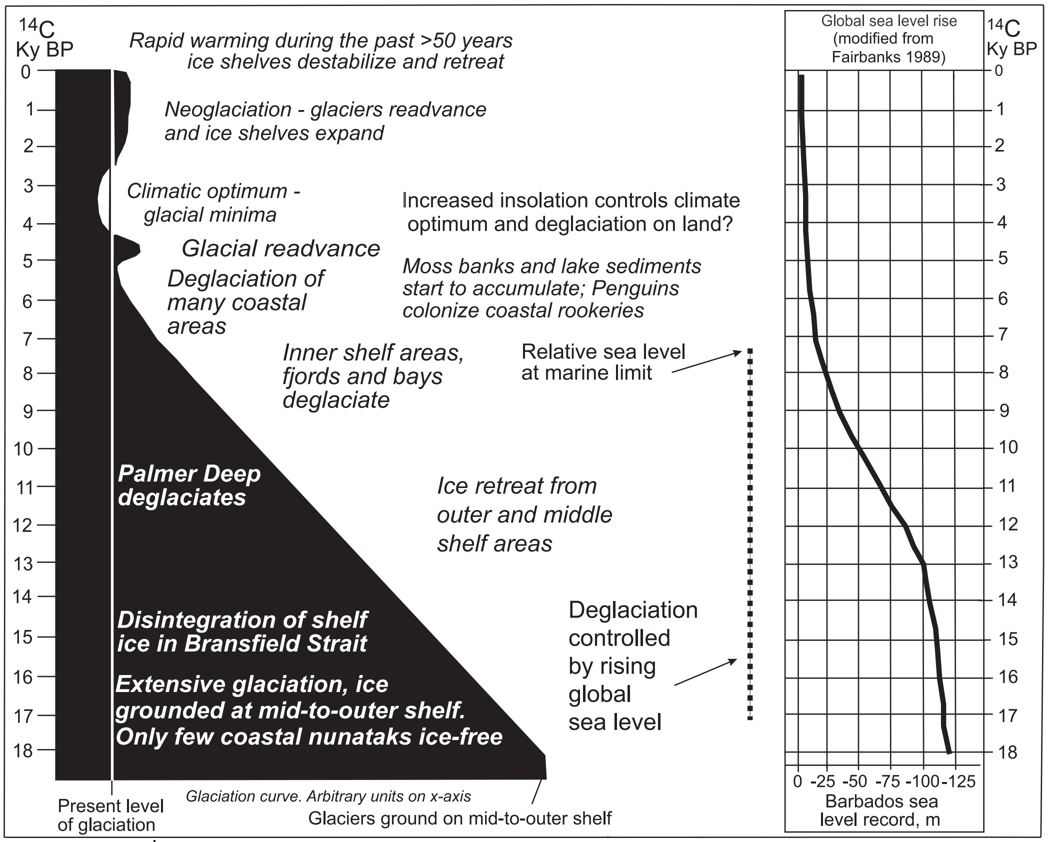

Fig. 2. Tentative syntheses of environmental changes in the Antarctic Peninsula since LGM.

The Holocene climatic optimum

Björck et al. (1996a) presented a palaeoclimatic synthesis for the Holocene development in the Antarctic Peninsula region, based on numerous variables in lake sediments and moss bank peats. They indicate that the climate conditions at ca. 5 Ky BP were relatively cold and arid. Around 4.2 Ky BP a warming set in, coupled with increasing humidity. These mild and humid conditions reached an optimum between 4 - 3 Ky BP, where after followed a distinct and rapid climatic deterioration. The best control of the climate optimum comes from a peat core from Walker Point on Elephant Island (Fig. 1), with its continuous and well-dated archive (Björck et al. 1991). The climatic optimum may have been driven by a late Holocene summer insolation maximum at Antarctic Peninsula latitudes (see Berger & Loutre 1991).

A marine record from Lallemand Fjord (Fig. 1) reveals a climatic pattern similar to the record on land (Domack et al. 1995; Shevenell et al. 1996; Taylor et al. 2001), with an earlier relatively warm period between ca. 7.5 - 5.8 Ky BP and a productivity optimum in the fjord between ca. 4.2 - 2.7 Ky BP. Domack et al. (2001a) defined a more prolonged Holocene climatic optimum in the Palmer Deep record, between ca. 8.2 - 3.1 Ky BP, characterized by enhanced biological productivity, sediment accumulation and minimum IRD concentrations.

After 3 Ky BP: climatic oscillations and increased ice volumes

The palaeoclimatic synthesis of Björck et al. (1996a) found that after ca. 3 Ky BP the climate became colder and drier, and this persisted until ca. 1.5 Ky BP. Thereafter, climate was somewhat warmer and more humid, but still cool compared to the situation during the climatic optimum.

A number of investigations suggest that glaciers have expanded somewhat in the Antarctic Peninsula region during the past ca. 3 Ky. Curl (1980), Birkenmajer (1981), Clapperton & Sugden (1988) and Björck et al. (1996b) found evidence for Neoglacial expansions in the South Shetland Islands, in the form of readvance moraines covering Holocene raised beaches. The marine record from Lallemand Fjord (Shevenell et al. 1996; Taylor et al. 2001) suggests decreased productivity in the fjord and more extensive and seasonally persistent sea ice after 2.7 Ky BP, and after ca. 0.4 Ky BP an ice shelf is documented in the fjord. Domack et al. (2001a) define a neoglacial cooling in the Palmer Deep record, starting at ca. 3.1 Ky BP and lasting until about 100 years ago. The neoglacial conditions are characterized by greater concentrations of IRD, decreasing sediment accumulation and decreasing biological productivity. Likewise, Barcena et al. (1998) found increase in sea ice taxa after 3 Ky BP among siliceous microfossils from the Bransfield Strait.

A distinct warming during the last 50 years

Air temperature records from the Antarctic Peninsula describe a dramatic warming trend for the past 50 years (King 1994; Stark 1994; Smith et al. 1996), and ecological transitions in response to this climate change have occurred (Fraser et al. 1992; Emslie 1995; Trivelpiece & Frasier 1996; Emslie et al. 1998; Smith et al. 1999). Some Antarctic Peninsula ice shelves have been retreating for the past century, with increasing speed since the late 1980s (Vaughan & Doake 1996; Cooper 1997; Skvarca et al. 1999). However, it has been pointed out that some of the ice shelves were not present earlier in the Holocene and that the recent collapses of the northern ice shelves may not be unprecedented (Domack et al. 2001b; Hjort et al. 2001; Pudsey & Evans 2001).

Summary and discussion

Our summary synthesis (Fig. 2) is only a tentative description of the environmental development. However, the following broad pattern can be recognized:

- There is evidence of much more extensive ice cover in the Antarctic Peninsula region than today prior to ca. 14 Ky BP.
- Deglaciation occurred mainly during the time period >14 - 6 Ky BP. Outer and middle shelf areas deglaciated between >14 - 8 Ky BP, and most inner shelf areas, fjords, bays and presently ice-free land areas were deglaciated prior to 6 Ky BP.
- Mid Holocene glacial and ice shelf readvances have been described from a number of sites.
- Terrestrial palaeoclimatic records suggest a climate optimum, with relatively warm and humid conditions, between ca. 4 - 3 Ky BP, but the marine archives suggest a broader period of relatively warm marine climate between ca. 8 - 3 Ky BP.
- Glaciers and ice shelves expanded again during the late Holocene, after ca. 3 Ky BP.
- Air temperature records show a distinct and rapid warming in the Antarctic Peninsula region during the past 50 years.

A detailed reconstruction of the glacial and climatic history of the Antarctic Peninsula region since the LGM is hampered by the scarcity of available archives, low resolution in many datasets and various chronological problems. To deal with the shortcomings, the following should be taken into consideration when developing future research strategies:

a) Offshore, the extent of ice on the shelf areas and timing of the last maximum glaciation is poorly constrained. Ice sheet thickness, location of domes and ice stream systems are not well known.

b) The chronology of deglaciation is constrained by relatively few absolute datings.

c) The relative sea level history is poorly constrained, and well-dated sea level curves are lacking.

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