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Glacial and marine geological evidence for the ice sheet configuration in the Weddell Sea–Antarctic Peninsula region during the Last Glacial Maximum

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Abstract: The Weddell Sea region arguably represents the largest unknown in quantifying the Antarctic contribution to the global water balance following the Last Glacial Maximum (LGM). This paper reviews the available onshore and offshore geological evidence constraining the volume of formerly expanded ice in the Weddell Sea embayment, focusing on the West Antarctic Ice Sheet (WAIS) and provides a preliminary reconstruction of the WAIS during the LGM. Dating control is generally poor and so our WAIS reconstruction is based on the assumption that the evidence of most recent ice sheet expansion dates to the LGM. Our reconstruction is intended to provide initial constraints with which glaciological models can be compared and shows grounded ice extent, flow directions, and ice surface elevations. Both marine and terrestrial geological evidence imply a substantial expansion of ice in the Weddell Sea embayment. Marine evidence shows that ice sheets were grounded in Crary Trough in the southern Weddell Sea and on the Antarctic Peninsula continental shelf during the LGM. Inland, the ice thickened by between 400 m (Ellsworth and Palmer Land) and 1900 m (Ellsworth Mountains). Ice core evidence suggests that the interior of the ice sheet remained the same or even thinned relative to present. The main unknowns now concern the exact location of the grounding line on some sectors of the shelf and the timing of ice sheet grounding and retreat. The limited radiocarbon data that exist on the eastern shelf indicates that the East Antarctic Ice Sheet retreated from the shelf prior to the LGM.

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Introduction

The Weddell Sea receives glacial drainage from the East Antarctic Ice Sheet (EAIS) in the east, the West Antarctic Ice Sheet (WAIS) in the south, and ice caps in the Antarctic Peninsula region in the west. Thus, it provides a natural laboratory in which to investigate the history of these different glacial systems. This review aims to identify the current state of knowledge on the Last Glacial Maximum (LGM) configuration of ice in and adjacent to the Weddell Sea embayment. We combine here onshore and offshore evidence for the extent and timing of ice expansion in the embayment.

It is generally believed that the two main components of the Antarctic ice sheet behaved differently during the last glacial maximum. Glacial geological data imply that the EAIS and some outlet glaciers thickened along its coastal fringe, while ice core data show that the interior of the EAIS remained at a similar elevation during the LGM to the present. In contrast, the WAIS is believed to have expanded significantly into the Ross Sea embayment, and grounded ice abutted against the eastern flank of the Transantarctic Mountains in Victoria Land, during the LGM (Denton *et al.* 1991, Anderson *et al.* 1992, Licht *et al.* 1994, Domack *et al.* in press, Shipp *et al.* in press).

The main areas of Antarctic ice volume change were apparently restricted to the coastal areas, particularly where there were wide continental shelves across which grounded ice could expand. The Weddell Sea embayment is important to reconstructions of Antarctic ice extent because, along with the Ross Sea, it potentially represents an area of substantial ice volume change on the continent.

Determining the past behaviour of the WAIS and EAIS in the Weddell Sea potentially has two important implications. First, a substantial grounded ice sheet in the embayment would contribute a significant amount to global sea-level fall at the LGM and to the subsequent sea-level rise. Second, differences and similarities between the WAIS, EAIS and the ice caps of the Antarctic Peninsula region could inform debate on the response of these ice masses to changes in forcing, such as atmospheric temperatures and sea level. Much of the latter debate is based on glaciological modeling studies, which at present remain poorly constrained in the Weddell Sea embayment.

Onshore evidence for the extent of the ice sheet

There are two main sources of onshore glacial geological evidence indicating the extent of a formerly grounded ice sheet in the Weddell Sea. These are features marking the altitudinal extent of the former ice sheet surface such as erosional trimlines and moraines, and former flow direction indicators such as striations and roches moutonnées. At present, the evidence for formerly more extensive grounded ice in the Weddell Sea has only been detailed from three main areas: southern Palmer Land (Antarctic Peninsula), the Ellsworth Mountains, and the Shackleton Range (Fig. 1). In addition, gas content analysis of the ice core taken at Byrd Station (80°S, 120°W) has yielded information on the altitude of the interior portion of the WAIS (Raynaud & Whillans 1982). Figure 2 shows our reconstruction for the ice sheets during the LGM.

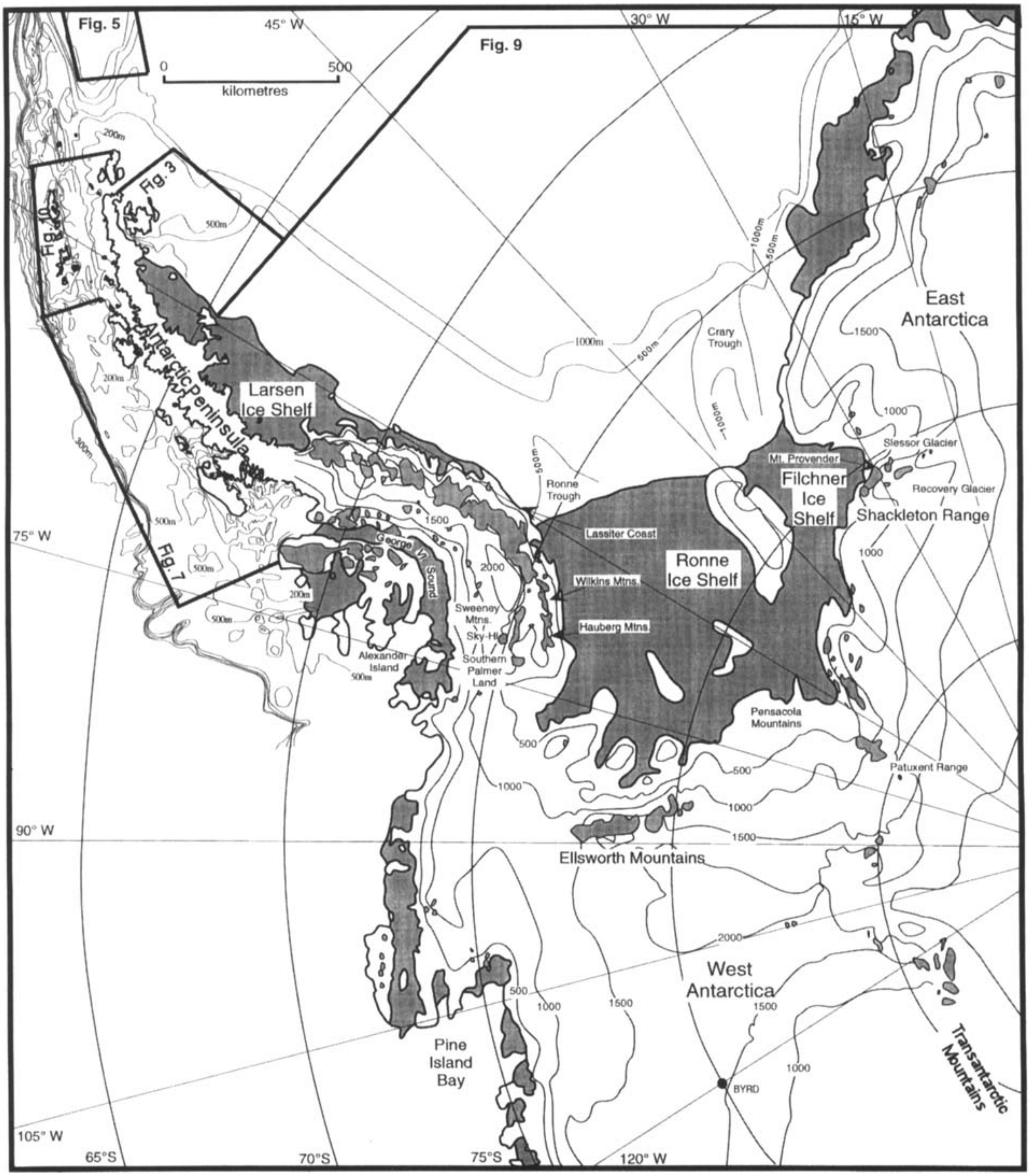

Fig. 1. Present-day configuration of the Weddell Sea embayment. Contours are shown at 500 m intervals.

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Southern Palmer Land

Carrara (1979, 1981) carried out reconnaissance mapping of striation orientations on the nunataks of the Orville Coast in southernmost Palmer Land. This included the nunataks forming the Hauberg, Behrendt, Wilkins and Sweeney mountains. The presence of striations on every summit visited showed that the entire area had been completely inundated by an expanded ice sheet. Thus, in this area it is

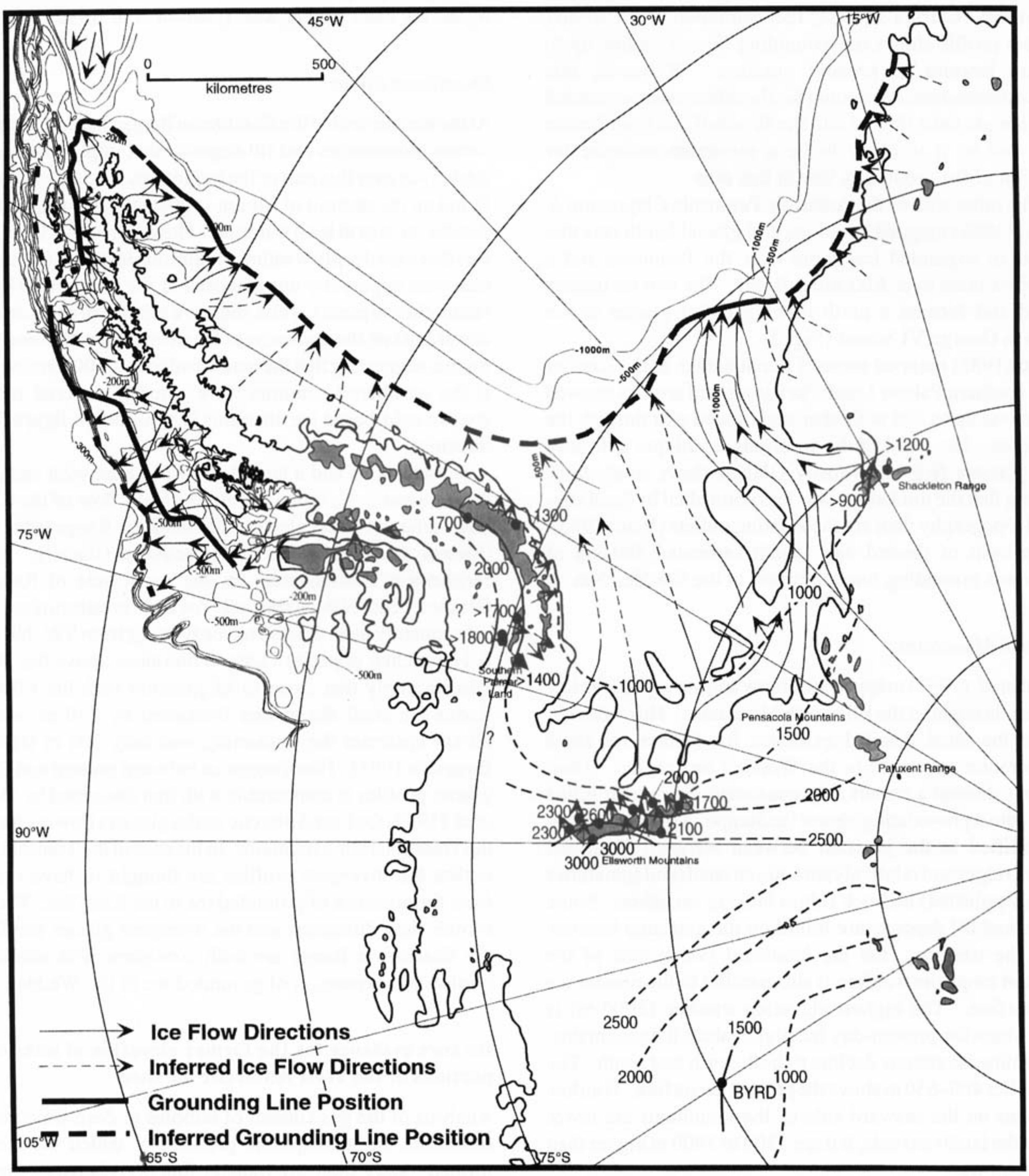

Fig. 2. Preliminary reconstruction of the Weddell Sea embayment and Antarctic Peninsula region during the LGM. Dots show sites where ice sheet elevations have been constrained by trimlines or over-ridden summits (minimum values). Arrows show flow direction indicators. Contours for the former ice sheet are drawn perpendicular to the flow directions and their altitudes are fixed by the trimlines. Solid lines indicate relatively confidently reconstructed contours and flow directions, whereas dashed contours are interpolated and are not well constrained. The elevation of the ice in the interior of West Antarctica is not well-constrained by our reconstruction.

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only possible to give minimum figures for former ice sheet elevation. For example, the presence of striations on the summit of Sky-Hi nunataks (75°S, 72°W, 1768 m altitude) shows that the ice sheet thickened to at least this elevation during a previous expansion. Striations showed that the ice flowed to the south or south-east into the Weddell Sea embayment. Carrara's (1981) reconstruction of the former ice sheet profile shows the grounding line extending up to 300 km beyond its present position. However, this reconstruction does not account for the effect of any grounded ice that might have flowed into the Weddell Sea from further south, and so it is likely to be a minimum estimate for migration of the grounding line in this area.

On the other side of the Antarctic Peninsula Clapperton & Sugden (1982) mapped striations and glacial landforms that showed an expanded ice dome over the Peninsula and a smaller ice mass over Alexander Island. The two ice masses merged and formed a north-flowing outlet glacier or ice stream in George VI Sound (Fig. 2).

Waitt (1983) mapped some of the nunataks in the Lassiter Coast, southern Palmer Land. Striations and erratics showed that ice was up to 500 m thicker and flowed east through the mountains. The trend of the striations is oblique to nearby outlet glaciers (e.g. the Mosby Glacier flows south-east), implying that the thicker ice was less controlled by local sub-glacial topography than are the existing outlets (Waitt 1983). On the basis of limited data, Waitt estimated 800 km of northwards grounding line migration in the Weddell Sea.

Ellsworth Mountains

Denton *et al.* (1992) mapped striations and surveyed trimline altitudes throughout the Ellsworth Mountains. This work has yielded the most detailed evidence for former ice sheet configuration anywhere in the Weddell Sea region. Their mapping showed a remarkably consistent ice sheet trimline etched into a pre-existing alpine landscape. The trimline can be identified as the junction between serrated, pinnacled bedrock ridges and relatively smooth, striated (and sometimes glacially polished) bedrock ridges lacking serrations. Some erratics and till deposits are found on the glaciated bedrock below the trimline. On the landward (west) side of the mountain range the trimline is sub-parallel to the present ice sheet surface. The highest elevation trimline (3000 m) is above where the present-day ice divide abuts the mountains, and trimline elevations decline to both north and south. The trimline lies 400–650 m above the present ice surface. Trimline elevations on the seaward side of the mountains are lower than on the landward side, but are 1300 to 1900 m higher than the present ice.

The regional striation pattern suggests ice flow across the mountain range (Denton *et al.* 1992). Eastward-directed striations cut across several cols, high ridges and summits, implying an expanded WAIS flowed around and through the range (Fig. 2). There are some sites which have been interpreted as recording expansion of Ellsworth alpine glaciers, but away from the cirques the pattern of these striations is consistent with the alpine glaciation merging with the expanded ice sheet. For example, close to Mount Hubley on the landward side of the mountains there is evidence of westward-flowing cirque glaciers which were deflected to a N–S trend by the ice sheet farther west (Denton *et al.* 1992).

Shackleton Range

At the western end of the Shackleton Range there are striations, roches moutonnées and till deposits that imply substantially thicker ice over this part of the mountains. Fresh striations are found on the summit of Mount Provender (900 m), implying that the ice was at least this thick. However, only 20 km to the east there are deeply weathered summits up to 1200 m altitude that were apparently not glaciated at the same time (Kerr & Hermichen in press). Thus, there are minimum and maximum constraints on the thickness of ice over the western end of the Range, suggesting that the ice extended to *c.* 1000 m elevation. If the weathered summits were actually covered by non-erosive cold-based ice, then this is a minimum figure for ice thickness.

The striations and a lateral moraine at the west end of the Range trend S–N, cross-cutting the E–W flow of the current East Antarctic outlet glaciers that flank the Range to the north (Slessor Glacier) and south (Recovery Glacier). In the Stephenson Bastion area, on the north side of Recovery Glacier, SE–NW oriented roches moutonnées have subsequently been striated by ice flowing from SW–NE (Kerr & Hermichen in press). Lateral moraines above the Slessor Glacier imply that close to its junction with the Filchner–Ronne ice shelf the glacier thickened by 350 m, whereas 20 km upstream the thickening was only 200 m (Höfle & Buggisch 1993). The divergence between present and former glacier profiles is comparable with that described by Denton *et al.* (1989) for East Antarctic outlet glaciers flowing through the Transantarctic Mountains. In the case of the Transantarctic outlets the divergent profiles are thought to have resulted from the presence of grounded ice in the Ross Sea. The S–N former flow directions and the divergent glacier profiles in the Shackleton Range are both consistent with substantial northwards expansion of grounded ice in the Weddell Sea.

Ice core evidence for the former elevation of interior portions of the West Antarctic ice sheet

Analysis of the gas content of bubbles in deep ice cores can determine the atmospheric pressure at which the ice was formed. Since there are transfer functions between present-day atmospheric pressure and elevation in the interior of Antarctica (Raynaud & Lebel 1979), it has been possible to suggest a record of past ice sheet elevation changes at drill sites such as Vostok and Byrd Station. These show that at the LGM the ice sheet surface was a few hundred metres lower

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than its current altitude (Jouzel *et al.* 1989). For example, the change in elevation at Byrd Station, West Antarctica has been estimated as a lowering of 200–250 m (Raynaud & Whillans 1982). One drawback of the gas content record is that it is not yet clear how much of the changes are attributable to changes in atmospheric pressure, rather than elevation change (Paterson & Hammer 1987). For example, an intensification of the high pressure cell over Antarctica during a glacial maximum would have a similar effect on gas bubbles as a lowering of the ice sheet elevation. The atmospheric shifts required to produce the gas bubble changes are relatively large and it is unlikely that all of the gas bubble record can be accounted for by this mechanism. However, the possibility of atmospheric shifts means that the elevation changes should probably be regarded as maximum estimates for interior ice sheet thinning.

Timing of ice sheet expansion

At present, there is an acute lack of published radiometric dates available from coastal areas to constrain the timing of ice sheet expansion in the Weddell Sea and Antarctic Peninsula region. This is largely a result of the paucity of organic and carbonate material around the embayment. This contrasts with the Ross Sea embayment where ice flowed onshore and dammed proglacial lakes in the Dry Valleys whose shorelines can be dated using algal remains (Denton *et al.* 1989). Moreover, along the Scott Coast and in Victoria Land there are numerous raised beaches and penguin colonies that have been dated to provide minimum ages for deglaciation, whereas around the Weddell Sea the coast is fringed by ice shelves which prevent the formation of raised beaches. In addition to the lack of radiometric dates, the age of trimlines around the region is ambiguous. This is related largely to the difficulties associated with relative weathering studies: non-uniform climate and lithology mean that correlating the degree of weathering at widely-spaced sites can be problematic.

Studies on James Ross Island, in the north-western Weddell Sea, indicate that deglaciation onshore occurred prior to 7400 yr BP (Hjort *et al.* 1997). Two radiocarbon dates from the Weddell embayment are on algal remains from lacustrine palaeoshorelines eroded into moraines on Mount Gass in the Shackleton Range. The moraines were deposited during the most recent expansion of ice and the dates show that the site was deglaciated some time prior to 4630 ± 150 yr BP (Höfle & Buggisch 1993).

Höfle & Buggisch (1993) dated a meteorite that lay at an altitude of 1540 m, 350 m above the surface of Recovery Glacier, an East Antarctic outlet glacier flowing along the southern margin of the Shackleton Range. They argued that the nature of the meteorite along with its intact state suggested that the meteorite must be *in situ* and so the ^{10}Be date of 415 ka they obtained implied that Recovery Glacier has not thickened by more than 350 m during the coldest parts of the Quaternary.

Denton *et al.* (1992) proposed two alternative models for the glaciation of the Ellsworth Mountains. These models suggest that the glaciation was either Late Wisconsin, i.e. LGM in age, or that it was pre-Late Quaternary. The LGM age is supported by weathering and soil development on the patches of 'Ellsworth drift'. These drift deposits below the trimline in the Ellsworth Mountains have similar weathering characteristics to Ross Sea and Britannia drifts in the Ross embayment (Denton *et al.* 1992). The Ross Sea drift has been radiometrically dated to the end of the last glaciation and the Britannia drift has been correlated with this. The penultimate drifts in the Ross Sea are substantially more weathered than the Ross Sea, Britannia, or Ellsworth drifts, implying that on the basis of weathering and soil development the Ellsworth drift dates to the last glaciation. However, Denton *et al.* (1992) pointed out that this correlation was based on the untested assumption that soil development in the Ellsworth Mountains is age-dependent in the same way as at sites thousands of kilometres away. The LGM age is also supported by the relative freshness of striations. However, relatively fresh striations which clearly predate the last glaciation have been found in the Transantarctic Mountains, and so striation appearance cannot be regarded as a firm indicator of age (Denton *et al.* 1992).

The Pre-Late Quaternary age model is based on the observation that in order to carve such a substantial trimline throughout the Ellsworth Mountains it would be necessary to have warm-based ice close to the trimline. The altitude of the trimline means it would have been in the accumulation zone of the ice sheet. The erosion would require significant summer melting in the accumulation area of the WAIS. This would imply significantly higher summer temperatures than present, which seems inconsistent with a Late Wisconsin age (Denton *et al.* 1992). Elsewhere in Antarctica the maximum glaciation trimline is higher than, and pre-dates, the Wisconsin glaciation (Mercer 1968, Denton *et al.* 1986). This provides circumstantial evidence that the Ellsworth Mountains trimline may be older than the last glaciation. Denton *et al.* (1992) favoured the LGM age model but emphasized that it was untested and that it still required an explanation of how the trimline was carved during the colder temperatures of the LGM.

On the west side of the Antarctic Peninsula, Clapperton & Sugden (1982) suggested from radiocarbon dates on shells in till that the most recent major ice expansion occurred some time after 30 000 yr BP. Dates on barnacles in an ice shelf moraine indicated that George VI Sound had been entirely deglaciated by *c.* 6500 yr BP and that the ice shelf only reformed subsequently (Clapperton & Sugden 1982). This is an important result because it is the only onshore area in the Weddell Sea–Antarctic Peninsula region where it has been demonstrated that the most recent major ice expansion occurred in the Late Wisconsin. If this result can be extrapolated to Palmer Land and the Ellsworth Mountains, then it would suggest that the Late Wisconsin age model is the more likely.

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Marine record of glaciation

In this section we report on the results of marine geological investigations in the Weddell Sea-Antarctic Peninsula region. For more detailed information about various types of tills and glacial-marine deposits, seismic facies and geomorphological features used to interpret the sea floor record of ice sheet expansion and retreat, the reader is referred to Anderson (in press).

North-western Weddell Sea

During cruise DF82 of the USCGC *Glacier*, high-resolution seismic data and 46 piston cores were acquired from the continental shelf offshore of Seymour Island and in Prince Gustav Channel and adjoining bays (Fig. 3), in order to study the glacial history of this region. The cores and seismic data were the subject of a detailed study by Smith (1985) and later Anderson *et al.* (1991). Sedimentological analyses led to the conclusion that none of the cores penetrated tills. However, a number of cores from the continental shelf penetrated diamictons that were interpreted as transitional glacial-marine sediments, indicating deposition in close proximity to the grounding line of an expanded ice sheet (Anderson *et al.* 1980, 1991). Petrographical analyses of the transitional glacial-marine sediments showed strong provinciality, indicating that these diamictons could also be deformation till.

This area was revisited in 1991 and a detailed high resolution seismic survey conducted (Anderson *et al.* 1992). The new survey showed a widespread erosional surface that extends to the shelf break (Fig. 4). This unconformity occurs at or near the sea floor on the outer shelf. Maps of this surface show several large glacial troughs (Sloan *et al.* 1995; Fig. 3). A prominent grounding zone wedge occurs above the unconformity on the outer shelf (Fig. 4). High-resolution seismic records and cores from Prince Gustav Channel and adjoining bays show that these areas have been virtually scraped clean of sediment, except for a thin layer of diatomaceous mud that locally drapes acoustic basement.

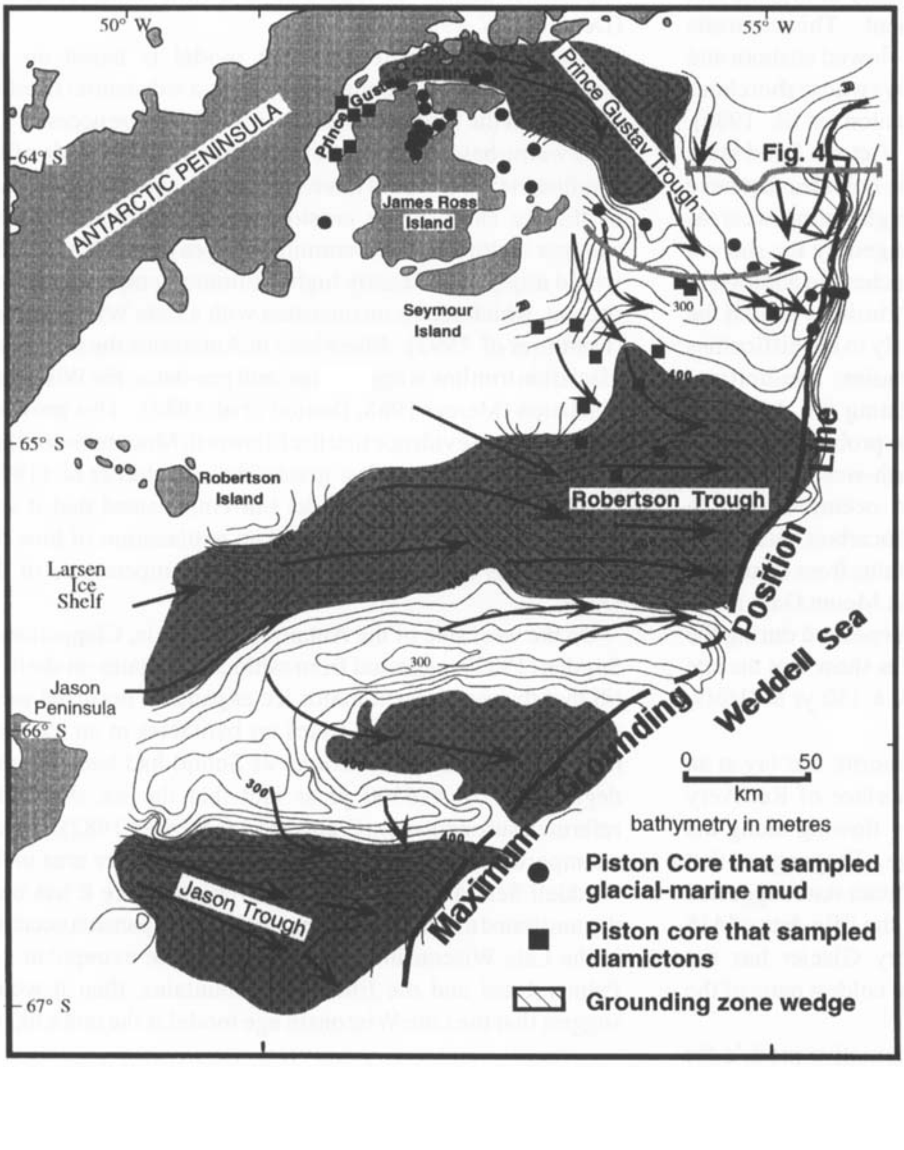

Fig. 3. Preliminary LGM reconstruction for the north-western Weddell Sea. Shaded areas are glacial troughs and arrows indicate ice flow directions based on shelf geomorphology. Also shown are the locations of piston cores and the seismic profile shown in Fig. 4.

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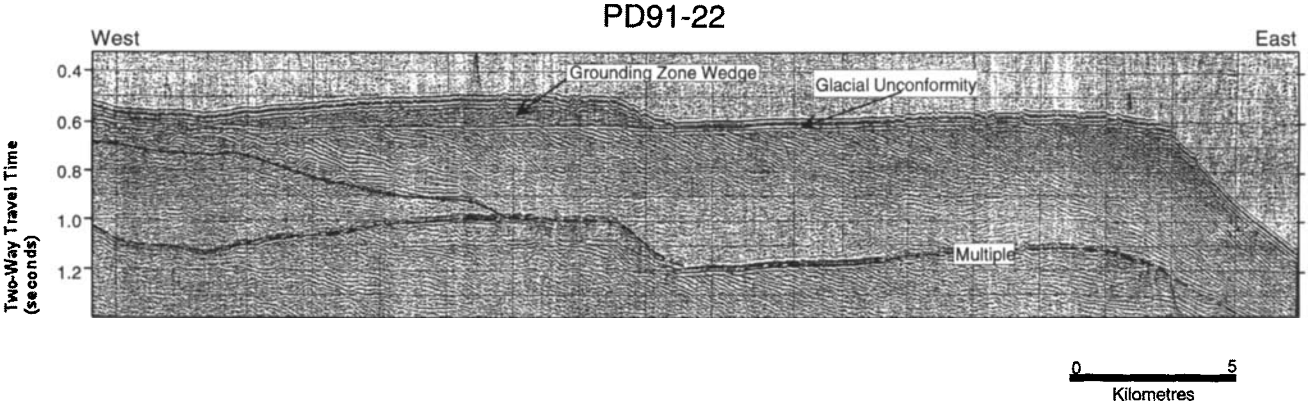

Fig. 4. Seismic profile PD91-22 across the north-western Weddell Sea continental shelf showing glacial unconformity that extends to the shelf break and grounding zone wedge resting above this unconformity. See Fig. 3 for profile location.

These combined data provide striking evidence that the ice sheet was grounded on the continental shelf in the recent past. Ongoing work focuses on obtaining radiocarbon ages from glacial-marine deposits in this area. To date, sea ice has prevented the collection of marine geological data on the shelf south of 67°S.

During 1985, piston cores and high resolution seismic records were acquired from the South Orkney Islands plateau by the USCGC *Glacier* (Herron & Anderson 1990). Several troughs occur offshore of the islands and indicate locations of major outlet glaciers (Fig. 5; Sugden & Clapperton 1977). A single seismic profile across the western side of the plateau imaged a prominent glacial unconformity that extends to approximately 300 m water depth, or the outer edge of the plateau (Herron & Anderson 1990). Piston cores from the plateau penetrated till overlain sharply by diatomaceous glacial marine sediments (Fig. 5). Radiocarbon analyses of articulated pelecypods found within diatomaceous glacial marine sediment in Core DF85-22 (Fig. 5) indicate that the ice cap retreated from the inner portion of the plateau prior to 6000 to 7000 yr BP (Herron & Anderson 1990).

Antarctic Peninsula region

It is reasonable to assume that the ice that grounded in the western Weddell Sea flowed from the Antarctic Peninsula region and was also grounded on the continental shelf west of the Peninsula. Thus, a brief review of the results of marine geological studies in this region is relevant to the topic of Weddell Sea glacial history.

During the Deep Freeze 85 and 86 expeditions, high resolution seismic data and 47 piston cores were collected from *Marguerite Bay* (Kennedy & Anderson 1987; Fig. 6). The seismic data revealed a prominent glacial erosion surface extending across the entire bay; the sediment above this surface is quite thin and the bay floor is characterized by hummocky relief (Anderson in press). The largest glacial trough is Marguerite trough, which extends from the bay to the shelf break (Fig. 7). Tills were sampled within Marguerite trough (Kennedy & Anderson 1989). Radiocarbon dates from a glacial-marine unit in two piston cores (PC 111 and

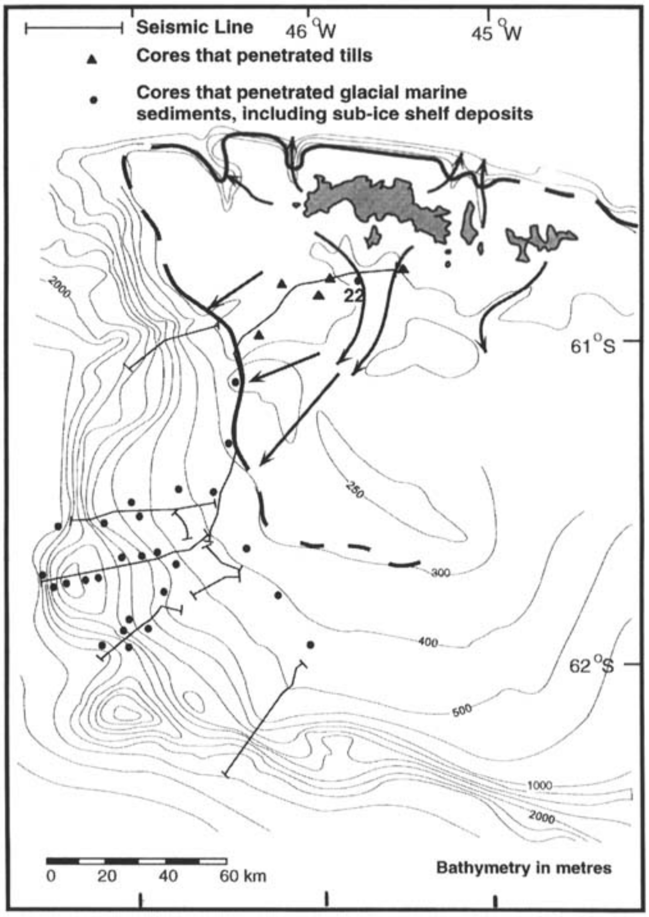

Fig. 5. Preliminary LGM reconstruction for the South Orkney Islands plateau. Arrows indicate inferred ice flow directions based on shelf bathymetry. The locations of seismic profiles and cores are also shown. Heavy line marks maximum grounding line position.

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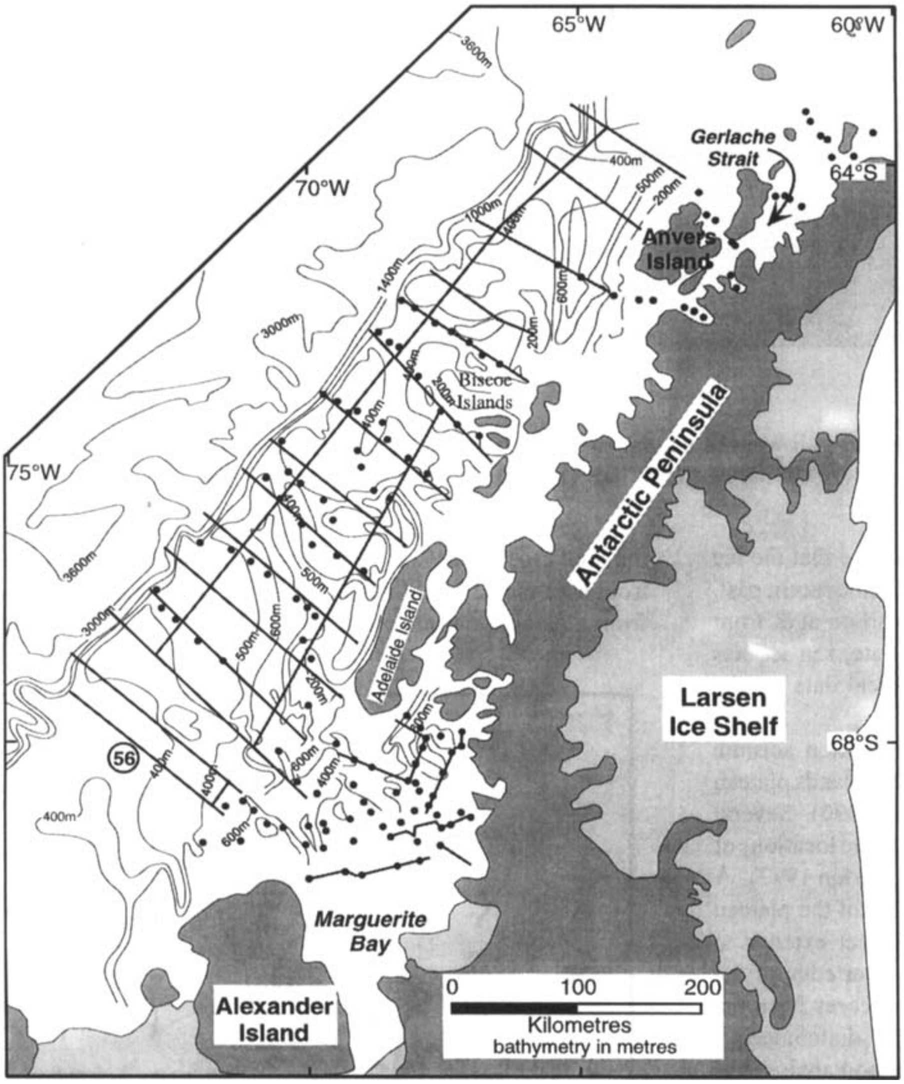

Fig. 6. Locations of seismic profiles and cores used to study the glacial geology of Marguerite Bay and the Antarctic Peninsula continental shelf.

112) yielded surface values in the range of 4100 ± 150 yr BP to 4260 ± 160 yr BP (Harden *et al.* 1992), indicating the presence of significant old carbon in these cores. The corrected dates for the oldest glacial-marine sediments resting above the tills are in the order of 6000 to 6700 yr BP, so the ice sheet had retreated from the central part of Marguerite Bay by this time. This agrees with the results of Clapperton & Sugden (1982) who suggested that George VI Sound was ice-free by 6500 yr BP.

Results of examinations of high-resolution seismic data, sidescan sonar records, bottom profiler records, and piston cores from the *Antarctic Peninsula shelf* (Fig. 6) have yielded strong evidence that an ice cap was grounded on the continental shelf during the LGM, but somewhat controversial results concerning the exact extent of grounded ice on the shelf (Pope & Anderson 1992, Pudsey *et al.* 1994). Pope & Anderson (1992) concluded that the LGM grounding line was situated on the inner shelf and that a fringing ice shelf extended across portions of the middle shelf. They based this on two lines of evidence. First, ridges within troughs, interpreted to be megaflutes, exhibit greater relief on the inner shelf and are partially draped by glacial-marine sediment on the outer shelf. Second, only two cores from the outer shelf, both within Biscoe Trough, penetrated tills. All other cores (60 in total) sampled glacial-marine sediment, up to 3 m thick in several cores (Fig. 6). Several cores did penetrate transitional glacial-marine deposits. Two cores from the inner shelf recovered tills, but most attempts at coring the inner shelf were unsuccessful due to the virtual absence of sediment cover.

Pudsey *et al.* (1994) examined sidescan sonar records and four sediment cores from a portion of the continental shelf offshore of Anvers Island. Their sidescan sonar records show glacial flutes, thus providing indisputable evidence of ice sheet grounding on the inner shelf. They reasoned that the grounding line of the ice sheet was situated at the shelf-break during the LGM, and Larter & Vanneste (1995) later showed a grounding zone on the outer shelf in this region. Bart & Anderson (1996) examined an extensive data set from the

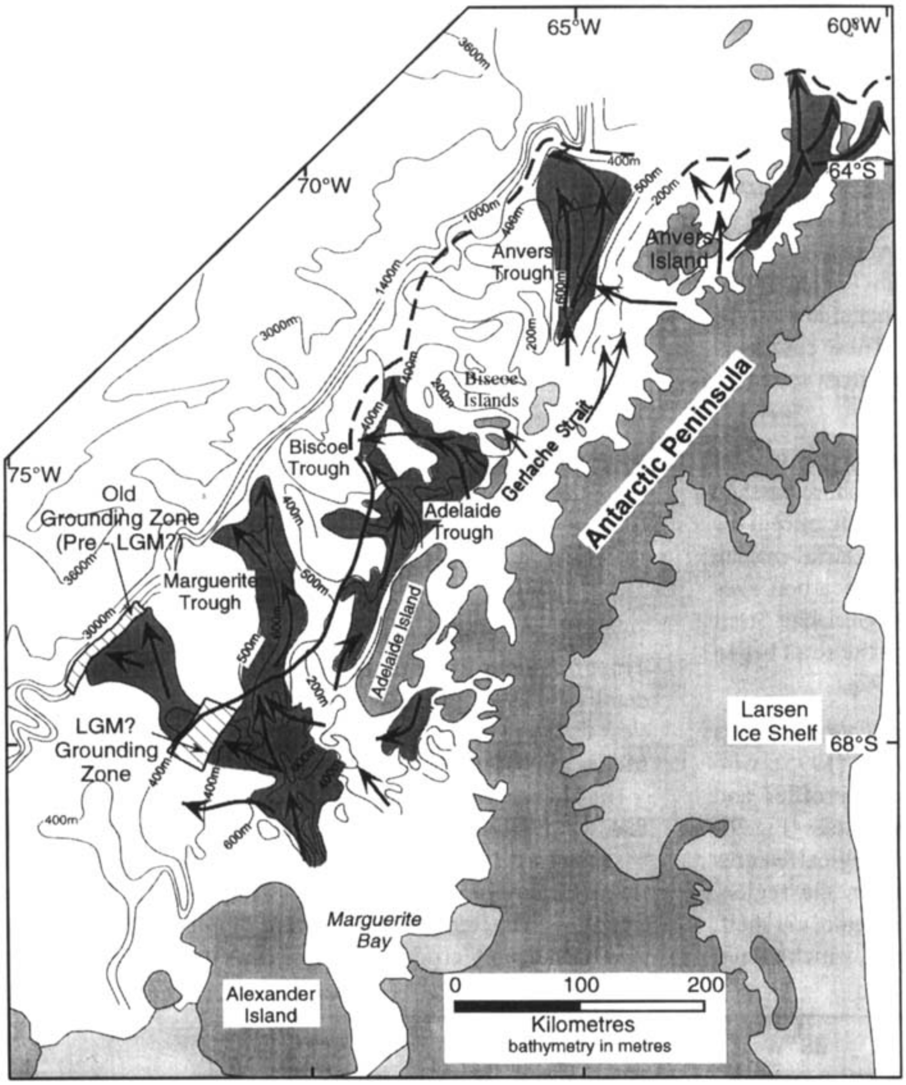

Fig. 7. Preliminary LGM glacial reconstruction for Marguerite Bay and the northern Antarctic Peninsula continental shelf. Shaded areas are glacial troughs and arrows indicate palaeoflow directions based on shelf geomorphology.

continental shelf extending from Marguerite Bay to Bransfield Strait (Fig. 6). These data were used to map glacial troughs on the shelf (Fig. 7) and to map a prominent glacial unconformity extending to the shelf-break (Fig. 8). The inner shelf has been scraped virtually clean of its sediment cover. Two prominent grounding zone wedges, one on the outer shelf and another on the mid-shelf, occur within the western branch of Marguerite Trough (Figs 7 & 8). The mid-shelf

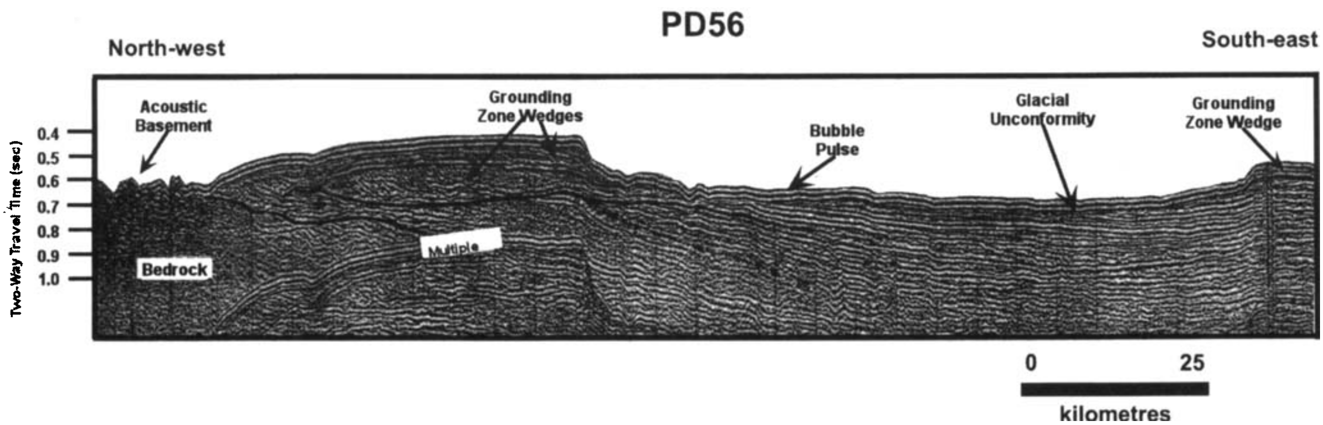

Fig. 8. Seismic profile PD56 showing glacial unconformity and grounding zone wedges on the Antarctic Peninsula continental shelf. Note that the inner shelf has been stripped of sediment cover.

grounding zone wedges rest on a glacial unconformity that extends to the shelf break (Fig. 8). Thus, a more recent mid-shelf grounding line is indicated by these data.

Radiocarbon dates from glacial-marine sediment above the grounding zone proximal facies (transitional glacial-marine sediments) in two cores (PC 99 and PC 76) yielded corrected ages of 11 481 to 12 430 ± 140 yr BP and 10 317 to 11 335 ± 110 yr BP respectively (Pope & Anderson 1992). Pudsey *et al.* (1994) also measured dates younger than 11 000 yr BP on glacial marine sediment overlying diamicton on the continental shelf offshore of Anvers Island. These combined data indicate that the ice sheet had retreated from the mid–outer shelf by 12 430 yr BP.

As in Marguerite Bay, high-resolution seismic records from *Gerlache Strait* show that this portion of the inshore passage has also been scraped virtually clean of sediment, except for a thin layer of post-glacial diatomaceous glacial-marine sediment (Griffith & Anderson 1989). Radiocarbon ages from a core collected in the central part of Gerlache Strait indicate that glacial marine sedimentation in the strait began sometime after 8000 yr BP (Harden *et al.* 1992).

The late Quaternary glacial history of *Bransfield Strait* was the subject of study by Banfield & Anderson (1995), who examined high-resolution seismic reflection profiles and cores acquired from the basin during several cruises (Fig. 9). These data were used to map major geomorphological features and the distribution of sedimentary facies in the region. Several glacial troughs dissect the Antarctic Peninsula shelf, including Orleans Trough and Crocker Trough, which extend from Gerlache Strait (Fig. 10). A widespread glacial unconformity extends to the continental shelf break. It is a sea floor unconformity on the inner shelf, where acoustic basement is exposed, and is buried beneath several tens of metres of glacial-marine sediment on the outer shelf (Fig. 11). Prominent morainal ridges occur within troughs in a mid-shelf location (Fig. 11). These ridges are situated above the glacial unconformity. Radiocarbon dates from glacial-marine deposits in core DF 82-48, using both bulk organic carbon and foraminiferal tests, indicate that the ice sheet had retreated from the outer continental shelf by 13 000 to 14 000 yr BP (Banfield & Anderson 1995).

Southern Weddell Sea

Two prominent subglacial features, Crary Trough and Ronne Trough, exist on the southern Weddell Sea continental shelf (Fig. 12). These features are extensions of a much larger subglacial depression, known as Thiel Trough (Behrendt 1962), that virtually encircles the southern shelf. Crary Trough extends to the outer shelf and has a maximum water depth of nearly 1200 m, whereas Ronne Trough is shallower (less than 600 m) and confined to the inner shelf (Fütterer & Melles 1990, Steve Ackley, personal communication 1998).

High-resolution seismic records across Crary Trough show that the eastern flank of the trough consists of acoustic basement with an unconformity that occurs at or near the sea floor (Elverhoi & Maisey 1983). The western flank of the trough is characterized by westward dipping strata that have also been deeply eroded. Lower-resolution seismic records

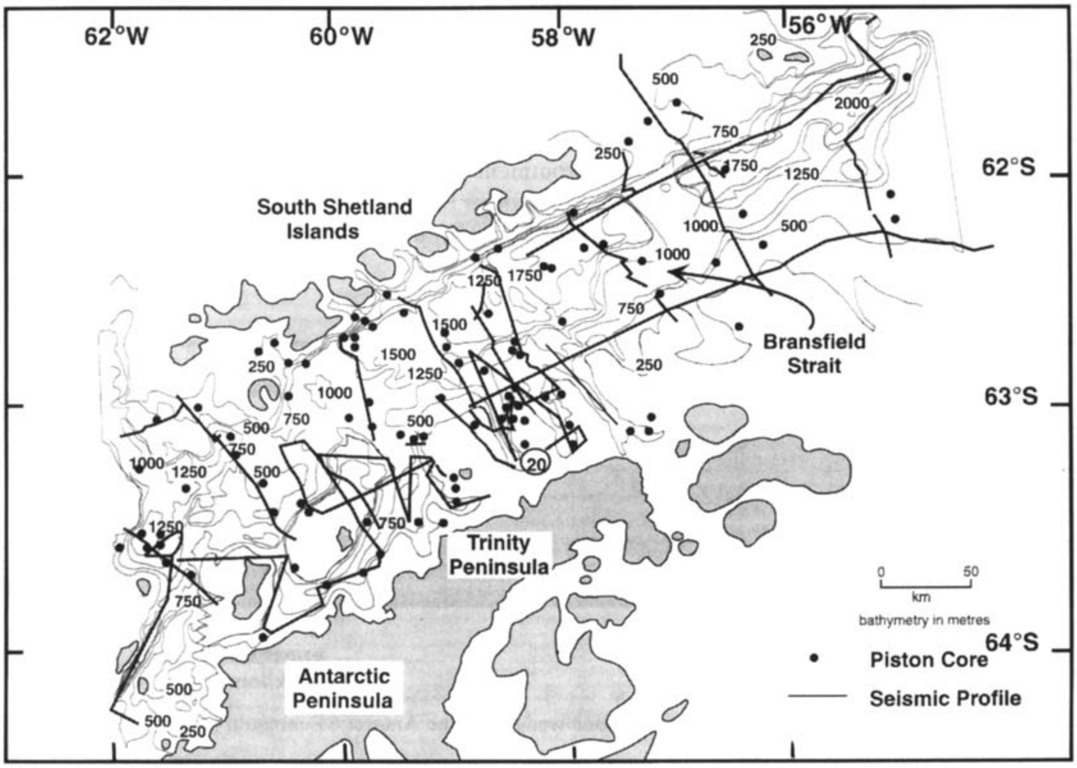

Fig. 9. Locations of seismic profiles and cores used to study the glacial history of Bransfield Strait.

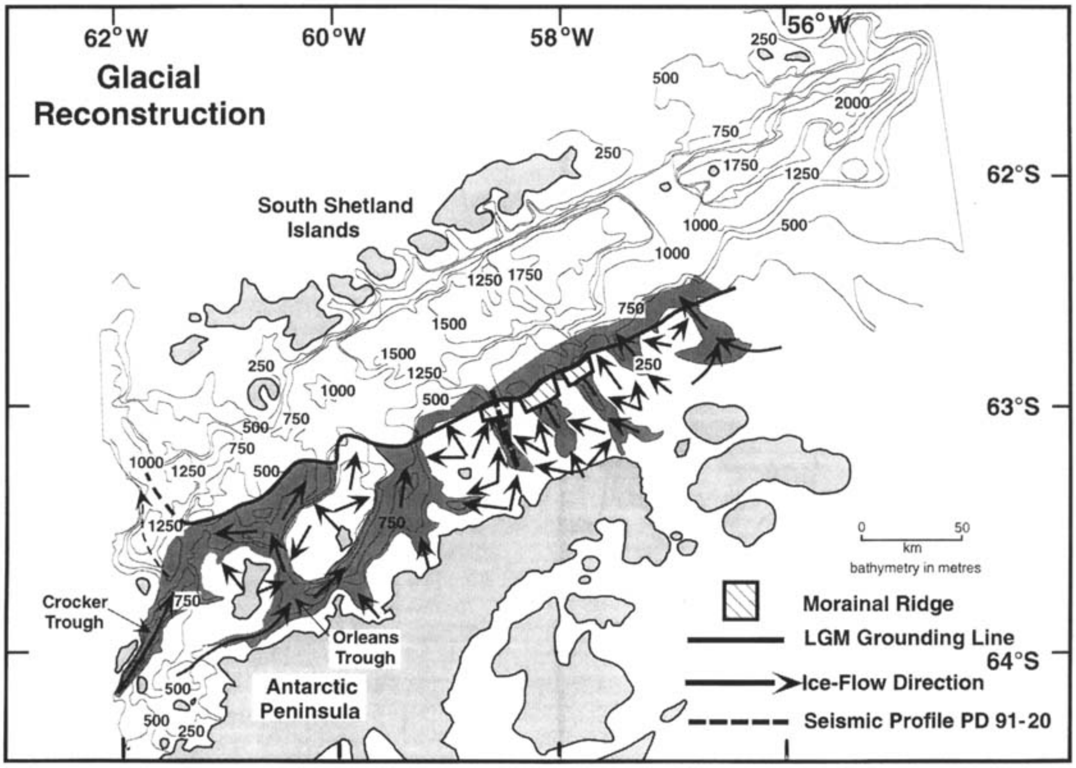

Fig. 10. Preliminary LGM reconstruction for Bransfield Strait. Shaded areas are glacial troughs and arrows indicate palaeoflow directions based on shelf geomorphology.

from the southern continental shelf (west of Crary Trough) have failed to image definitive subglacial features, such as grounding zone wedges (Fechner & Jokat 1995). However, the stratigraphical resolution of these data may be too low to image such features.

The deposits excavated from Crary Trough now reside on the continental slope, rise and basin floor as a large fan, Crary Fan (Fig. 12). Detailed seismic stratigraphical analysis of the fan has led to the interpretation that it originated in the Miocene (Moons *et al.* 1992), but the most recent erosional event in Crary Trough has not been determined, although cores from the slope offshore of the trough have sampled debris flows near the sea floor (Kurtz & Anderson 1979) and high resolution seismic records from this region indicate that the fan has been active in the recent past (Melles & Kuhn 1993).

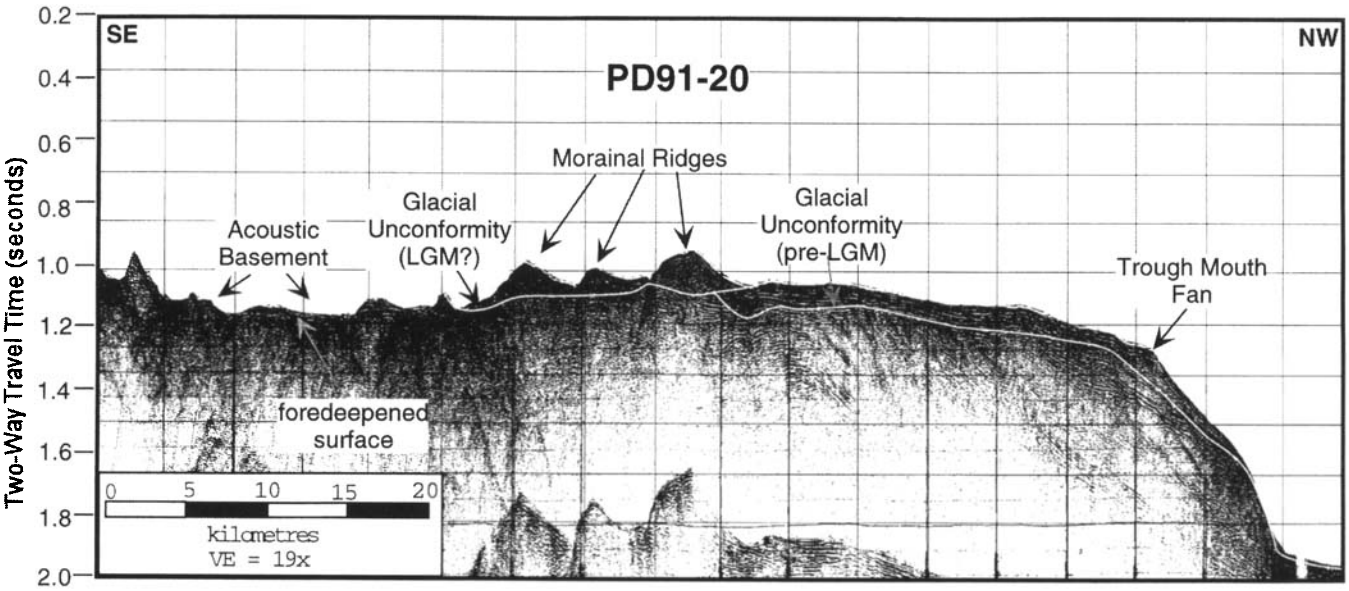

Fig. 11. Seismic profile PD91-20 from Bransfield Strait showing the glacial unconformity and morainal ridges on the shelf. Location in Fig. 10.

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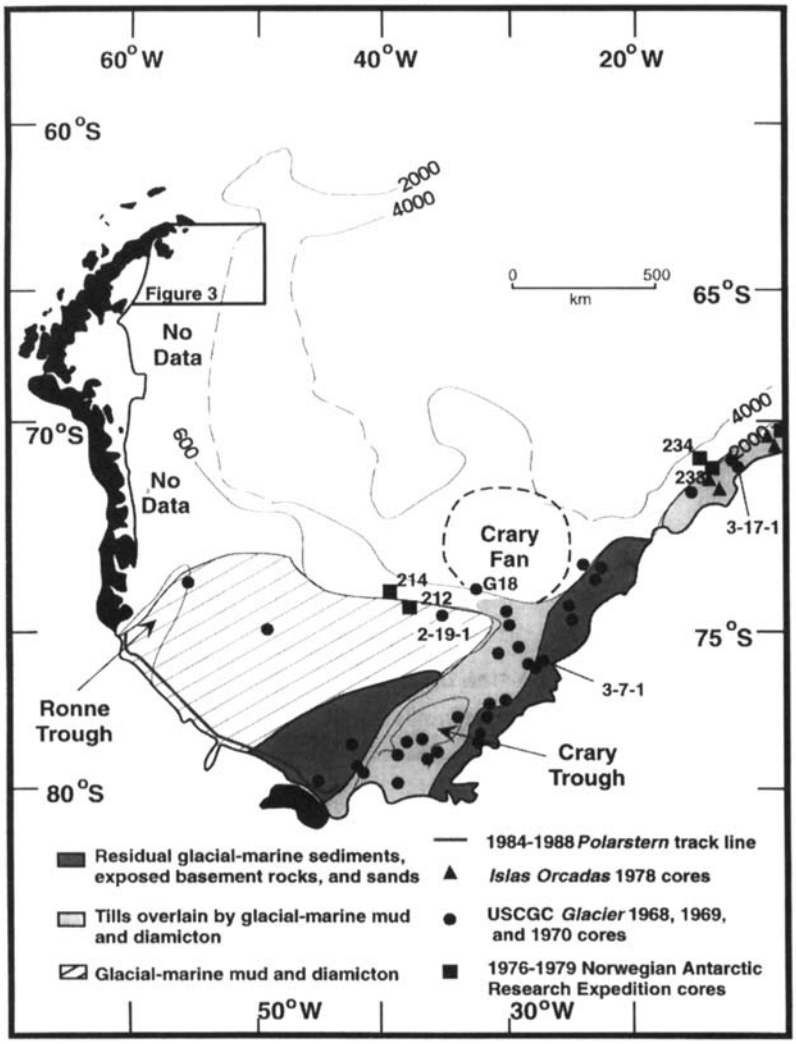

Fig. 12. Distribution of glacial marine sediments and tills in the Weddell Sea. Also shown are the sites of cores referred to in the text. The outline of Crary Fan includes only the area which is believed to have been active during the late Pleistocene, based on high-resolution seismic data (Melles & Kuhn 1993) and cores (Kurtz & Anderson 1979).

Cores from Crary Trough sampled less than 1.2 m of glacial marine mud resting sharply on stiff diamicton. The diamicton is mostly barren of fossils, whereas the glacial marine mud contains a low diversity assemblage of arenaceous benthic foraminifera (Anderson 1972b). Detailed analyses of diamictons by Anderson *et al.* (1980) led to the interpretation that they are tills. The tills extend to the outer portion of the trough (Fig. 12). Petrographical analysis of these tills showed mainly West Antarctic affinities (Anderson *et al.* 1991).

West of Crary Trough, the continental shelf is covered by residual glacial-marine sediments and by well sorted, unconsolidated quartz sands, including aeolian sands (Rex *et al.* 1970, Anderson 1971, Haase 1986, Fütterer & Melles 1990). One core sampled nearly 3 m of aeolian sand, so the sands appear to be in place, although some downslope movement of sand into the western portion of Crary Trough has occurred (Anderson 1971). The origin of these sands remains a mystery, but they imply an extreme interglacial setting at some point in the recent past. Unfortunately, no calcareous material for radiocarbon dating has been recovered from these sands.

Haase (1986) and Fütterer & Melles (1990) described a series of short sediment cores and 3.5 kHz sub-bottom profiles acquired by FS *Polarstern* along the front of the Ronne Ice Shelf. Their data show a thin layer of glacial-marine sediment resting on a hummocky, acoustically opaque surface. Cores from Ronne Trough recovered diamictons, interpreted as glacial-marine deposits (Haase 1986). Only two cores have been acquired from the middle shelf and both sampled glacial-marine mud resting in sharp contact on diamicton of uncertain origin (Anderson *et al.* 1980). Given the paucity of long cores and high resolution seismic data from the region, the glacial setting of the continental shelf west of Crary Trough, where ice flowing from the WAIS would have been grounded, remains problematic.

Attempts to obtain sufficient material for radiocarbon dating of glacial marine sediments that overlie tills in Crary Trough were unsuccessful. Thus, all that can be said is that these tills and the glacial unconformity they overlie are situated near the sea floor, which suggests a relatively recent grounding event. Sediment core G18 was collected directly down slope of Crary Trough in the apex of Crary Fan (Fig. 12). It sampled

1.88 m of glacial marine mud, with an *in situ* benthic foraminiferal assemblage, resting on diamicton with displaced foraminifera and interpreted as a debris flow deposit (Kurtz & Anderson 1979). An uncorrected radiocarbon date of 11 840 ± 200 yr BP was acquired at a depth of 1.0 m within the glacial marine mud unit, suggesting that mass movement on the slope, perhaps related to excavation of Crary Trough, took place prior to this time.

The longest sediment core from the western shelf (west of Crary Trough) is Deep Freeze 70 Core 2-19-1 (Fig. 12). This core sampled 4.65 m of glacial-marine diamicton (Anderson *et al.* 1980). Unfortunately, two radiocarbon dates from this core showed an inverted stratigraphy of 16 190 yr BP at 0.3 m and 11 270 yr BP at 3.5 m depth in the core. The older age near the top of the core is probably due to iceberg reworking.

The only other radiocarbon ages from the western shelf were obtained by Elverhoi (1981) on two short cores (212 and 214) from the shelf break and upper slope (Fig. 12). Core 212 was collected at 512 m water depth and sampled a glacial marine mud which yielded an age (uncorrected) of 31 290 (+1880/-1520) yr BP. Elverhoi's lithologic log of this core shows evidence of disturbance, again probably related to iceberg reworking. Core 214 was collected from the upper slope in 730 m of water and recovered 3 m of glacial-marine sediment with *in situ* bivalve shells at 1.75 m depth in the core. These shells yielded a radiocarbon age of >35 100 yr BP. This portion of the slope is subject to scour by strong contour currents (Anderson *et al.* 1979) and the samples analysed by Elverhoi were taken below a sandy lag deposit that is widespread on the upper slope (Anderson in press). In summary, attempts to date the glacial-marine sediments of the western continental shelf have met with poor success, so the age of tills in Crary Trough remains problematic.

Eastern Weddell Sea

There is a paucity of high resolution seismic data from the eastern continental shelf. Seismic records that do exist show a glacial unconformity situated just below the sea floor, which extends to the shelf break, and a possible mid-shelf grounding zone wedge (Elverhoi & Maisey 1983, Miller *et al.* 1990).

Sediment cores were collected on the eastern continental shelf during 1969 and 1970 cruises to the region by the USCGC *Glacier* (Anderson 1972a, 1972b) and during Islas Orcadas Cruise 1578 (Fig. 12). Residual glacial-marine sediments (sands and gravels) up to 5.2 m thick blanket the relatively shallow eastern shelf, south of approximately 72°S (Fig. 12). These glacial-marine sediments contain abundant marine fossils, and stratification and grain size data indicate that they were deposited under the influence of strong marine currents (Anderson *et al.* 1980). Cores from the outer shelf recovered till overlain by glacial-marine sediments.

Sediment cores collected on the eastern shelf, north of approximately 72°S, recovered diamictons with a thin surface unit of pebbly mud. The diamictons in two cores from this sector of the shelf contain a low diversity benthic foraminiferal assemblage and exhibit sedimentological properties indicative of deposition near the grounding line of the ice sheet (Anderson *et al.* 1990). The longest core recovered in these glacial-marine diamictons, Core 3-17-1 (Fig. 12), was 5.5 m long. Two other cores sampled tills beneath the glacial-marine unit. Petrographic analysis of the tills showed an East Antarctic origin (Anderson *et al.* 1991).

Elverhoi (1981), obtained uncorrected ages of 21 240 ± 760 to 37 830 ± 3110 yr BP from glacial marine sediments in core 234, taken at 650 m water depth on the upper slope off Queen Maud Land (Fig. 12). Radiocarbon (AMS-uncorrected) ages for two cores from the eastern Weddell Sea continental shelf, cores 3-17-1 and 3-7-1 collected at 418 and 235 m water depth respectively, were acquired as part of this study (Fig. 12). Samples from 2.05 and 4.0 m depth in a transitional glacial-marine unit in core 3-17-1 yielded ages of 14 940 and 23 870 yr BP, respectively. Core 3-7-1 was collected on the southeastern shelf and recovered 5.3 m of residual glacial-marine sediment with abundant *in situ* benthic foraminifera. Samples from 200 and 400 cm depth in core 3-7-1 yielded ages in the range of 13 640 ± 130 to 26 660 ± 490 yr BP, respectively. The implication of the combined radiocarbon ages from the eastern continental shelf is that the EAIS retreated from the shelf prior to the LGM.

Discussion

A preliminary field-based reconstruction of LGM ice sheet expansion in the Weddell Sea region is shown in Fig. 2. This reconstruction is based on three key assumptions. First, it makes the untested assumption that the expansion of the WAIS into the Weddell Sea embayment described above was synchronous, and dates to the LGM. Second, it assumes that regional ice contours can be drawn perpendicular to flow indicators, implying that the local flow indicators represent regional flow. In most cases this seems reasonable since the striations on several nunataks in a region are oriented sub-parallel to one another. The third assumption is that erosional trimlines represent the upper surface of the ice sheet rather than a boundary between warm- and cold-based ice below an overriding ice sheet (in which case trimline elevations would only give a minimum figure for ice thickness). Using these assumptions, the reconstruction has been drawn with the orientation and elevation of contours fixed by trimline elevations and flow directions.

The pattern of trimlines and flow indicators is remarkably consistent in showing a substantially expanded ice mass in the Weddell Sea and on the Antarctic Peninsula shelf (Fig. 2). Reconstructed ice sheet elevations in all three mapped areas around the embayment are close to, or greater than, 1000 m at the present-day grounding-line. In southern Palmer Land, flow directions were broadly similar to today, showing a radial flow away from the axis of the Peninsula, but the major Peninsula ice dome was significantly higher than present and

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its axis may have been shifted to the west. The Ellsworth Mountains were inundated by a much thicker ice sheet, flowing roughly parallel to present-day flow directions. However, in the Shackleton Range the western end of the mountains were over-run by ice with an elevation of 1000 m, derived from the south and perpendicular to dominant present-day glacier flow.

The ice sheet elevations in the interior of West Antarctica are not so clear. The increase in ice sheet thickness abutting the landward side of the Ellsworth Mountains might suggest that the interior West Antarctic ice dome thickened. However, the gas content analysis from Byrd Station implies that the ice sheet remained at the same altitude or was even lower at this site during the LGM. It is difficult to envisage how the ice dome could thicken and the Weddell and Ross Sea embayments fill with ice (see Denton *et al.* 1989) without an increase in the elevation of the Byrd site. There are at least two possible explanations for this. First, the gas content data may not accurately reflect ice surface elevation changes during the LGM. Second, the Ellsworth Mountains trimline may not be LGM in age and thus the thickening of the West Antarctic ice dome could have occurred prior to the LGM. Testing these alternatives requires that the trimline be dated.

Marine geological studies have documented that ice sheets were grounded on the continental shelf all around the Weddell Embayment, on the shelf on the opposite side of the Antarctic Peninsula between Marguerite Bay and Bransfield Strait, and on the South Orkney Plateau. But the available radiocarbon ages suggest that the WAIS and EAIS may have experienced their maximum extent at different times.

Data are scarce from the eastern Weddell Sea, but there is evidence that an ice sheet was grounded on the shelf during the recent past. The available radiocarbon dates from eastern Weddell Sea indicate that the EAIS had retreated from the shelf by about 26 000 to 28 000 yr BP.

Crary Trough provides the only compelling evidence for a much expanded WAIS on the Weddell Sea continental shelf. The ice sheet that was grounded in Crary Trough must have been in excess of 1200 m thick, which is consistent with ice sheet elevations onshore in the Shackleton Range. However, there is very little radiometric control on the timing of this ice sheet expansion. We do know that the WAIS was grounded on the Ross Sea continental shelf during the LGM (Denton *et al.* 1991, Licht *et al.* 1996, Domack *et al.* in press, Shipp *et al.* in press), and it seems reasonable to infer that tills in Crary Trough record this expansion. The WAIS retreated from the Ross Sea continental shelf during the early-mid Holocene, but there is some evidence that the EAIS may have retreated earlier (Licht *et al.* 1996, Domack *et al.* in press, Shipp *et al.* in press), including bioclastic carbonates that occur on the outer shelf and yield pre-LGM ages (Taviani *et al.* 1993). Thus, both the Ross Sea and the Weddell Sea marine geological data sets show evidence for diachronous advance and retreat of the WAIS and EAIS into these regions.

Marine geological data from the Antarctic Peninsula continental shelf provide compelling evidence for ice caps having been grounded there during the LGM. The ice caps retreated from the continental shelf in the northern Antarctic Peninsula region by approximately 14 000 to 11 000 yr BP and from the Gerlache Strait and Marguerite Bay between 8 000 and 6 000 yr BP.

We do not intend the reconstruction shown in Fig. 2 to be regarded as a firm reconstruction, but rather an initial best estimate to stimulate debate and to identify the biggest weaknesses in the onshore and offshore glacial geological evidence. For this reason, we have distinguished clearly between those areas constrained by data where we believe it is possible to reconstruct ice sheet contours with some confidence, and those areas where the contours are speculative and based on what is glaciologically reasonable. Because of the uncertainties in our field-based reconstruction, it is not intended as a rigid configuration with which to validate glaciological models. However, it does provide a useful initial comparison, particularly in the areas of southern Palmer Land, the Ellsworth Mountains, and the Shackleton Range. If our assumption that the expansion in these areas was synchronous and LGM in age is valid, then we believe that the reconstructions in the latter two areas do provide confident constraints against which the models can be tested, whilst the reconstruction in southern Palmer Land provides a confident minimum estimate of ice sheet expansion.

Comparison to glaciological models

It is useful to compare our field-based reconstruction to numerically-derived reconstructions of the WAIS. An LGM simulation using the glaciological model of Huybrechts (1992) reproduced the expanded ice in the Ross embayment and provides a reasonable match to our reconstruction of an expansion of grounded ice in the Weddell embayment (Fig. 2). The model simulates the expanded southern Palmer Land ice dome, and suggests that it may have reached over 2000 m elevation. The model also simulates a change to a more northerly ice flow direction in the Shackleton Range. The grounding line position in the model is similar to the position inferred here from field evidence (Fig. 2). However, there are a number of interesting differences between the numerical model and the field evidence. The altitude at the present grounding line in Huybrecht's (1992) simulation is greater than the *c.* 1000 m recorded by the onshore field evidence. Also, the southerly flow directions in the Orville Coast area are not reproduced; in the model the area is inundated by ice from the south. The Ellsworth Mountains form a relatively narrow range and the steepening of contours seen in the field-based reconstruction is not reproduced by the model, which shows a smoother, shallower ice sheet surface in this area. This latter difference between field evidence and model may be attributable to the horizontal resolution (40 km grid) of the model, which is comparable to the width of the mountains. Interestingly, when compared to the ice core data, Huybrechts'

(1992) model reproduces the lower East Antarctic elevations well but suggests thicker West Antarctic ice at Byrd station. This highlights the critical role of the gas content analysis at Byrd for constraining reconstructions of the WAIS. Huybrechts (1992) suggested a total Antarctic contribution to LGM sea level change of 8–12 m. This estimate is lower than most previous studies but our field-derived reconstruction appears to support Huybrechts (1992) modelled West Antarctic contribution to this change.

The westward shift of the axis of the southern Peninsula ice dome matches the model simulations of Payne *et al.* (1989), which showed a similar effect, although less pronounced than that shown in Fig. 2. The radial flow away from this dome shown by the field evidence in southern Palmer Land and George VI Sound is supported by the model.

Conclusions and further work

Our main conclusion from this review is that there was a significantly expanded WAIS in the Weddell Sea embayment during the LGM. Ice caps were also grounded on the Antarctic Peninsula continental shelf and on the South Orkney Islands plateau. The maximum extent of these ice masses remains problematic, but ice was grounded to at least the middle shelf on the Antarctic Peninsula region. The WAIS appears to have extended to the outer shelf within Crary Trough, but its extent on the southwestern Weddell Sea shelf is unknown. The EAIS does not appear to have been grounded on the eastern Weddell Sea continental shelf during the LGM, hence the EAIS and WAIS do not appear to have advanced and retreated in phase with one another.

We can reconstruct the former WAIS if we assume that the evidence of its expansion around the embayment is synchronous. Our reconstruction shows a northward expansion onto the continental shelf and substantially thicker ice in the embayment (Fig. 2). Ice sheet elevations at the present-day grounding line (< 200 m altitude) were close to 1000 m.

It is useful here to summarize the main gaps and weaknesses in the understanding of the former extent of ice in the Weddell Sea embayment. Onshore, there is a striking lack of dates for former glaciation of the embayment. The ice sheet configuration in the interior of West Antarctica is still unclear because there is a disparity between trimline elevations and ice core evidence. The advent of cosmogenic surface exposure dating gives the opportunity to date striated surfaces and erratic boulders around the embayment, and this would provide an initial test of the age models for former ice expansion in the embayment.

There are also a number of geographical gaps in the onshore data. Although only a few mountainous areas exist around the embayment, some of these have still not been mapped from a glacial geological perspective. Evidence from the Pensacola Mountains, Patuxent Range and the Theron Mountains would all improve the accuracy of our reconstruction in the south-east of the embayment. Unfortunately, there are no good sites that allow the reconstruction between the Ellsworth Mountains and southern Palmer Land to be constrained and so this must remain speculative. The glacial reconstruction of southern Palmer Land can currently only provide a minimum constraint because the ice dome there apparently covered all of the nunataks. If the former ice dome had a similar form to the present day ice dome in southern Palmer Land, then it would have declined in altitude to the north. Therefore, mapping to the north, in the mountains of the east coast, might yield a better constrained ice sheet surface than the minimum estimates farther south. It might also be possible to reconstruct the former profiles of some Peninsula outlet glaciers – thus providing firmer constraints on the altitude of grounded ice in the embayment to the east.

The area of greatest uncertainty in the offshore setting is the south-western Weddell Sea, due to a paucity of marine geological data from this part of the continental shelf. As with the onshore data, more dating control is required to develop a glacial chronology for the offshore record in all parts of the Weddell Sea embayment.

It is still not possible to determine accurately the contribution of ice sheets within the Weddell embayment region to the global sea level rise of the past 18 000 years, but we believe that the field evidence matches well the modelled contribution of the WAIS described by Huybrechts (1992). The timing of ice sheet retreat is even more problematic, but existing evidence suggests that the region could have contributed to the overall sea level rise well into the Holocene.

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References

Anderson, J.B. 1971. Marine origin of sands in the Weddell Sea. *Antarctic Journal of the United States*, 6(5), 261-269.

Anderson, J.B. 1972a. *The marine geology of the Weddell Sea.* Ph.D. thesis, Florida State University, 222 pp.[Unpublished.]

Anderson, J.B. 1972b. Nearshore glacial-marine deposition from modern sediments of the Weddell Sea. *Nature*, **240**, 189-192.

Anderson, J.B. in press. *Antarctic marine geology.* Cambridge: Cambridge University Press.

Anderson, J.B., Kurtz, D.D. & Weaver, F.M. 1979. Sedimentation on the Antarctic continental slope. *In* Doyle, L.J. & Pilkey, O., *eds. Geology of continental slopes. Society of Economic Paleontologists and Mineralogists Special Publication.* No. 27, 265-283.

ANDERSON, J.B., KURTZ, D.D., DOMACK, E.W. & BALSHAW, K.M. 1980. Glacial and glacial marine sediments of the Antarctic continental shelf. *Journal of Geology*, **88**, 399-414.

ANDERSON, J.B., ANDREWS, B.A., BARTEK, L.R. & TRUSWELL, E.M. 1991. Petrology and palynology of glacial sediments: implications for subglacial geology of the eastern Weddell Sea, Antarctica. *In* THOMSON, M.R.A., CRAME, J.A. & THOMSON, J.W., *eds*., Geological evolution of Antarctica. Cambridge: Cambridge University Press, 231-235.

ANDERSON, J.B., SHIPP, S.S. & SIRINGAN, F.P. 1992. Preliminary seismic stratigraphy of the northwestern Weddell Sea continental shelf. *In* YOSHIDA, Y., KAMINUMA, K. & SHIRAISHI, K., *eds*. Recent progress in Antarctic earth sciences. Tokyo: Terra Scientific Publishing Company, 603-612.

BANFIELD, L.A. & ANDERSON, J.B. 1995. Seismic facies investigation of the late Quaternary glacial history of Bransfield Basin, Antarctica. *Antarctic Research Series*, **68**, 123-140.

BART, P.J. & ANDERSON, J.B. 1996. Seismic expression of depositional sequences associated with expansion and contraction of ice sheets on the northwestern Antarctic Peninsula continental shelf. *In* DE BATIST, M. & JACOBS, P., *eds. Geology of siliciclastic seas. Geological Society Special Publication*, No. 117, 171-186.

BEHRENDT, J.C. 1962. Geophysical and glaciological studies in the Filchner ice shelf area of Antarctica. *Journal of Geophysical Research*, **68**, 5973-5990.

CARRARA, P. 1979. Former extent of glacial ice in Orville Coast region, Antarctic Peninsula. *Antarctic Journal of the United States*, **14**(5), 45-46.

CARRARA, P. 1981. Evidence for a former large ice sheet in the Orville Coast-Ronne Ice Shelf area, Antarctica. *Journal of Glaciology*, **27**, 487-491.

CLAPPERTON, C.M. & SUGDEN, D.E. 1982. Late Quaternary glacial history of George VI Sound area, West Antarctica. *Quaternary Research*, **18**, 243-267.

DENTON, G.H., ANDERSEN, B.G. & CONWAY, H.B. 1986. Late Quaternary surface ice level fluctuations of the Beardmore Glacier, Antarctica. *Antarctic Journal of the United States*, **21**(5), 90-92.

DENTON, G.H., BOCKHEIM, J.G., WILSON, S.C. & STUIVER, M. 1989. Late Wisconsin and Early Holocene Glacial History, Inner Ross Sea embayment, Antarctica. *Quaternary Research*, **31**, 151-182.

DENTON, G.H., PRENTICE, M.L. & BURCKLE, L.H. 1991. Cainozoic history of the Antarctic Ice Sheet. *In* TINGEY, R.J., *ed. The geology of Antarctica*. Oxford: Clarendon Press, 365-433.

DENTON, G.H., BOCKHEIM, J.G., RUTFORD, R.H. & ANDERSEN, B.G. 1992. Glacial history of the Ellsworth Mountains, West Antarctica. *Geological Society of America Memoir*, **170**, 403-432.

DOMACK, E.W., JACOBSON, E.A., SHIPP, S.S. & ANDERSON, J.B. in press. Sedimentologic and stratigraphic signature of the late Pleistocene/ Holocene fluctuations of the West Antarctic Ice Sheet in the Ross Sea: a new perspective part 2. *Geological Society of America Bulletin*.

ELVERHOI, A. 1981. Evidence for a late Wisconsin glaciation of the Weddell Sea. *Nature*, **293**, 641-642.

ELVERHOI, A. & MAISEY, G. 1983. Glacial erosion and morphology of the eastern and southeastern Weddell Sea shelf. *In* OLIVER, R.L., JAMES, P.R. & JAGO, J.B., *eds. Antarctic earth science*. Cambridge: Cambridge University Press, 483-487.

FECHNER, N. & JOKAT, W. 1995. A seismic transect across the Ronne shelf. *Seventh International Symposium on Antarctic Earth Sciences*, 10-15 September, Siena, Italy, 12. [Abstract].

FÜTTERER, D.K. & MELLES, M. 1990. Sediment patterns in the southern Weddell Sea, Filchner Shelf and Filchner Depression. *In* BLEIL, U. & THIEDE, J., *eds*. Geological history of the polar oceans: Arctic versus Antarctic. Amsterdam: Kluwer Academic Publishers, 381-401.

GRIFFITH, T.W. & ANDERSON, J.B. 1989. Climatic control of sedimentation in bays and fjords of the northern Antarctic Peninsula. *Marine Geology*, **85**, 181-204.

GROBE, H. & MACKENSEN, A. 1992. Late Quaternary climatic cycles as recorded in sediments from the Antarctic continental margin. *Antarctic Research Series*, **56**, 349-376.

HAASE, G.M. 1986. Glaciomarine sediments along the Filchner/ Ronne Ice Shelf, southeastern Weddell Sea – first results of the 1983/84 Antarktis-II/4 Expedition. *Marine Geology*, **72**, 241-258.

HARDEN, S.L., DEMASTER, D.J. & NITTROUER, C.A. 1992. Developing sediment geochronologies for high-latitude continental shelf deposits: a radiochemical approach. *Marine Geology*, **103**, 69-97.

HERRON, M.J. & ANDERSON, J.B. 1990. Late Quaternary glacial history of the South Orkney Plateau, Antarctica. *Quaternary Research*, **33**, 265-275.

HJORT, C., INGÓLFSSON, Ó., MÖLLER, P. & LIRIO, J.M. 1997. Holocene glacial history and sea-level changes on James Ross Island, Antarctic Peninsula. *Journal of Quaternary Science*, **12**, 259-273.

HÖFLE, H.C. & BUGGISCH, W. 1993. Glacial geology and petrography of erratics in the Shackleton Range, Antarctica. *Polarforschung*, **63**, 183-201.

HUYBRECHTS, P. 1992. The Antarctic ice sheet and environmental change: a three-dimensional modeling study. Ph.D. thesis, Bremerhaven, 241 pp.

JOUZEL, J., RAISBECK, G., BENOIST, J.P., YIOU, F., LORIUS, C., RAYNAUD, D., PETIT, J.R., BARKOV, N.I., KOROTKEVITCH, Y.S. & KOTLYAKOV, V.M. 1989. A comparison of deep Antarctic ice cores and their implications for climate between 65,000 and 15,000 years ago. *Quaternary Research*, **31**, 135-150.

KENNEDY, D.S. & ANDERSON, J.B. 1989. Glacial-marine sedimentation and Quaternary glacial history of Marguerite Bay, Antarctic Peninsula. *Quaternary Research*, **31**, 255-276.

KERR A.R. & HERMICHEN, W.-D. in press. The glacial history of the Shackleton Range. *In* THOMSON, M.R.A. & TESSENSOHN, F., *eds*. EUROSHACK, Geological Expedition. *Terra Antartica*.

KURTZ, D.D. & ANDERSON, J.B. 1979. Recognition and sedimentologic description of recent debris flow deposits from the Ross and Weddell Sea. *Journal of Sedimentary Petrology*, **49**, 1159-1170.

LARTER, R.D. & VANNESTE, L.E. 1995. Relict subglacial deltas on the Antarctic Peninsula outer shelf. *Geology*, **23**, 33-36.

LICHT, K.M., JENNINGS, A.E., ANDREWS, J.T. & WILLIAMS, K.M. 1996. Chronology of late Wisconsin ice retreat from the western Ross Sea, Antarctica. *Geology*, **24**, 223-226.

MELLES, M. & KUHN, G. 1993. Sub-bottom profiling and sedimentological studies in the southern Weddell Sea, Antarctica; evidence for large-scale erosional/depositional processes. *Deep-Sea Research*, **40**, 739-760.

MERCER, J.H. 1968. Glacial geology of the Reedy Glacier area, Antarctica. *Geological Society of America Bulletin*, **79**, 471-486.

MILLER, H. HENRIET, J.P. KAUL, N. & MOONS, A. 1990. A fine-scale seismic stratigraphy of the eastern margin of the Weddell Sea. *In* BLEIL U. & THIEDE, J., *eds*., *Geological history of the polar oceans: Arctic versus Antarctic*. Amsterdam: Kluwer Academic Publishers, 131-161.

MOONS, A., MILLER, H., DEBATIST, M. & HENRIET, J.P. 1991. Sequence stratigraphy of the Crary Fan, southeastern Weddell Sea. *In* YOSHIDA, Y., KAMINUMA, K., & SHIRAISHI, K., *eds. Recent progress in Antarctic earth science*. Tokyo: Terra Scientific Publishing Company, 613-618.

PATERSON, W.S.B. & HAMMER, C.U. 1987. Ice core and other glaciological data. *In* RUDDIMAN, W.F. & WRIGHT, H.E., *eds. North America and adjacent oceans during the last deglaciation'*. The Geological Society of America. The Geology of North America, v. K-3, 501 pp.

PAYNE, A.J., SUGDEN, D.E. & CLAPPERTON, C.M. 1989. Modeling the growth and decay of the Antarctic Peninsula Ice Sheet. *Quaternary Research*, **31**, 119-134.

POPE, P.G. & ANDERSON, J.B. 1992. Late Quaternary glacial history of the northern Antarctic Peninsula's western continental shelf: evidence from the marine record. *Antarctic Research Series*, **57**, 63-91.

PUDSEY, C.J., BARKER, P.F. & LARTER, R.D. 1994. Ice sheet retreat from the Antarctic Peninsula shelf. *Continental Shelf Research*, **14**, 1647-1675.

RAYNAUD, D. & LEBEL, B. 1979. Total gas content and surface elevation of polar ice sheets. *Nature*, **281**, 289-291.

RAYNAUD, D. & WHILLANS, I.M. 1982. Air content of the Byrd core and past changes in the West Antarctic Ice Sheet. *Annals of Glaciology*, **3**, 269-273.

REX, R.W., MARGOLIS, S.V. & MURRAY, B. 1970. Possible interglacial dune sands from 300 meters water depth in the Weddell Sea, Antarctica. *Geological Society of America Bulletin*, **81**, 3465-3472.

SHIPP, S.S., ANDERSON, J.B., & DOMACK, E.W. in press. Seismic signature of the late Pleistocene fluctuations of the West Antarctic Ice Sheet system in Ross Sea: a new perspective, Part 1. *Geological Society of America Bulletin*.

SLOAN, B.J., LAWVER, L.A. & ANDERSON, J.B. 1995. Seismic stratigraphy of the Palmer Basin. *Antarctic Research Series*, **68**, 235-260.

SMITH, M.J. 1985. *Marine geology of the northwestern Weddell Sea and adjacent coastal fjords and bays: implications for glacial history*. M.A. thesis, Rice University, 157 pp [Unpublished].

SUGDEN, D.E. & CLAPPERTON, C.M. 1977. The maximum ice sheet extent on island groups in the Scotia Sea, Antarctica. *Quaternary Research*, **7**, 268-282.

SUGDEN, D.E. & CLAPPERTON, C.M. 1980. West Antarctic Ice Sheet fluctuations in the Antarctic Peninsula area. *Nature*, 286, 378-381.

TAVIANI, M., REID, D. & ANDERSON, J. 1993. Skeletal and isotopic composition and paleoclimatic significance of Late Pleistocene carbonates, Ross Sea, Antarctica. *Journal of Sedimentary Petrology*, **63**, 84-90.

WAITT, R.B. 1983. Thicker West Antarctic ice sheet and peninsula icecap in late-Wisconsin time – sparse evidence from northern Lassiter Coast. *Antarctic Journal of the United States*, **18**(5), 91-93.