Chapter 11

Antarctic Ice Sheet changes since the Last Glacial Maximum

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11.1 Introduction

Antarctica is comprised of two main grounded ice sheets: the West Antarctic Ice Sheet (WAIS) and the East Antarctic Ice Sheet (EAIS) separated by the Transantarctic Mountains (McMillan, 2018). The marine-terminating margins of these two ice sheets are characterised by direct interaction with the ocean, either at a calving front or through floating ice shelves. Another, smaller ice sheet, the Antarctic Peninsula Ice Sheet (APIS), covers the Antarctic Peninsula in West Antarctica (Fig. 11.1). The present volume of ice in Antarctica is around 27 million km^3 (equivalent to $\sim$58 m of global sea level) of which 91% is within the EAIS (Fretwell et al., 2013). The maximum ice-sheet surface elevation of 4093 m occurs at Dome A, which, along with several other subsidiary ice domes connected by ridges, forms a major ice divide through the centre of East Antarctica. Ice thickness in the central regions of the continent varies commonly between 2000 and 4000 m, mainly as a consequence of bed topography which is known to vary spatially by more than a vertical kilometre over just a few kilometres (Fretwell, 2013; Morlighem, 2020). If the ice were to be removed from East Antarctica, the bed surface would be largely above sea level (apart from notable low-lying areas such as the Wilkes and Aurora basins). However, if the same were to happen over West Antarctica, even accounting for isostatic rebound, most of the bed underlying the WAIS would remain well below the modern sea level (e.g., Jamieson et al., 2014). Thus, the WAIS is often referred to as a 'marine-based' ice sheet (Mercer, 1978).

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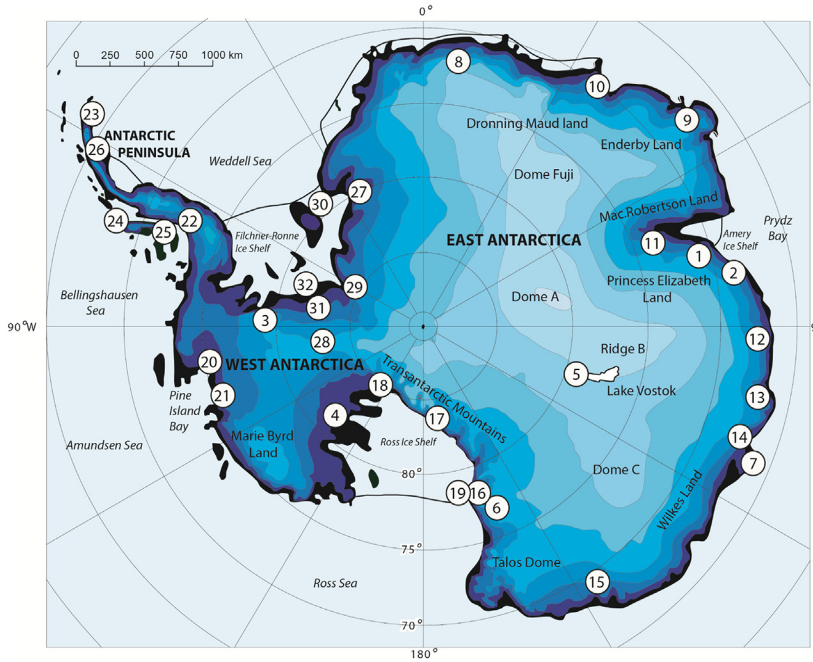


FIGURE 11.1 Surface elevation of Antarctica with placenames mentioned in the text. Contours are at 500 m intervals, with the elevation at Dome A over 4000 m. Numbers refer to locations cited in the text as follows: (1) Larsemann Hills; (2) Vestfold Hills; (3) Ellsworth Mountains; (4) Siple Coast; (5) Vostok Station (with Subglacial Lake Vostok outlined); (6) Taylor Dome; (7) Law Dome; (8) Schirmacher Oasis with Lake Glubokoye; (9) Mount Riiser Larsen; (10) Lützow-Holm Bay; (11) Grove Mountains; (12) Gaussberg; (13) Bunger Hills; (14) Windmill Islands; (15) Mertz and Ninnis Glaciers; (16) McMurdo Dry Valleys; (17) Beardmore Glacier; (18) Reedy Glacier; (19) Ross Island; (20) Pine Island Glacier; (21) Thwaites Glacier; (22) Mount Jackson; (23) James Ross Island; (24) Marguerite Bay; (25) Alexander Island and George VI Ice Shelf; (26) Larsen A & B embayments; (27) Shackleton Range; (28) Whitmore Mountains; (29) Pensacola Mountains; (30) Filchner Trough; (31) Robin Subglacial Basin; (32) Bungenstock Ice Rise.

Ice drains from the interior domes predominantly via fast flowing rivers of ice known as 'ice streams', where the dominant method of flow is by sliding or basal sediment deformation. These contribute grounded ice to numerous floating ice shelves that surround the ice sheets. The Ross and the Filchner-Ronne ice shelves are Antarctica's largest, with areas of 497,000 and 438,000 km^2, respectively (e.g., Rignot et al., 2013). Icebergs, usually of tabular form, calve from the marine margins of ice shelves, where ice thickness is usually 250–300 m. This process represents an important mechanism by which ice is lost from the ice sheet system, accounting for 52%–79% (Rignot et al., 2013) or 60%–70% (Depoorter et al., 2013) of all ice discharged from the Antarctic Ice Sheets. Sub-ice shelf melting and other basal processes cause the remaining ice loss; they vary locally and account for

10%–90% of mass loss from an individual glacial system (e.g., Depoorter et al., 2013; Rignot and Jacobs, 2002; Rignot et al., 2013, 2019; Shepherd et al., 2018). Better knowledge of ice loss processes, especially at ice-sheet grounding lines and beneath ice shelves, represents a major challenge in glaciology as they are critical to projecting future sea level change through ice sheet modelling (Siegert et al., 2020; Siegert and Golledge, 2021, this volume). Evidence of past changes, where the ice sheet grew during cool periods and shrank during warming episodes, is also important in glaciology, as it can help us understand ice sheet sensitivity and vulnerability to external climate and ocean forcing, and help constrain and improve ice sheet models. In this chapter, we concentrate on the geological evidence for ice sheet expansion at the last glacial maximum (LGM, centred at ~20 ka) and for the changes that occurred subsequently. Such knowledge can be used in ice-sheet modelling exercises to understand the processes responsible for changes observed, to help determine where important data gaps remain and to improve the models where ice flow calculations are at irreconcilable odds with observations.

11.2 Response of the ice sheets to glacial climate and late Quaternary ice sheet reconstructions

The climate around Antarctica during 'full glacial' periods, such as the LGM, is likely to have been highly conducive to the presence of expanded ice sheets, and so the 'minimum' reconstruction for the LGM Antarctic ice sheets is similar to the present configuration. However, due to the sea-level reduction of around 120–130 m (e.g., Austermann et al., 2013; Bard et al., 1990; Shackleton, 2000; Siegert, 2001; Simms et al., 2019) and ocean and air temperature reductions that occurred during the LGM, the ice sheets in Antarctica are known to have grown out towards the continental shelf edge in most places. The ice shelves bordering the Antarctic ice sheets thickened, grounded and became part of the ice sheet proper. A 'maximum' reconstruction would therefore be a major expansion of the Antarctic ice sheets (compared with today) to reach the continental shelf break right around the continent (see Siegert, 2001; The RAISED Consortium, 2014, for a broad overview).

Evidence from ice cores and internal radio-echo layering from around Antarctica (Siegert, 2003) reveals a much lower rate of ice accumulation at the LGM compared with today. Towards the East Antarctic Ice Sheet margin, the Taylor Dome ice core also shows that LGM (and post-LGM) wind and storm path directions were different from the modern day. This implies a reorganisation of the climate system that needs to be taken into account when interpreting and correlating paleoclimate data, at least at this part of the ice sheet (Morse et al., 1998), a feature corroborated at nearby Talos Dome (Mezgec et al., 2017; Siegert and Leysinger Vieli, 2007). While reductions in both sea level and air and seawater temperatures at the LGM would have been conducive to ice sheet expansion, decreasing ice accumulation may well have had a restraining effect on ice sheet growth. Resolving how the ice sheets responded to such complicated changes in forcing requires the application of numerical models.

Ice-sheet behaviour in the late Quaternary is coupled with, and sensitive to, connected processes in the cryosphere, ocean, Earth and atmosphere (e.g., Colleoni et al., 2018; Noble et al., 2020; Siegert et al., 2020; Whitehouse, 2018). For example, if the sea ice extent increased due to cooling of the air temperature over the Southern Ocean (Armand, 2000; Gersonde et al., 2005), then the moisture supply to the ice sheets may have decreased and so ice sheet growth may have been impeded. This introduces the possibility that independent mountain glaciers in Antarctica may have responded differently to LGM conditions than areas connected to the ice sheet (as it is known to happen today, see Miles et al., 2013). In other words, ice sheet advance may have been predominantly related to sea level fall while, at the same time, glacier decay may be related to a significant reduction in rates of snow precipitation.

Since the influential CLIMAP (1976) reconstruction of ice age Earth, there have been numerous reconstructions of LGM ice extent in Antarctica based on evidence from sediments and geomorphology, isostatic rebound and ice-flow modelling. These reconstructions provide estimates of ice volume varying considerably, from just 0.5-2.0 m up to 38 m of sea level equivalent (SLE) (e.g., Budd and Smith, 1982; Colhoun et al., 1992; Nakada and Lambeck, 1988). While the techniques used vary, many of the early estimates placed the grounding line at the edge of the continental shelf, with relatively steep ice profiles. As such these are at the upper end of estimates of sea-level lowering. More recent work has advanced our understanding of the dynamics of ice flow (in particular the longitudinal profile of ice streams and their controls), produced sophisticated 3D thermomechanical ice sheet models and provided reliable geomorphic evidence that indicates relatively limited ice expansion in some areas. These advances have rendered the upper estimates implausible. More recent reconstructions indicate a more limited increase of Antarctic ice volume at the LGM. Compilations by Anderson et al. (2002), Bentley (1999) and Simms et al. (2019) show that average estimates for Antarctica's contribution to the LGM sea-level lowstand were 25 m SLE in the literature published until CE (common era) 2000 (e.g., Denton et al., 1991; Nakada et al., 2000), 13 m SLE in studies published between CE 2000 and 2010 (e.g., Bassett et al., 2007; Huybrechts, 2002; Pollard and DeConto, 2009), and just 10 m SLE in papers published after CE 2010 (e.g., Briggs et al., 2014; Golledge et al., 2013, 2014; Whitehouse et al., 2012). Estimates of 10 m SLE are largely in agreement with reconstructions from geological data (e.g., The RAISED Consortium, 2014) and with a recent global reconstruction of LGM ice volume (Gowan et al., 2021). However, far field data on global sea level at the LGM and calculated meltwater contributions from all LGM ice outside Antarctica still suggest a larger Antarctic contribution in some studies (e.g., Clark and Tarasov, 2014; Lambeck et al., 2014; Simms et al., 2019).

11.3 Constraining late Quaternary ice sheet extent, volume and timing

The geometry of the Antarctic ice sheets throughout the last glacial cycle has been compiled using a number of different methods. In terrestrial environments, the areal extent of former ice cover is generally recognised by mapping the lateral extent of ice-marginal landforms such as moraines or pro-glacial lake sediments, or by mapping subglacial landforms such as drumlins and erosional features such as striae. Ice volume can equally be reconstructed by mapping glacial debris, striae, the locations of erratic boulders and the height/extent of mountain trimlines. The relative age of each mapped unit is usually constrained using a measure of exposure age, most often by the degree of weathering (such as soil formation or development of tafoni or iron staining on boulders) and by optically stimulated luminescence (OSL) dating or the measurement of isotopes produced by cosmogenic radiation. Stratigraphic correlations are generally difficult due to a lack of natural exposures.

Similar techniques are also used in marine environments, but rather than investigating the geomorphology of former glacial landscapes using field mapping and aerial photography, the ocean floor is imaged using techniques such as swath bathymetry and side-scan sonar. These techniques commonly identify ice marginal landforms such as moraines, or subglacial landforms such as mega-scale glacial lineations, meltwater channels and drumlins. Stratigraphic techniques are more useful in the marine environment due to the ease of data acquisition via acoustic and seismic surveys, particularly when the bedforms and sedimentary strata are also sampled by coring.

Establishing detailed late Quaternary glacial chronologies in Antarctica can be challenging (e.g., Anderson et al., 2002; Ingólfsson, 2004; see also Wilson, 2021). The most direct dating is usually achieved in present terrestrial environments, through cosmogenic exposure or OSL dating of clasts from moraines or exposed bedrock and through radiocarbon or electron spin resonance dating (e.g., Takada et al., 1998, 2003) of fossil organisms contained within emergent marine sediments or ice-marginal lakes. However, factors such as cosmogenic nuclide production rate uncertainties (e.g., Gosse and Phillips, 2001), recycling of clasts with prior exposure and post-depositional reworking of glacial sediments (e.g., Brook et al., 1995) can reduce the precision of exposure age and OSL chronologies. Where such materials are preserved, the algal mats commonly found in proglacial lake sediments can provide reasonably accurate radiocarbon ages if the water column is well mixed and at least a part of the lake-surface ice cover melts out each summer (Gore, 1997b; Hendy and Hall, 2006). Limiting ages on glacial events in terrestrial environments can also be constrained by radiocarbon dating of the small amount of organic material sometimes found in ice-marginal or postglacial sediments (e.g., Baroni and Orombelli, 1994a; Burgess et al., 1994).

Radiocarbon dates on carbon sourced from marine environments, such as the bodies of seals and penguins, or carbonate shells in former (and emergent) marine environments such as raised beaches, are subject to a marine reservoir effect that varies around the Antarctic continent but is on average about 1.3 ka (e.g., Berkman and Forman, 1996; Harden et al., 1992; but also see Kiernan et al., 2003). On the continental shelf, the majority of published ages for grounded ice retreat after the LGM, and the few dates constraining pre-LGM ice advance, have been obtained by Atomic Mass Spectrometry (AMS) radiocarbon dating of calcareous microfossils or, due to the scarcity of calcareous microfossils in Antarctic shelf sediments, the acid-insoluble fraction of organic material (AIO; mostly derived from diatoms) that is preserved in glacimarine sediments above or below a layer of subglacially-derived sediment (e.g., Heroy and Anderson, 2007; Livingstone et al., 2012). While non-reworked calcareous microfossils frequently occur well above the subglacial-glacimarine transition in sediment cores, several problems remain with AIO dating, mainly due to the influx of subglacially eroded and reworked fossil organic matter. This is evident from the fact that AIO dates from the modern sediment/water interface often provide uncorrected radiocarbon ages of >2 ^{14}C ka before present (BP; referring to CE 1950), and sometimes >6 ^{14}C ka BP in areas of little biological productivity and/or where carbon-rich rocks are eroded (e.g., Andrews et al., 1999; Hemer et al., 2007; Mosola and Anderson, 2006; Pudsey et al., 2006). These ages exceed the marine reservoir effect of $\sim$1.3 ka, which is derived from ^{14}C ages of carbonate shells from living biota at such sites. Usually, down-core AIO ^{14}C dates are corrected by subtracting the core-top AIO ^{14}C age (e.g., Heroy and Anderson, 2007; Pudsey et al., 2006), but this approach assumes that contamination with fossil organic matter was constant through time and that the age of this contaminating material remained the same. In some studies, the problem of AIO ^{14}C dating is overcome by relying on (1) AMS ^{14}C dates of discrete carbonate shells only (e.g., Kirshner et al., 2012), or (2) a combination of AMS ^{14}C dates from AIO and calcareous microfossils (e.g., Domack et al., 2005; Leventer et al., 2006; Prothro et al., 2020). More recent studies applied AMS ^{14}C dating by selective extraction of the most labile portions of the dispersed organic phase through compound specific extraction (e.g., Yamane et al., 2014; Yokoyama et al., 2016), ramped pyrolysis (Rosenheim et al., 2008, 2013; Subt et al., 2016, 2017) or utilising the MICADAS ^{14}C dating technique, which requires only a very small amount of calcareous material (e.g., Arndt et al., 2017; Klages et al., 2014). In addition, sediment cores from the Antarctic continental shelf have been successfully dated by analysing their relative geomagnetic palaeointensity (Brachfeld et al., 2003; Hillenbrand et al., 2010a; Klages et al., 2017; Willmott et al., 2006), and in few cases using tephra layers or cryptotephra as volcanic event markers for age correlation (Di Roberto et al., 2019). Despite the difficulties in dating Antarctic shelf sediments, considerable progress has been made in constraining the timing of post-LGM ice retreat from the shelf in many sectors of the Antarctic continent.

11.4 Last interglacial (Eemian, ~130–116 ka)

Data from sources including dated coral terraces and the oceanic $\delta^{18}O$ record have fixed the timing of the Eemian interglacial at 130–116 ka (Shackleton et al., 2003; Stirling et al., 1998). During this period, there was less ice in the world than at present and global sea level was between 3 and 9 m higher than today (Dutton et al., 2015; Kopp et al., 2009; Overpeck et al., 2006; Stirling et al., 1998; Voosen, 2018). While part of this sea-level rise occurred through decay of the Greenland Ice Sheet (e.g., Cuffey and Marshall, 2000; Tarasov and Peltier, 2003), preservation of ice in northwest Greenland during this time limits the Greenland Ice Sheet contribution to ~2 m SLE (Dahl-Jensen et al., 2013), although a possible contribution of up to 5 m SLE has also been suggested (Yau et al., 2016). Some believe that the Eemian sea-level highstand was caused by a smaller WAIS (e.g., Mercer, 1978; Scherer et al., 1998), which could have contributed up to 3.5 m of sea level rise (Bamber et al., 2009; DeConto and Pollard, 2016; Hein et al., 2016a), and/or the marine portions of the EAIS (Wilson et al., 2018), which could contribute over 10 m in a substantive deglacial event. Evidence to support the reduction in volume of at least a part of the WAIS at the last interglacial comes from observations of marine diatoms of Quaternary age and the measurement of high concentrations of ^{10}Be in subglacial sediments recovered from the UpB drill site beneath the Whillans Ice Stream on the Siple Coast of the Ross Sea embayment (Scherer et al., 1998). ^{10}Be and diatoms are not thought to accumulate under a grounded ice sheet, and any small amounts of ^{10}Be and diatoms that may be introduced by subglacial melt at the base of the ice sheet will be eroded. Scherer et al. (1998) argued that the marine components in the tills retrieved from the UpB site were probably emplaced during the last interglacial, when marine conditions prevailed. However, a recent study on modern subglacial tills from the Siple Coast ice streams, including samples from the UpB site, detected young ^{14}C-dated organic carbon and concluded that the WAIS grounding line had undergone a short-term retreat to the UpB and other drill sites at the beginning of the Holocene (Kingslake et al., 2018). This finding raises the question whether ocean currents also had advected marine diatoms and any adhering ^{10}Be to the UpB site during the last and/or earlier glacial terminations, which would not require a major WAIS collapse. In any case, the current dynamics of the

WAIS is certainly affected by the location of these low shear strength, now subglacial, sediments (Anandakrishnan et al., 1998; Siegert et al., 2016; Studinger et al., 2001).

11.5 Last Glacial Maximum, subsequent deglaciation and the Holocene (~20–0 ka)

Regardless of ice sheet geometry at the last interglacial, there is persuasive evidence from the geological record to indicate that the Antarctic ice sheets were larger than present around the time of the global sea-level lowstand at ~20 ka, although the extent of this expansion is well constrained at only a few sites around the continental margin (The RAISED Consortium, 2014; Whitehouse, 2018). Evidence of former ice surface elevations is particularly sparse, in part due to the lack of sites at which such information can be preserved but also due to the difficulty in accessing remote inland mountain ranges, where this evidence might occur.

Since the publication of the Antarctic Climate Evolution book in 2008 (Florindo and Siegert, 2008), there has been a significant amount of new research to explore the past behaviour of the Antarctic ice sheets over a range of timescales. Much of this research covering the time span back to 20 ka has been synthesised in a Reconstruction of Antarctic Ice Sheet Deglaciation (RAISED) in a coordinated effort by the Antarctic glacial geology community in 2014 (The RAISED Consortium, 2014). The RAISED Consortium developed a synthesis of Antarctic ice-sheet history and created a series of time-slice maps that described ice thickness and extent at 25, 20, 15, 10 and 5 ka based on a comprehensive review of available marine and terrestrial geological and glaciological data (The RAISED Consortium, 2014). In the next sections, we discuss glacial history by dividing Antarctica into seven sectors (see Fig. 11.2, and placename locations in Fig. 11.1). Our summaries rely heavily on the RAISED Consortium review for each sector (The RAISED Consortium, 2014, and related sector papers), and we

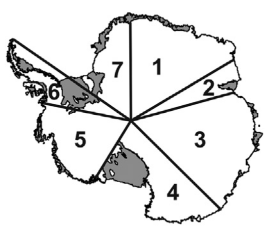


FIGURE 11.2 Broad locations of the sectors discussed in this chapter, including (1) Queen Maud/Enderby Land; (2) Mac.Robertson Land/Lambert Glacier/Amery Ice Shelf/Prydz Bay; (3) Princess Elizabeth Land to Wilkes Land; (4) Ross Sea sector; (5) Amundsen-Bellingshausen Seas; (6) Antarctic Peninsula; and (7) Weddell Sea Embayment. Ice shelves are grey shaded. *Modified from* Wright et al. (2008).

encourage readers to consult these reviews for full details of the original publications that present the data underpinning the reconstructions. We also discuss the most recent advances in our understanding of ice sheet change in each sector, with a focus on the age of maximum extent, and the timing and style of deglaciation.

The changes in ice thickness, and timings of deglaciation across the first three sectors are summarised in Fig. 11.3 (after Mackintosh et al., 2014). Descriptions of notable geological evidence from these East Antarctic sectors are provided, followed by a review of evidence from the other Antarctic sectors.

11.5.1 Queen Maud/Enderby Land

Schirmacher Oasis (11.5°E) is a 34 km^2 large area located at the transition between the Novolazarevskaya Ice Shelf and the EAIS. Infra-red stimulated luminescence dating of lake floor sediments yielded burial ages of ~52 ka in Lake Glubokoye (Krause et al., 1997), which was in part corroborated by AMS ^{14}C ages of 35 ka BP from 2 m above the glacial diamict at the base of the lake sediments (see also Mackintosh et al., 2014). On the northern side of Fimbulheimen, the mountain range to the south of Schirmacher Oasis, deposition of mumijo (proventricular ejecta of the snow petrel, *Pagodroma nivea*) throughout the LGM indicates that ice thickening in this sector of the ice sheet was also limited, with <80 m thickening occurring at Insel Range (72°S, 11°E) during this time (Hiller et al., 1995).

The 46–30 old ka marine shorelines along the eastern shore of Lützow–Holm Bay (39.6°E) indicate that the northern islands may have remained ice-free through the LGM, constraining the expansion of the ice sheet in this area (Igarashi et al., 1995, 1998). Ice was covering the peak of Skarvsnes in the southern Soya Coast and then retreated ca. 10 km landward from 9 to 5 ka (Kawamata et al., 2020). Ice-free areas in the southern shore record at least 350 m of thinning between 10 and 6 ka (Yamane et al., 2011) and correlate with a regional decrease in ice load (Nakada et al., 2000) recorded by Holocene shorelines reaching 15–20 m above present sea level and dating from 8.0 cal. (calibrated) ka BP to the present day (Maemoku et al., 1997; Miura et al., 1998; Yamane et al., 2011; Yoshida and Moriwaki, 1979). Marine sediment cores collected in Lützow–Holm Bay only recovered glacimarine deposits but no subglacial tills. Thus, their oldest AIO dates constrain the last ice advance to sometime before 13.0 cal. ka BP (Igarashi et al., 2001).

Despite an abundance of small ice-free areas that are suitable for Quaternary studies, including Mt Riiser–Larsen (50.7°E), Øygarden Group (57.5°E) and Stillwell Hills (59.3°E), there is limited information regarding the geometry of the Enderby Land sector of the EAIS during or following the LGM. Ice thinning of at least 400 m occurred along lower Rayner

Glacier between 9 and 7 ka (White and Fink, 2014) (Fig. 11.3). At Mt Riiser–Larsen, basal fresh-water sediments from Richardson Lake reveal that the area has been deglaciated since at least 9.9 uncorrected ^{14}C ka BP (Zwartz et al., 1998a). Mega-scale glacial lineations in Edward VIII Gulf (57.9°E) record a likely LGM advance across the continental shelf, but sediment cores from this site did not retrieve subglacial or grounding-line proximal glacimarine diamictons and provide only minimum limiting retreat ages around 8.7 cal. ka BP (Dove et al., 2020).

11.5.2 Mac.Robertson Land/Lambert Glacier-Amery Ice Shelf/Prydz Bay

^{10}Be and ^{26}Al cosmogenic isotope exposure ages on glacial erratics show that the ice sheet thickness at Framnes Mountains (62.5°E) was ~350 m greater than present during the LGM, had begun lowering at 13 ka and had reached the modern ice margin by 6 ka (Mackintosh et al., 2007) (Fig. 11.3). This evidence agrees reasonably well with side-scan sonar/swath bathymetry and sediment core data which indicate that grounded ice had retreated from the mid-outer continental shelf in Nielsen Basin ~80 km to the east of Framnes Mountains by ~14 cal. ka BP (Leventer et al., 2006; Mackintosh et al., 2011) and had reached the inner shelf by 6 cal. ka BP (Harris and O'Brien, 1998). The mid-inner shelf in Burton Basin between Nielsen Basin and Cape Darnley had become free of grounded ice by ~13 cal. ka BP (Borchers et al., 2015).

At Mt Harding (72°88′S, 75°03′E) in Grove Mountains, the EAIS forming the eastern flank of Lambert Glacier did not thicken above the present ice surface altitude throughout the LGM (Lilly, 2008; Lilly et al., 2010). Former ice advances of the Lambert Glacier-Amery Ice Shelf system (70°E) into Prydz Bay are relatively well constrained through geophysical

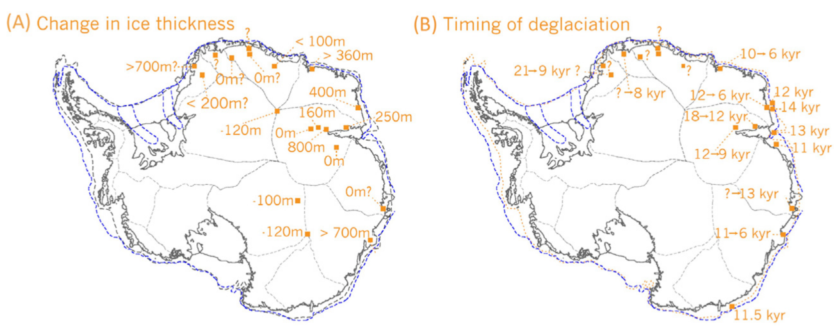


FIGURE 11.3 (A) Change in ice thickness and (B) timing of deglaciation across a range of sites in East Antarctica. *Taken from Mackintosh et al. (2014) and reproduced with permission from Elsevier.*

investigations and marine sediment cores (Domack et al., 1991, 1998; O'Brien et al., 1999; Taylor and McMinn, 2002), and by drilling through the ice shelf (Hemer and Harris, 2003; Hemer et al., 2007). The sedimentary record indicates that ice was grounded on shallow (<500 m water depth) banks in Prydz Bay and across most of the area currently occupied by the Amery Ice Shelf at the LGM. However, the age of the base of an uninterrupted sequence of terrigenous glacimarine and biogenic-bearing seasonally open-marine sediments was constrained by a radiocarbon date on foraminifera to >34 ^{14}C ka BP (uncorrected) within Prydz Channel, a 700 m deep trench that cuts across the continental shelf in Prydz Bay (Domack et al., 1998). This suggests that grounded ice may not have extended all the way to the continental shelf at the LGM.

Investigations into glacial and lake sediments deposited on mountains flanking the major outlet glaciers (Lilly, 2008; Lilly et al., 2010' Wagner et al., 2004; White and Hermichen, 2007) also constrain the LGM thickness of the ice sheet. With the exception of the area around the southern tip of the modern Amery Ice Shelf, glacial sediments dating from the LGM are restricted to <200 m above the modern ice margin. Also, there are no emergent shorelines around epishelf Beaver Lake (Adamson et al., 1997), but there are subaerially deposited postglacial sediments on the lake bottom at 60 m below modern sea level (Wagner et al., 2007). These data support the results from the continental shelf and indicate that both thickening and expansion of ice in this region at the LGM was limited (e.g., Hemer et al., 2007). One reason for this may be the deep basin along which the outlet glaciers flow, which reduces the ability of the ice sheet to advance to the continental shelf edge (Taylor et al., 2004).

Deglaciation from the ice maximum is first recorded by cosmogenic records of ice thinning from 18 to 12 ka at Loewe Massif in the Amery Oasis beside Amery Ice Shelf (White et al., 2011), with thinning proceeding inland, concluding at ~9 ka at the southern part of the modern grounding line at Mt Stinear, and a hundred kilometres further inland at Mt Ruker. Minimum ages for grounding line retreat are available from only a few marine sediment cores in Prydz Bay, but it is clear that retreat was underway from the most seaward grounding zone wedge at Prydz Channel by 11.3 cal. ka BP (Domack et al., 1991), while the northern part of the Amery Ice Shelf has been ungrounded since at least 13.5 cal. ka BP (Hemer and Harris, 2003; Hemer et al., 2007). Grounded ice had retreated from the near-coastal part of Svenner Channel, located just to the east of Prydz Bay, by ~10.1 cal. ka BP (Barbara et al., 2010; Leventer et al., 2006).

11.5.3 Princess Elizabeth Land to Wilkes Land

Larsemann Hills (76.2°E) host lake sediments dated to ^{14}C background (>42 ka BP). Lake sediment stratigraphy (Hodgson et al., 2005, 2009) and cosmogenic ^{10}Be exposure ages (Kiernan et al., 2009) have been used to infer continual exposure from the ice sheet since the last interglacial (see also Mackintosh et al., 2014). An OSL age of 21 ka was obtained from glaciofluvial sediments within 500 m of the ice margin (Hodgson et al., 2001), supporting interpretations of continual exposure through the LGM.

Rauer Islands (77.8°E), on the south side of Sørsdal Glacier, are formed by small peninsulas jutting out from the ice sheet to small islands some 12 km offshore. Ice free conditions were recorded in the islands from before 44 to <32 cal. ka BP. A modest expansion of ice occurred during the LGM, with progressive re-exposure of the outer islands from 16 ka to the present margin by 11 ka (Berg et al., 2010, 2016; White et al., 2009). This modest regional ice expansion created Holocene emergent shorelines of <10 m above sea level (asl).

Vestfold Hills (78°E) have emergent marine shorelines to <10 m asl (Zwartz et al., 1998b). A sediment core from Abraxas Lake in the northeast of the Hills suggests that the LGM ice sheet did not cover that area (Gibson et al., 2009). Ice-free conditions enabled penguin occupation of the northeastern portion of the hills by 14 cal. ka BP (Gao et al., 2018) and a ^{14}C age on a shell demonstrated that the Sørsdal Glacier margin was near its present position by 8.4 cal. ka BP (Adamson and Pickard, 1986a). Near-shore geomorphological features mapped on the seabed by multibeam and sonar data revealed a landscape formed by slow-moving grounded ice that was subsequently modified by glacimarine processes during and after deglaciation (O'Brien et al., 2015). Cosmogenic ^{10}Be analyses indicate that the ice sheet margin had retreated to within 5 km of the present margin by 12.5–9 ka (Fabel et al., 1997) and to within 1 km since 8 ka (Lilly 2008). There has been a minor (<4 km) lateral expansion and retraction of the flank of Sørsdal Glacier during the late Holocene (Adamson and Pickard, 1983; Gore, 1997a).

Gaussberg (89.2°E) is a 370 m high, glacially striated volcano on the coast. Its benched morphology and presence of palagonite encrusted pillow lavas indicate an eruption that occurred at 56 ka in a water filled subglacial vault, and that the ice sheet has since retreated to its present position (Tingey et al., 1983), thereby depositing erratics from the summit to the mountain foot.

Bunger Hills (101°E) have emergent marine shorelines to <11 m asl (Colhoun and Adamson, 1992; Colhoun et al., 1992). OSL ages from glacial lake shorelines and glaciofluvial sediments indicate that deglaciation commenced ~40–30 ka (Gore et al., 2001), with the area largely deglaciated by ~25 ka. Like Vestfold Hills, the oasis attained most of its present form around 11 cal. ka BP and warm conditions from around 9.6 cal. ka BP (Berg et al., 2020).

Windmill Islands (110.3°E) have emergent marine shorelines to 35 m asl (Goodwin, 1993; Goodwin and Zweck, 2000), with deglaciation of the southern islands by 11 cal. ka BP and the northern peninsulas by 8 cal. ka BP (Kirkup et al., 2002). Geomorphological bedforms mapped on the adjacent shelf include lineations and meltwater channels formed at the LGM and potentially during earlier glacial periods as well as mid-late Holocene moraines deposited during episodic grounded ice retreat following ice surging of the Law Dome margin (Carson et al., 2017).

The Sabrina Coast has been recently investigated to seek evidence of the retreat and advance of Totten Glacier. Multibeam bathymetry data from the inner shelf revealed mega-scale glacial lineations and drumlins inside a deep glacial trough and transversal ridges suggesting a step-wise grounded ice retreat possibly after the LGM (Fernandez et al., 2018). Gullies on the adjacent upper continental slope (Post et al., 2020) indicate that ice had expanded to near the shelf edge around this time.

Offshore from the large Mertz and Ninnis glaciers (145–150°E) of George V Land, swath bathymetry identified mega-scale glacial lineations within Mertz Trough (McMullen et al., 2006) and a moraine on Mertz Bank, which flanks this trough to the west on the outer shelf (Beaman and Harris, 2003; Beaman et al., 2011). The bedforms indicate LGM expansion of grounded ice to the outer continental shelf. Successive grounding zone wedge (GZW) deposits, which record pauses in the retreat of the grounded ice from the shelf, were also imaged in Mertz Trough (McMullen et al., 2006). Radiocarbon dating of molluscs and AIO predominantly provided uncorrected ^{14}C ages of 5–6 ^{14}C ka BP, suggesting grounded ice retreat before the Mid-Holocene, but overall the LGM extent of the EAIS on the shelf in this area, as well as the chronology of its retreat, remain poorly constrained (Mackintosh et al., 2014; McMullen et al., 2006).

Further west along the Adélie Land coast (135–145°E) the grounded EAIS had retreated from the mid-shelf in Mertz-Ninnis Trough, which is located just to the west of Mertz Trough on the inner-mid shelf and which is also referred to as George V Basin (Beaman et al., 2011), by ~10.5 cal. ka BP according to ^{14}C dates on calcareous shells and AIO (Leventer et al., 2006; Maddison et al., 2006). Post-LGM deglaciation of the inner shelf in Dumont d'Urville Trough to the west of Adélie Bank, which separates this trough from Mertz-Ninnis Trough, occurred in two phases at 10.6 and 9.0 cal. ka BP (Denis et al., 2009). A rapid glacier readvance happened at 7.7 cal. ka BP but was limited to the inner shelf. The middle to late Holocene was characterised by a series of similar episodes of limited glacier advance and subsequent retreat (Denis et al., 2009).

A new study combining ocean modelling with results from multi-proxy investigations on sediment cores from Dumont d'Urville Trough concluded that the end of cavity expansion under the Ross Ice Shelf caused modification of surface water-mass formation on the Ross Sea and Adélie Land continental shelves at ~4.5 cal. ka BP and contributed to widespread surface water cooling and increased coastal sea ice during the late Holocene (Ashley et al., 2021). Since ~4.5 cal. ka BP ocean-driven glacial ice discharge has increased in the EAIS sector between the Ross Sea and Prydz Bay (Crosta et al., 2018), with the simultaneous sea-ice expansion believed to have slowed down basal ice-shelf melting (Ashley et al., 2021). On decadal timescales, regional changes in sea-ice extent and sea-surface temperatures in this part of the East Antarctic margin were driven by variations of El Niño Southern Oscillations (ENSO) and the Southern Annular Mode (SAM) throughout at least the last 2000 years (Crosta et al., 2021).

11.5.4 Ross Sea sector

Since the 1990s a comprehensive geophysical and sedimentological dataset was compiled across the Ross Sea continental shelf using seismic profiles (see Anderson et al., 2014), swath bathymetry and side-scan sonar imagery of the sea-floor sediments in front of the present-day Ross Ice Shelf (Anderson, 1999; Bart et al., 2017a,b; Domack et al., 1999; Greenwood et al., 2012, 2018; Halberstadt et al., 2016; Lee et al., 2017; Shipp et al., 1999, 2002; Simkins et al., 2017). Recently, even the bathymetry below the ice shelf itself has been modelled (Tinto, 2019). Seaward of the Ross Ice Shelf, a suite of subglacial landforms, such as mega-scale lineations, drumlins and large-scale grooves, document advance of grounded ice streams within bathymetric troughs across the shelf, with GZWs and moraines documenting phases of episodic rapid and slow continuous retreat (e.g., Dowdeswell et al., 2008a). Predominantly on the central and eastern Ross Sea shelf, these subglacial features extend right to the shelf edge, but in the western Ross Sea, they only extend to the mid-outer parts of the shelf (Fig. 11.4). Sediment cores taken from the mega-scale lineations and GZWs retrieved deformation tills and overlying sub-ice shelf and glacimarine sediments of LGM to Holocene age (e.g., Bart et al., 2018; Domack et al., 1999; Licht, 2004; Licht et al., 1996, 1999; McGlannan et al., 2017; McKay et al., 2008, 2016; Mosola and Anderson, 2006; Prothro et al., 2018, 2020), while glacimarine sediments of Pliocene to Pleistocene age were recovered in cores from the outer shelf in the western Ross Sea documenting that grounded ice did not reach the shelf edge there at the LGM (Bart et al., 2011; Licht et al., 1996, 1999; Melis and Salvi, 2020).

Lateral moraines deposited by the many glaciers flowing through the Transantarctic Mountains and into the Ross Sea during the LGM have very similar profiles. These moraines are located high above the present-day ice surface at the feet of these glaciers but merge towards the modern-day surface of the ice sheet when traced upstream. LGM thickening indicated by these moraines therefore increases towards the marine margin, indicative of a thicker, grounded Ross Sea ice sheet, whereas the interior of the ice sheet in East Antarctica appears to have maintained a relatively constant thickness (Broecker and Denton, 1990).

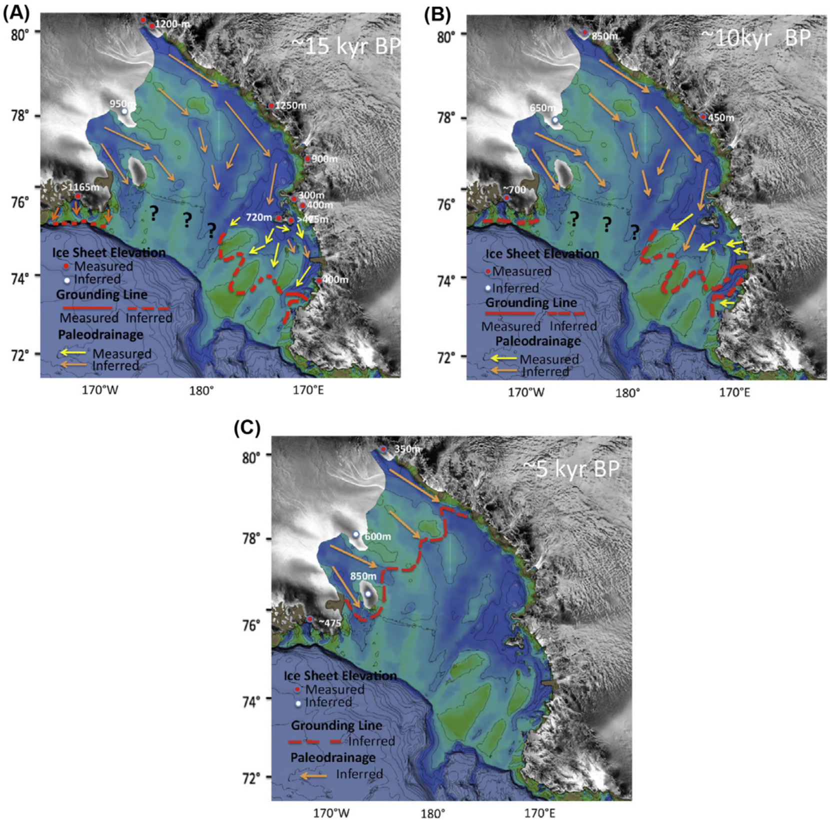


FIGURE 11.4 Ice-sheet drainage maps for the Ross Sea at (A) 15, (B) 10 and (C) 5 kyr BP. *Taken from Anderson et al. (2014) and reproduced with permission from Elsevier.*

The mineralogical, geochemical and geochronological provenance of glacial diamicts, including LGM tills, from the Ross Sea continental shelf is similar to that of source areas in Marie Byrd Land (Perotti et al., 2017) and on the Siple Coast in the eastern Ross Sea, and of sources in the Transantarctic Mountains in the central and western Ross Sea (Farmer et al., 2006; Licht and Palmer, 2013 Licht et al., 2005, 2014). These associations indicate more complicated glacial flow patterns at the LGM (Licht et al., 2005, 2014) than just a simple expansion of the present-day Siple Coast ice streams as previously assumed (e.g., Hughes, 1977) (Fig. 11.5).

Model investigations, which have attempted to reconstruct the late Holocene change in the thickness of Siple Dome from the depth-age relationship of the Siple Dome ice core, and plausible scenarios for the changes in accumulation rate since the LGM, have led to estimates of surface height increase of 200−400 m. For the ice sheet to extend ~1000 km to the

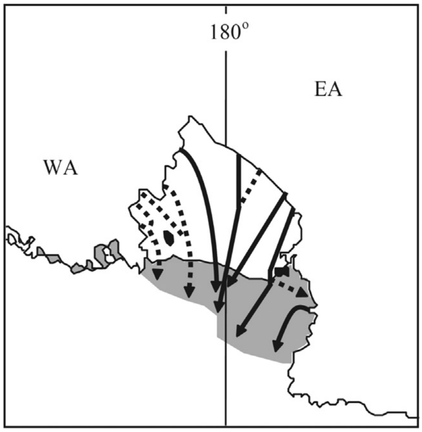


FIGURE 11.5 Flow lines for the Ross Ice Sheet during glacial episodes proposed by Licht et al. (2005) based on Ross Sea, East Antarctic (EA) and West Antarctic (WA) till provenance (cf. Licht et al., 2014). Dashed lines represent flow that could only be inferred due to lack of sample coverage. *Reproduced with permission from Elsevier.*

continental shelf edge, the required ice surface gradient would have been much shallower than that of present-day ice streams, and thus only possible by invoking a very slippery bed (Waddington et al., 2005). This supports the interpretation that ice from the Transantarctic Mountains must have contributed significantly to the Ross Sea ice sheet.

The timing of ice retreat in the Ross Sea sector has received considerable attention and includes some of the best-resolved records in the broader Antarctic region. Records of ice sheet thickness and extent maxima are documented through several different techniques and locations. Fossil algae that grew in ice marginal lakes at the LGM glacial limit on Ross Island, in the McMurdo Dry Valleys and headlands adjacent to western McMurdo Sound, provide strong evidence of ice extent and thickness reaching their maxima between 19.6 and 12.3 cal. ka BP (Christ and Bierman, 2020; Hall et al., 2015). This is supported by cosmogenic ages from erratics at the LGM limit along the Transantarctic Mountains of between ~16 and 19 ka at Reedy Glacier (Todd et al., 2010), 16 and 20 ka at Scott Glacier, and 16 and 23 ka at Beardmore Glacier (Spector et al., 2017), although it is unclear whether the age spread of these erratics represents the true duration of the LGM maxima or simply small amounts of inheritance of cosmogenic nuclides from prior periods of exposure. Radiocarbon dates from algae combined with exposure ages from the valley flanks around proglacial Lake Wellman indicate that Hatherton Glacier slowly thickened from 13.0 to 9.5 cal. ka BP (King et al., 2020). Offshore in the western Ross Sea, AMS ^{14}C dates on (reworked) foraminifera and AIO from diamictons indicate that the grounding line was located at its most advanced position in Pennell Trough between

24.2 and 15.1 cal. ka BP (Prothro et al., 2020), while a date from foraminifera from the central Ross Sea shelf suggests that maximum advance of grounded ice there had occurred by 16.8 cal. ka BP (Licht, 2004).

Multi-proxy data from a sediment core recovered on the upper continental slope offshore from JOIDES Trough document an abrupt warming event at 17.8 cal. ka BP, which was followed by a period of increasing biological productivity (Melis et al., 2021). Grounding line retreat appears to have been underway in several of the shelf basins by ~15 cal. ka BP as it is documented by ^{14}C dates from foraminifera. Ice had started to retreat from the westernmost Ross Sea shelf in JOIDES Trough by ~13 cal. ka BP (Prothro et al., 2020), shortly before ice recession from the headlands adjacent to western McMurdo Sound at 12.8 cal. ka BP (Hall et al., 2015). The Ross Ice Shelf remained extended in outer JOIDES Trough until ca. 9.5 cal. ka BP (Prothro et al., 2020) and its front had retreated to Ross Island by 8.6 cal. ka BP (McKay et al., 2016). Grounded ice retreat started as early as 15.1 cal. ka BP in Pennell Trough (Prothro et al., 2020) and at 14.7 cal. ka BP in Whales Deep Basin in the eastern Ross Sea (Bart et al., 2018). Retreat in these troughs appears to coincide with thinning along the major East Antarctic outlet glaciers draining through the Transantarctic Mountains. Here, ice thinning had begun by ~16 ka in the north at Tucker Glacier (Goehring et al., 2019) and 14.5 ka in the southern Transantarctic Mountains at Beardmore Glacier (Spector et al., 2017). In Marie Byrd Land on the WAIS flank of the Ross Sea sector, exposure age dated moraines and recessional deposits indicate that ice thickness was around 45 m greater than present when thinning began at ~10 ka (Ackert et al., 1999, 2013). In the Ohio Range, located at the divide between the Ross Sea drainage sector of the WAIS and the EAIS, ice had thickened by ~125 m at 11.5 ka (Ackert et al., 2007, 2013).

Timing of ice withdrawal across the shelf basins was complex, and likely influenced by topography. Rapid retreat or thinning has been documented in several glacier systems, for example abrupt thinning of EAIS glaciers draining through the southern Transantarctic Mountains at 8–9 ka (Spector et al., 2017), thinning of Mackay Glacier by ~200 m within a few hundred years at ~7 ka (Jones et al., 2015) and 200 km of ice retreat in Whales Deep Basin by 11.5 cal. ka BP (Bart et al., 2018). Both thinning of Mackay Glacier and retreat in Whales Deep Basin have been linked to grounding zone retreat through over-deepened basins. Ice appears to have reached the modern position at different times. Along the Siple Coast the grounding line apparently had retreated briefly upstream of its present location at the start of the Holocene before it readvanced to its modern position due to isostatic rebound (Kingslake et al., 2018). In the western Ross Sea, ice had largely cleared around Ross Island by 8.6 cal. ka BP (McKay et al., 2016), but retreat is assumed to have continued into the late Holocene near the southern grounding line. Terrestrial ice-free conditions enabled penguin recolonisation progressing southward along the coast from the early to middle Holocene but during the late Holocene conditions for penguin and seal colonies varied (Baroni and Orombelli, 1994b; Emslie et al., 2007; Hall et al., 2006). Cosmogenic records of the cessation of ice retreat are variable. For example, Beardmore Glacier was at or near its modern ice margin by ~8 ka, while other glaciers thinned until the mid-late Holocene – e.g., ~5 ka at Tucker Glacier (Goehring et al., 2019), ~3 ka at Scott Glacier (Spector et al., 2017) and at least ~2.8 ka at Hatherton Glacier (King et al., 2020).

With the exception of its westernmost part, the timing of retreat of the calving front of Ross Ice Shelf is poorly constrained. The ice shelf probably covered considerable portions of the central and eastern Ross Sea shelf until well into the Holocene. A substantive ice shelf occupied outer Whales Deep Basin in the eastern Ross Sea until ~12 cal. ka BP, and the inner part of the basin until ~3 cal. ka BP, several thousand years after grounding line retreat (Bart and Tulaczyk, 2020; Bart et al., 2018). Ice shelf cover of the basins on the central Ross Sea shelf apparently persisted for even longer, with the calving front in the Eastern Basin retreating from the outer shelf to near its modern position from ~5 until 1.5 cal. ka BP (Yokoyama et al., 2016). In the western Ross Sea seasonal open-marine deposition on the outer shelf parts of JOIDES Trough and Pennell Trough began at ~5 cal. ka BP (Yokoyama et al., 2016), while in the westernmost Ross Sea the ice-shelf front had retreated to near Ross Island already by 8.6 cal. ka BP (McKay et al., 2016).

Recent numerical modelling has investigated post-LGM grounding line retreat in the Ross Sea sector (Lowry et al., 2019). The work demonstrates that retreat was forced by two main factors acting in sequence: first, immediately after the glacial maximum, atmospheric conditions moderated the influence of rising ocean temperatures on melting at the grounding line; and second, during the early Holocene, ocean-forced basal melting became dominant, leading to significant retreat of the grounding line. A high-resolution ocean model combined with proxy data from sediment cores retrieved on the Adélie Land margin found that the expansion of the sub-ice shelf cavity under the Ross Ice Shelf was complete by ~5 cal. ka BP (Ashley et al., 2021). This led to modification of surface water masses formation processes on the Ross Sea and Adélie Land shelves and contributed to widespread surface water cooling and increased coastal sea ice during the late Holocene (Ashley et al., 2021). Previously, a study analysing sea-ice proxies in both marine sediment cores and ice cores from the Ross Sea sector found that a combination of wind forcing and an increase in the efficiency of regional latent-heat polynyas had increased coastal sea-ice cover but decreased overall sea-ice extent in the western Ross Sea since 3.6 cal. ka BP (Mezgec et al., 2017).

Today, warm modified Circumpolar Deep Water (CDW) may locally intrude under the Ross Ice Shelf, but it fails to reach the grounding line (Tinto, 2019). However, conditions may have been different when the ice sheet grounding line was positioned on the outer continental shelf at the end of the LGM. Modern and buried gullies, observed at the shelf edge of the Pennell Trough and Glomar Challenger basin, document periods of intense seafloor erosion, likely occurring when ice was grounded near to the shelf edge (Gales et al., 2021). These gullies likely formed at the beginning of the last (and previous) deglacial period, when sediment-laden subglacial meltwater was released at the shelf edge. Further sampling and analysis and dating of sediment cores along the slope are needed to confirm this hypothesis.

11.5.5 Amundsen-Bellingshausen Seas

Exposure dating studies in Marie Byrd Land and around the Amundsen Sea Embayment (ASE) (see also Larter et al., 2014) support the view that ice in this drainage sector of the WAIS was significantly thicker at the LGM (Johnson et al., 2008, 2014; Lindow et al., 2014; Stone et al., 2003; Sugden et al., 2006). Although the exact age for the onset of post-LGM WAIS thinning is still unconstrained in most of these areas, the exposure dates demonstrate that surface lowering began at least at ~10 ka, continued steadily and rapidly throughout the early Holocene until ~6 ka around the ASE, and continued well into the late Holocene in parts of Marie Byrd Land (Johnson et al., 2014, 2017, 2020; Lindow et al., 2014; Stone et al., 2003; Sugden et al., 2006).

Large palaeo-ice stream troughs have been identified offshore from all the major present-day outlet glaciers in the Amundsen Sea sector of West Antarctica (Anderson and Shipp, 2001; Nitsche et al., 2007; Wellner et al., 2001). Subglacial bedforms mapped with swath bathymetry revealed that Pine Island Glacier and Thwaites Glacier had merged in the past and eroded a cross-shelf trough into the eastern ASE shelf (Evans et al., 2006; Graham et al., 2010; Hogan et al., 2020; Jakobsson et al., 2012; Lowe and Anderson, 2002; Nitsche et al., 2013; Fig. 11.6). Gullies incised into the uppermost continental slope seaward of the trough mouth suggest that grounded ice had reached the shelf break at the LGM (Dowdeswell et al., 2006; Gales et al., 2013; Kirshner et al., 2012), with GZWs mapped on the outer and middle shelf parts of the trough documenting stepwise ice-stream retreat after the LGM (Graham et al., 2010; Jakobsson et al., 2012). Grounded ice also reached an outermost shelf position in Dotson-Getz Trough in the western ASE (Graham et al., 2009; Larter et al., 2009). On the westernmost Amundsen Sea shelf, a prominent GZW on the inner shelf part of Hobbs Trough was interpreted to mark a temporary stillstand in post-LGM grounding-line retreat rather than the maximum LGM extent (Klages et al., 2014), while the outer shelf part of Abbot-Cosgrove Trough on the easternmost ASE shelf was only covered by a floating ice shelf during the last glacial period (Klages et al., 2015, 2017). Geomorphological features, such as subglacial meltwater channels and cavities that probably hosted subglacial lakes, as well as sedimentary records, show that a complex subglacial hydrological

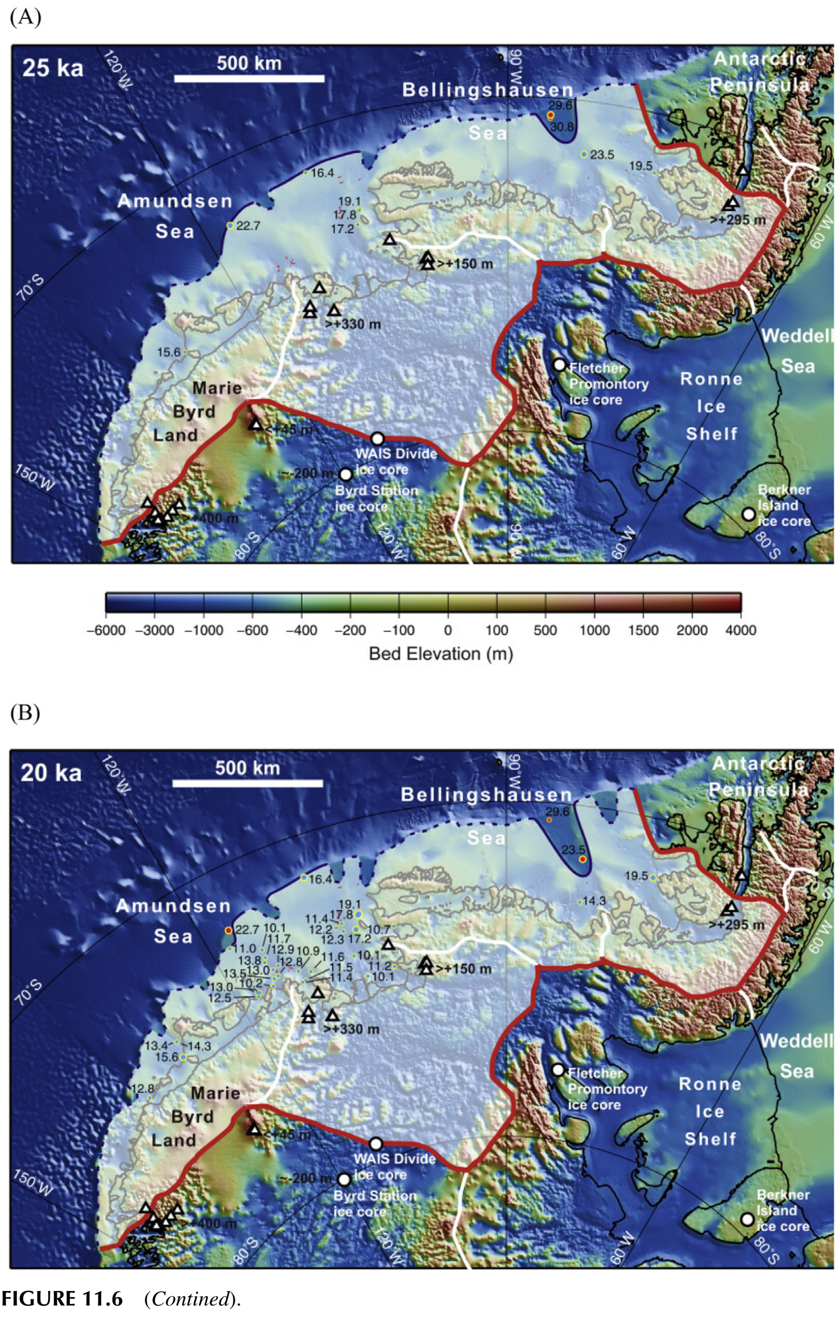
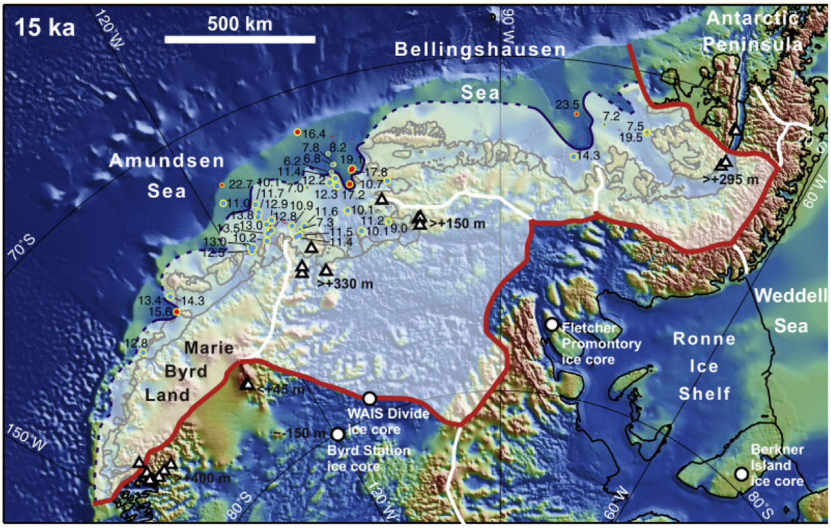


FIGURE 11.6 (*Contined*).

(C)



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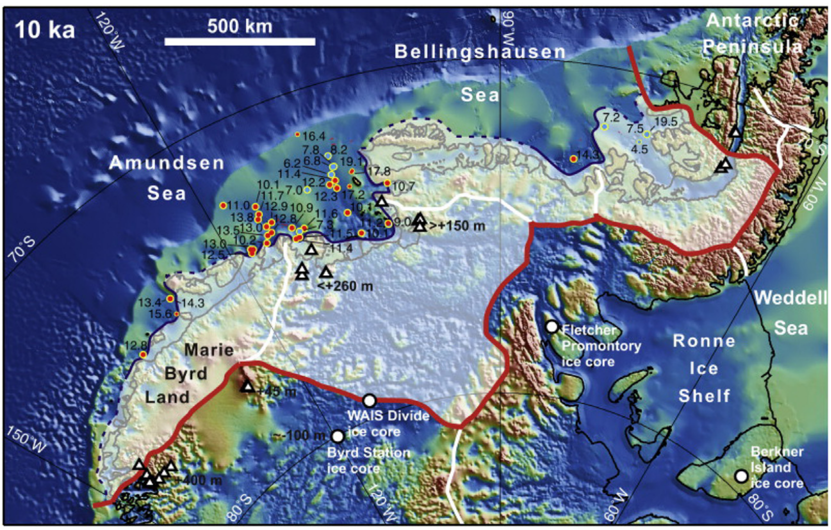

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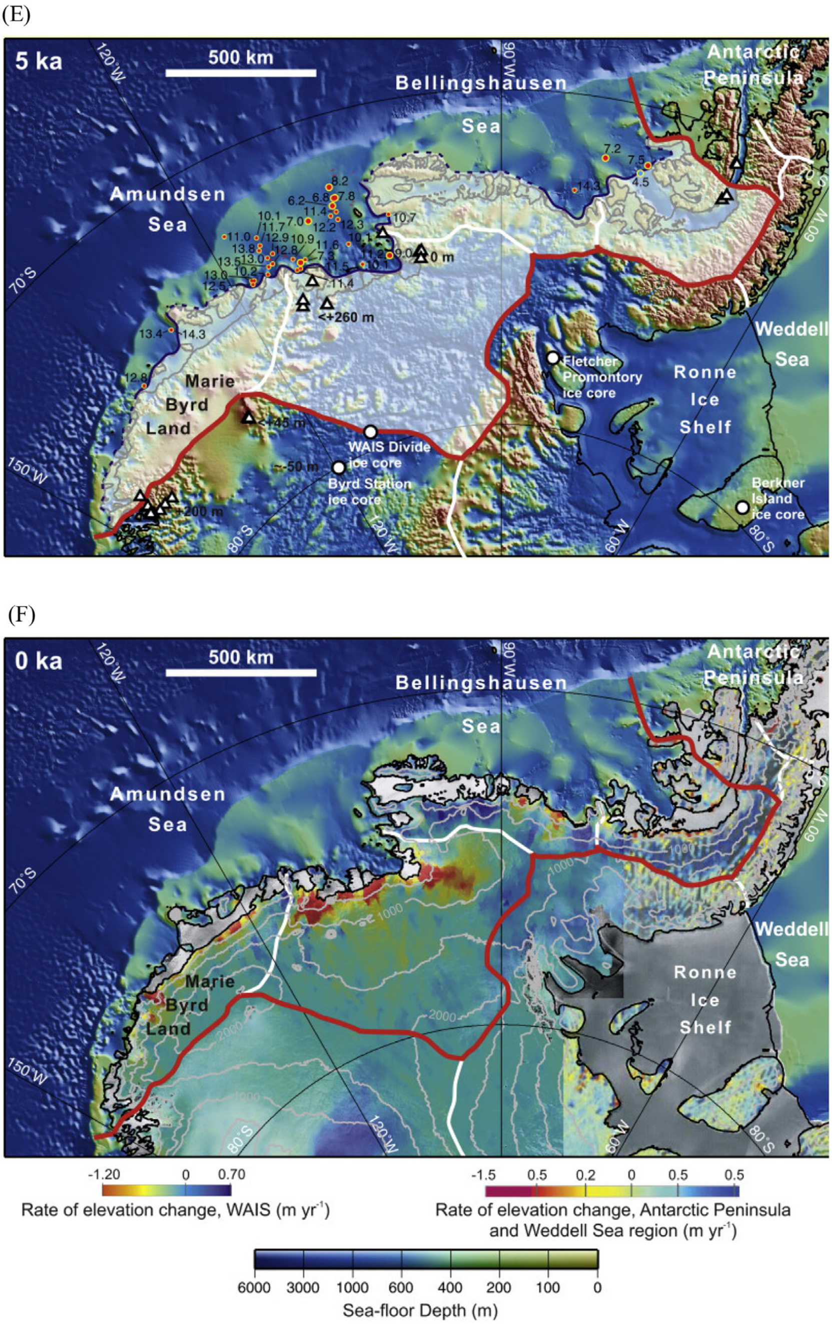

FIGURE 11.6 Ice sheet reconstructions for the Amundsen and Bellingshausen Sea sectors at (A) 25 ka, (B) 20 ka, (C) 15 ka, (D) 10 ka, (E) 5 ka and (F) 0 ka. Reconstructions are overlain (*Continued*)

system existed at the base of the WAIS on the inner ASE shelf during the LGM and earlier glacial periods (Graham et al., 2009; Kirkham et al., 2019; Kuhn et al., 2017; Lowe and Anderson, 2002, 2003; Nitsche et al., 2013; Smith et al., 2009; Witus et al., 2014).

The Pine Island-Thwaites palaeo-ice stream retreated from the outer shelf before 20.6 cal. ka BP and reached an inner shelf position by 11.7 cal. ka BP (Hillenbrand et al., 2013; Kirshner et al., 2012; Lowe and Anderson, 2002; Smith et al., 2014). Geomorphological and sedimentological evidence from the mid-shelf part of the trough indicates that an ice shelf collapse between 12.3 and 11.4 cal. ka BP had triggered rapid grounding-line retreat into the deep basins on the inner shelf (Jakobsson et al., 2011, 2012; Kirshner et al., 2012), which probably deglaciated by ice-cliff failure (Wise et al., 2017). The palaeo-ice stream occupying Dotson-Getz Trough had cleared the outer shelf by 22.4 cal. ka BP, reached the middle shelf by 13.8 cal. ka BP and the inner shelf near the present ice shelf front between 12.6 and 10.1 cal. ka BP (Smith et al., 2011). An advance of the Getz Ice Shelf front across the inner shelf during the Antarctic Cold Reversal (14.5−12.9 ka) has been concluded from biomarker analyses on a sediment core retrieved from the western tributary of the Dotson-Getz palaeo-ice stream trough (Lamping et al., 2020). Along the entire Amundsen Sea coastline the WAIS grounding line had retreated to within 100 km of, and at most locations much closer to, its modern position between ∼20.9 and 11.0 cal. ka BP (Anderson et al., 2002; Hillenbrand et al., 2013; Klages et al., 2014; Minzoni et al., 2017). Ocean forcing, caused by enhanced advection of relatively warm deep water onto the ASE shelf, is believed to have been the main driver of both post-LGM grounding-line retreat (Hillenbrand et al., 2017) and late Holocene ice-shelf retreat at the eastern ASE coast (Minzoni et al., 2017).

Ice-surface elevation upstream of Pine Island Glacier at Mt Moses and Maish Nunatak rapidly decreased by ∼142 m from ∼8.5 to ∼6.0 ka, when it reached its present elevation (Johnson et al., 2014, 2020). This indicates a considerable delay between grounding line retreat of the palaeo-ice stream

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◀ on Bedmap2 bed topography and bathymetry. Ice sheet extent is indicated by semi-transparent white fill (only shown within the Amundsen-Bellingshausen sector). Thick line is the sector boundary, which follows the main ice-drainage divides. Thick white lines mark other major ice divides. Core sites constraining the minimum time of deglaciation are marked by the circles with yellow outlines (see Larter et al., 2014; for minimum ages of deglaciation). Red fills are ages older than time of reconstruction, blue fills are younger ages; large circles are ages within 5 kyr of time of reconstruction; small circles are ages within 5 and 0 kyr. Cosmogenic surface exposure age sample locations are marked by white-filled triangles, and deep ice core sites by white-filled circles, with surface elevation constraints they provide for time of reconstruction annotated. In the modern configuration (F), contours on the ice sheet (thin grey lines) show surface elevation at 500 m intervals, from Bedmap2. Colours on ice sheet show the rate of change of surface elevation over the period 2003−2007 from Pritchard et al. (2009). *Taken from Larter et al. (2014) and reproduced with permission from Elsevier.*

and rapid thinning in its hinterland, which has been attributed to the collapse of a buttressing ice-shelf covering Pine Island Bay until ~7.5 cal. ka BP (Hillenbrand et al., 2017). Recent thinning, flow acceleration and grounding-line retreat of Pine Island Glacier and other ice streams draining into Pine Island Bay (e.g., Rignot et al., 2019; Turner et al., 2017) are believed to have been triggered by another phase of intensified upwelling of warm deep-water onto the ASE shelf that had started in the 1940s (Hillenbrand et al., 2017; Smith et al., 2017).

On the shelf of the Bellingshausen Sea, only a single but major cross-shelf trough, called 'Belgica Trough', has been mapped with multibeam bathymetry (Graham et al., 2011; Ó Cofaigh et al., 2005b; Wellner et al., 2001). This trough exhibits geomorphological evidence of a palaeo-ice stream, which presumably drained both a large part of the Ellsworth Land sector of the WAIS and the southernmost APIS during the last glacial period (Ó Cofaigh et al., 2005b). Gullies incised into the uppermost continental slope at the mouth of Belgica Trough indicate a shelf-wide advance of the palaeo-ice stream (Dowdeswell et al., 2008b; Gales et al., 2013). As for the glacial troughs on the Amundsen Sea shelf, GZWs documenting stepwise grounding line retreat were also identified in Belgica Trough (Ó Cofaigh et al., 2005b). The reconstructed timing of grounded ice advance and retreat in Belgica Trough is based on AIO ^{14}C dates only and therefore not very well constrained. Available ages suggest that the Belgica palaeo-ice stream had advanced across the shelf after ~40.0 cal. ka BP and had retreated from the outer shelf by ~30.0 cal. ka BP, the middle shelf by ~23.5 cal. ka BP, the inner shelf in Eltanin Bay by ~14.3 cal. ka BP and the inner shelf in Ronne Entrance by ~7.2 cal. ka BP (ages from Hillenbrand et al., 2010b, and calibration from Larter et al., 2014). An early onset of grounded ice retreat may be supported by onshore cosmogenic nuclide data from the eastern side of George VI Ice Shelf, suggesting that thinning of the APIS there had started by 27.2 ka (Bentley et al., 2006).

11.5.6 Antarctic Peninsula

The LGM extent of grounded ice in the Antarctic Peninsula (see also Ó Cofaigh et al., 2014) and the post-LGM glaciological and environmental history in this region have received a significant amount of attention during the past few decades, which is summarised in several review papers (Bentley and Anderson, 1998; Bentley et al., 2009; Davies et al., 2012; Heroy and Anderson, 2005, 2007; Ingólfsson et al., 2003; Johnson et al., 2011; Livingstone et al., 2012;). To date, the RAISED Consortium (Ó Cofaigh et al., 2014) has produced the most comprehensive review of deglaciation of this sector of Antarctica from terrestrial and marine geological and geophysical data (Fig. 11.7). Here, we summarise some of the patterns that emerge from the reconstruction, while also including more recent progress.

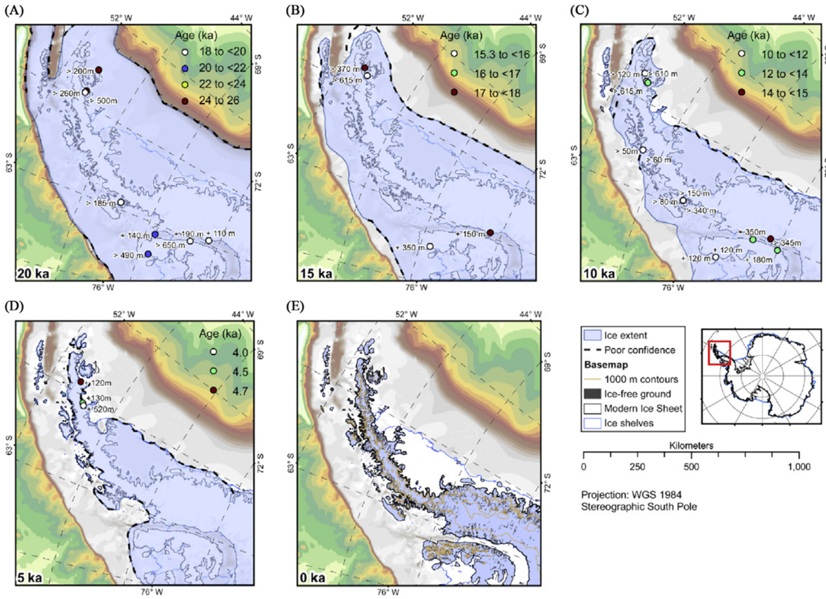


FIGURE 11.7 Ice sheet reconstructions for the Antarctic Peninsula at (A) 20 ka, (B) 15 ka, (C) 10 ka, (D) 5 ka and (E) 0 ka. *Reproduced from Ó Cofaigh et al. (2014) with permission from Elsevier.*

Terrestrial geomorphic evidence including glacial erratics and striations on nunatak summits along the length of the Antarctic Peninsula indicate that the APIS thickened significantly during the LGM. The centre of the ice sheet thickened by at least 500 m in places, reaching a maximum height of 2350 m asl at Mt Jackson (72°S), and there is evidence for at least two distinct ice domes along the spine of the southern part of the peninsula (Bentley et al., 2000, 2006; Ingólfsson, 2004). Striation orientations in the southeastern part of the Antarctic Peninsula also suggest that ice flow was deflected by an expanded WAIS in the Weddell Sea, indicating that ice advance in these two regions was synchronous (Bentley et al., 2006). The timing of maximum LGM ice thickness is not well constrained. Most data derive from cosmogenic nuclide ages from near James Ross Island and Marguerite Bay. At James Ross Island, LGM ice thickness is thought to have exceeded 370 m above present (Davies et al., 2013; Glasser et al., 2014), while to the west of James Ross Island, ice thickness was locally up to 520 m above present sea level (Balco et al., 2013). Ice core data suggest Haddington Ice Cap remained an independent ice dome (Mulvaney et al., 2012), which expanded to cover the island and merge with the APIS (Johnson et al., 2009; Mulvaney et al., 2012; Ó Cofaigh et al., 2014). Further south along the Lassiter Coast exposure dates suggest that the LGM ice surface was at least 385 m above present (Johnson et al., 2019). An LGM ice thickening of

>650 m at 27.2 ka was reconstructed for the western Antarctic Peninsula flanking George VI Ice Shelf, and thickening of >490 m at 21.8 ka is evident from eastern and northwestern Alexander Island (Bentley et al., 2006; Johnson et al., 2012).

Marine geophysical research of the continental shelf around the Antarctic Peninsula using a combination of swath bathymetry, side-scan sonar and seismic surveys, have revealed a comprehensive set of subglacial landforms that indicate the APIS was drained by several topographically-steered ice streams that were grounded at or very near the continental shelf edge during the LGM (e.g., Amblas et al., 2006; Anderson and Oakes-Fretwell, 2008; Banfield and Anderson, 1995; Campo et al., 2017; Canals et al., 2000, 2002; Domack et al., 2006; Dowdeswell et al., 2004; Evans et al., 2004, 2005; Graham and Smith, 2012; Heroy and Anderson, 2005; Larter and Vanneste, 1995; Larter et al., 2019; Lavoie et al., 2015; Livingstone et al., 2013; Ó Cofaigh et al., 2002, 2005a; Pope and Anderson, 1992; Pudsey et al., 1994). Such landforms are observed in cross-shelf bathymetric troughs around the Antarctic Peninsula and include mega-scale glacial lineations and GZWs in the outer and middle shelf sections of the troughs, and ice-moulded bedrock and subglacial meltwater channels in their inner shelf sections. Age control is only available in a few locations, and so the timing and duration of the maximum LGM ice extent remains poorly resolved (Ó Cofaigh et al., 2014). Ice likely remained at or near the shelf-edge in the Vega and Robertson troughs in the northern and northeastern Antarctic Peninsula from 25 to 20 cal. ka BP (Evans et al., 2005; Heroy and Anderson, 2005; Ó Cofaigh et al., 2014).

Retreat of the APIS grounding line from its maximum LGM position at the shelf edge is mainly constrained by a suite of AMS ^{14}C ages obtained from marine sediment cores on the western Antarctic Peninsula shelf, which suggest that its onset progressed from northeast to southwest (Heroy and Anderson, 2007; Livingstone et al., 2012; Ó Cofaigh et al., 2014). The earliest deglaciation ages of 17.5 cal. ka BP come from both Lafond Trough south of Bransfield Basin (Banfield and Anderson, 1995) and Smith Trough, with one older, but less reliable, AIO date of 18.7 cal. ka BP obtained from Biscoe Trough (Heroy and Anderson, 2007). Grounded ice had retreated to the modern coastline in this part of the Antarctic Peninsula between ~12.9 and 10.7 cal. ka BP (Domack et al., 2001, 2006; Subt et al., 2016). Further south, the grounding line of the Marguerite Trough palaeo-ice stream had retreated from the shelf edge before 14.4 cal. ka BP (Heroy and Anderson, 2007; Kilfeather et al., 2011; Pope and Anderson, 1992), the mid-shelf by ~14.1 cal. ka BP and the inner shelf by 9.6 cal. ka BP, and it reached the modern coastline before 9.1 cal. ka BP (Heroy and Anderson, 2007; Peck et al., 2015), shortly after an ice shelf extending to the middle shelf had disintegrated (Kilfeather et al., 2011). Cosmogenic nuclide dating from locations across Marguerite Bay, including Pourquois-Pas Island, Horseshoe

Island, Alexander Island and the Batterby Mountains above George VI Ice Shelf, together with ^{14}C dates on lake sediments and raised beaches show that onshore thinning was underway by 18 ka and that its main phase had ended by 10−9 ka (Bentley et al., 2006, 2011; Çiner et al., 2019; Davies et al., 2017; Hodgson et al., 2013; Johnson et al., 2012). Data from around George VI Ice Shelf also show that its northern part, or even the entire ice shelf, broke up at least once during the early Holocene (Bentley et al., 2005; Davies et al., 2017; Hodgson et al., 2006; Roberts et al., 2009; Smith et al., 2007). While post-LGM deglaciation of the western Antarctic Peninsula did not follow an entirely uniform pattern, its main phase apparently occurred from 15 to 10 cal. ka BP, with modern ice limits having been reached no later than the mid-Holocene (e.g., Heroy and Anderson, 2007; Kim et al., 2018; Ó Cofaigh et al., 2014).

Deglaciation of the northeastern Antarctic Peninsula also progressed from north to south (Ó Cofaigh et al., 2014). Initial retreat had begun by ~18.3 cal. ka BP in Vega Trough (Heroy and Anderson, 2005, 2007), and ice surface elevations had dropped below 370 m at Lachman Crags on James Ross Island at 17.7 ka (Glasser et al., 2014). The APIS grounding line is thought to have reached its modern position by 11−10 cal. ka BP at several locations along the eastern Antarctic Peninsula margin (Campo et al., 2017; Evans et al., 2005; Pudseyet al., 2001), including Prince Gustav Channel and the Larsen A and B embayments, where the transition from grounded to floating ice occurred by 10.7−10.6 cal. ka BP (Domack et al., 2005; Pudsey et al., 2006 Rosenheim et al., 2008). High-resolution multi-beam data suggest that the APIS underwent episodes of very fast grounding-line retreat, possibly >10 km/yr, during the post-LGM deglaciation (Dowdeswell et al., 2020). Cosmogenic nuclide dates from around the Larsen A and B embayments and southern Prince Gustav Channel region indicate that most thinning had occurred by ~9 ka, but that thinning continued until 8−6 ka in the southern Larsen B embayment. A north to south trend in ice sheet/shelf thinning is evident based on the emergence of ice-free areas at 8.0−6.5 ka near Prince Gustav Channel (Balco et al., 2013; Johnson et al., 2011), 6.2−4.7 ka in the Larsen A Embayment (Balco et al., 2013) and 5.1−4.9 ka in the Larsen B Embayment (Jeong et al., 2018). This trend in thinning is also consistent with marine evidence for collapses and subsequent reformations of the Larsen A and Prince Gustav Channel Ice Shelves during the Holocene (Brachfeld et al., 2003; Pudsey and Evans, 2001; Pudsey et al., 2006), which again collapsed in CE 1995 in response to recent regional warming (e.g., Hodgson et al., 2006; Vaughan et al., 2003), whereas the Larsen B Ice Shelf remained a persistent feature throughout the Holocene and did not collapse until CE 2002 (Domack et al., 2005, Rebesco et al., 2014). At the Lassiter Coast to the south, the ice surface dropped by at least 250 m from 7.5 to 6.0 ka according to ^{14}C exposure ages on bedrock (Johnson et al., 2019).

Throughout the Holocene (sub-)surface sea temperatures in Palmer Deep, western Antarctic Peninsula, cooled by either 3°C−4°C (Shevenell et al., 2011) or 1.5°C (Etourneau et al., 2013) and sea-ice cover increased in response to a long-term decline in annual and spring insolation, which influenced the location of the Southern Hemisphere westerlies and upwelling of warm deep water onto the shelf. These long-term trends were superimposed by strong centennial- to millennial-scale variations derived from ENSO variability (Etourneau et al., 2013; Shevenell et al., 2011). Glacial discharge from the APIS in Palmer Deep showed a strong dependence on increasing occurrence of La Niña events and rising levels of summer insolation (Pike et al., 2013).

On the east side of the northern Antarctic Peninsula, heavy sea ice conditions and reduced primary productivity prevailed from 8.8 until 7.4 cal. ka BP, with a southward shift of the westerly winds and the Antarctic Circumpolar Current causing warming and reduced sea ice coverage between 7.4 and 5 cal. ka BP (Barbara et al., 2016). Expansion of the Weddell Gyre and development of a strong oceanic connection between the eastern and western Antarctic Peninsula caused a gradual increase in annual sea-ice duration from 5 cal. ka BP until 1.9 cal. ka BP (Barbara et al., 2016). Glacial discharge from the eastern APIS remained unchanged from 6.3 to 1.6 cal. ka BP but has increased significantly since CE 1700, with a major increase observed since CE 1912 (Dickens et al., 2019). This trend has been attributed to a positive SAM, which drove stronger westerly winds, atmospheric warming and surface ablation on the eastern Antarctic Peninsula (Dickens et al., 2019). Increases in subsurface (50−400 m) ocean temperatures by 0.3°C−1.5°C are believed to have affected the stability and extent of ice shelves at the northeastern Antarctic Peninsula both during the Holocene and since the 1990s (Etourneau et al., 2019). Sea ice and temperature data from both sides of the northern Antarctic Peninsula show ocean warming and sea-ice reduction from CE 1935 to 1950 and notable variability but no clear trend thereafter, suggesting that multi-decadal sea ice variations over the last century were forced by the recent atmospheric warming affecting the Antarctic Peninsula (e.g., Vaughan et al., 2003), whereas the observed annual-to-decadal variability was mainly governed by synoptic and regional wind fields (Barbara et al., 2013).

11.5.7 Weddell Sea Embayment

The Weddell Sea sector may have contributed a similar magnitude of post-LGM sea level rise to that of the Ross Sea sector, yet our knowledge of the extent of the grounding line and the change in thickness of the inland ice is by comparison not as well constrained (see also Hillenbrand et al., 2014) (Fig. 11.8). The great uncertainty in LGM grounded ice thickness and extent has been fully described in the RAISED Consortium review for the Weddell

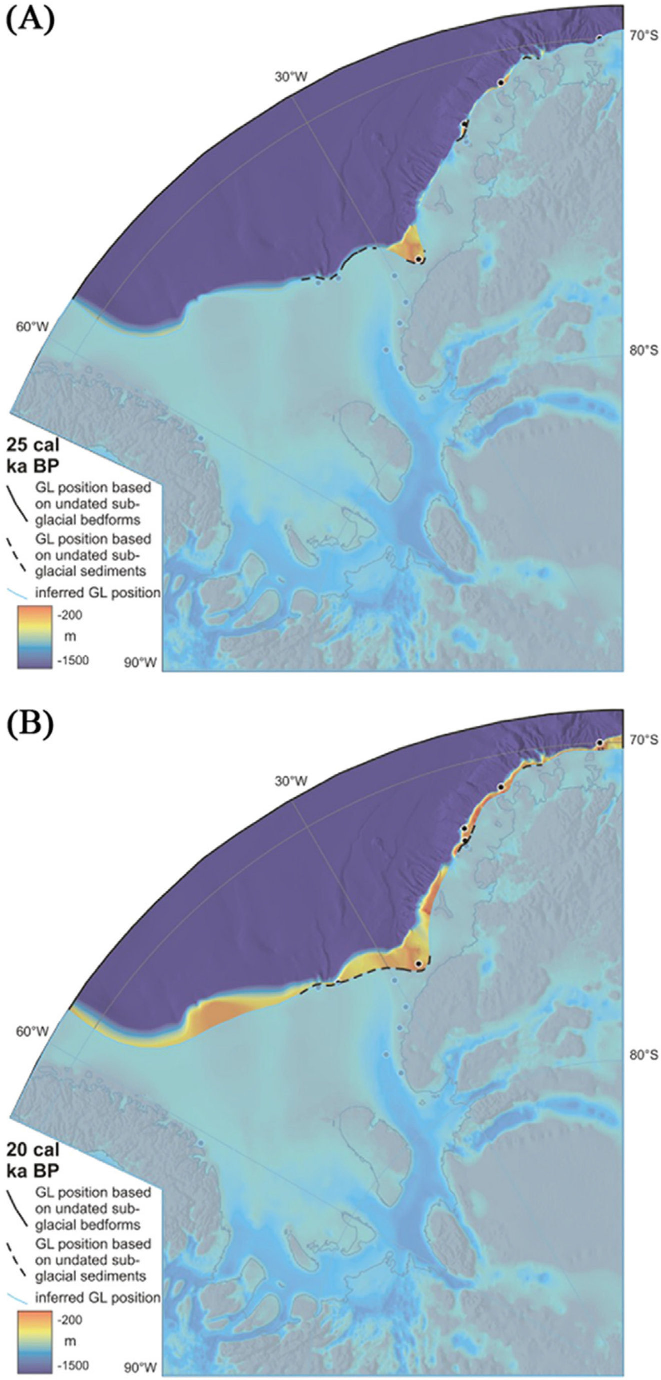


FIGURE 11.8 Ice sheet reconstructions across the Weddell Sea sector of Antarctica, revealing both a 'maximum' LGM extent based mainly on marine data and a 'minimum' LGM extent based mainly on terrestrial geological data. (A) 25 ka maximum, (B) 20 ka maximum, (C) 20 ka minimum, (D) 15 ka maximum, (E) 15 ka minimum, (F) 10 ka maximum, (G) 10 ka minimum, (H) 5 ka maximum, and (I) 5 ka minimum. *Reproduced from Hillenbrand et al. (2014) with permission from Elsevier.*

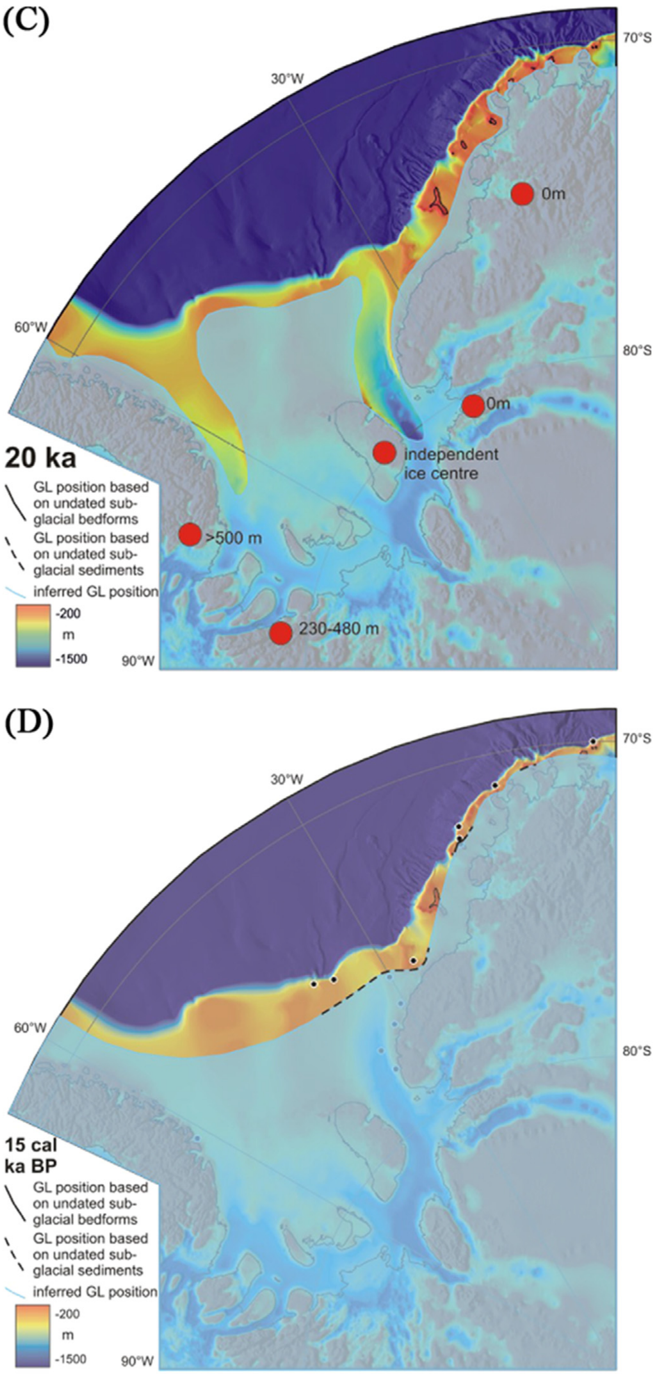
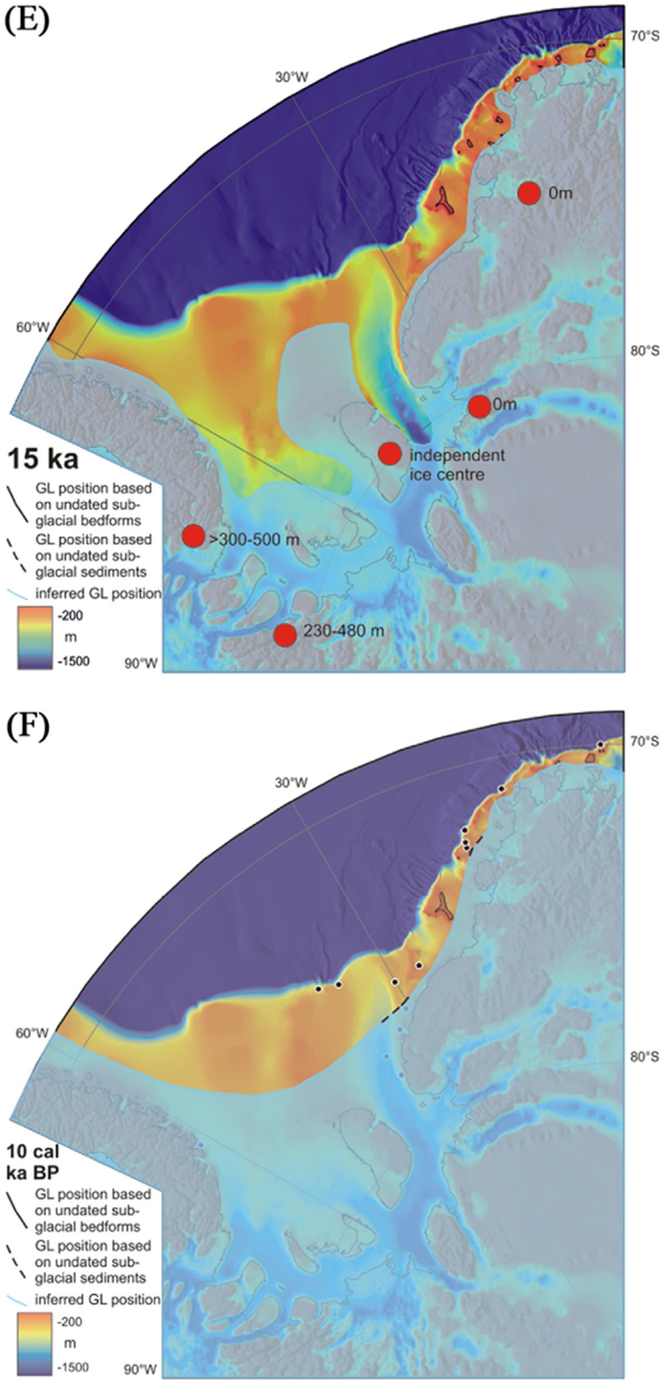


FIGURE 11.8 (*Contined*).



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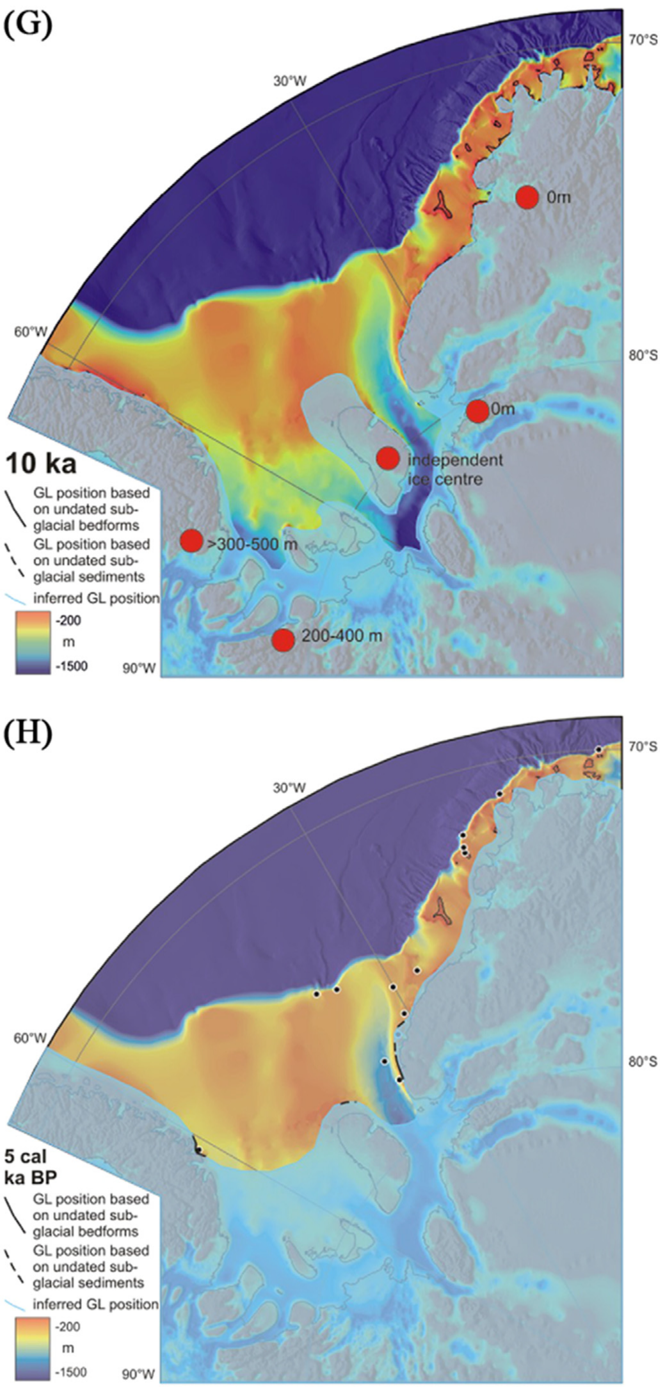

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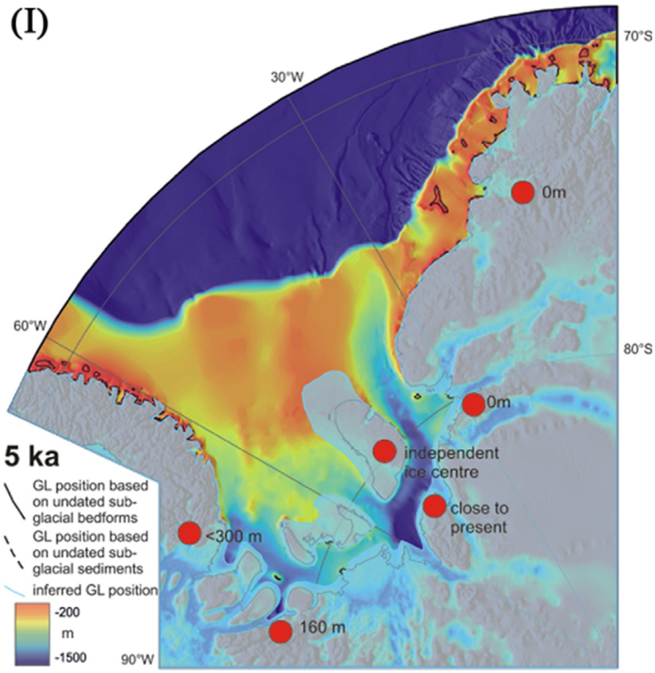

FIGURE 11.8 (*Contined*).

Sea sector (Hillenbrand et al., 2014). In this review, two deglaciation scenarios based on either marine or terrestrial data were presented. The key difference is the extent of grounded ice in the over-deepened troughs that extend beneath Filchner-Ronne Ice Shelf; the marine data favour grounded ice near the shelf edge while the terrestrial data favour more restricted grounded ice within Filchner Trough. Both configurations appear glaciologically plausible based on glacier flowline modelling (Whitehouse et al., 2017). The fact that two incompatible reconstructions of ice extent exist demonstrates the dearth of geochronological and geomorphological data in this sector. The situation is now changing. In the past decade, several new marine and terrestrial studies have provided important information on the thickness and extent of ice in this sector and the timing of its retreat.

In the Shackleton Range (80.2°S, 30.0°W), cosmogenic nuclide exposure-age dating of erratics and surface bedrock has been used to constrain the LGM thickening of the ice near the present-day grounding line of Slessor Glacier, where it joins Filchner Ice Shelf (Fogwill et al., 2004; Hein et al., 2011, 2014; Nichols et al., 2019). Here, ^{10}Be and ^{26}Al exposure dates of LGM age were found only on the modern ice margin, which suggests Slessor Glacier at the LGM was not significantly thicker or more extensive than today (Hein et al., 2011, 2014). Recent advances have made it possible to measure in situ ^{14}C in quartz, and this nuclide is better suited to date recent exposure because of its short half-life, which makes it comparatively insensitive to inheritance. Nichols et al. (2019) measured in situ ^{14}C in some of the same rock samples with ^{10}Be and ^{26}Al data and found clear evidence for thicker ice in the Shackleton Range during the late glacial period and the early Holocene. LGM ice surfaces in the Shackleton Range are now thought to have been between 310 and 650 m above the present Slessor Glacier surface.

In the Dufek Massif, northern Pensacola Mountains (centred at 83.5°S, 57.0°W), mapping of bouldery moraines and cosmogenic surface exposure dates of erratics on the moraines, along with radiocarbon ages around the margins of a pond, had suggested only moderate ice sheet thickening and advance of less than 2.5 km along-valley during the last glacial advance, which was assumed to have occurred at the LGM (Hodgson et al., 2012). Later on, cosmogenic nuclide exposure-age dating of erratics and bedrock was used in the southern Pensacola Mountains to constrain the LGM thickening of the ice near the present-day grounding line of Foundation Ice Stream, where it feeds into Filchner Ice Shelf (reviewed in Nichols et al., 2019; Siegert et al., 2019). Here, recent in situ ^{14}C exposure ages from Schmidt Hills indicate LGM thickening of at least 800 m (Nichols et al., 2019). This result supersedes the results of Balco et al. (2016) and Bentley et al. (2017) that indicated thickening of less than 200 m based on long-lived cosmogenic ^{10}Be data. Further upstream at Williams Hills there is evidence for at least 500 m of thickening of Foundation Ice Stream and Academy Glacier before 11 ka, with this amount of thinning occurring throughout the Holocene from 11 to 2.5 ka (Balco et al., 2016; Bentley et al., 2017). In the Thomas Hills further upstream, LGM thickening of at least 400 m is recorded by both ^{10}Be and in situ ^{14}C ages (Balco et al., 2016; Bentley et al., 2017; Nichols et al., 2019).

In the southern Weddell Sea sector, exposure dates demonstrate that erosional glacial trimlines preserved more than 1000 m above the present ice surface in the Ellsworth Mountains (Denton et al., 1992) are much older than LGM (Sugden et al., 2006). In the southern Heritage Range (80.2°S, 82.0°W), measurements of cosmogenic ^{26}Al, ^{10}Be and ^{21}Ne in a depth-profile through an ice-moulded bedrock surface indicate this erosional trimline pre-dates the Quaternary with an age of first exposure between 3.5 and 5.1 Ma; its true age is likely much older (Sugden and Jamieson, 2018; Sugden et al., 2017).

In the southern Ellsworth Mountains, ice elevations during the LGM were up to 475 m higher than today as evidenced by cosmogenic ^{10}Be exposure ages from elevated, ice marginal blue-ice moraine deposits in Marble Hills (Bentley et al., 2014; Hein et al., 2016a,b). Here, thinning began by 10 ka with a pulse of rapid thinning of ~400 m occurring at 6.5–3.5 ka (Hein et al., 2016b). The present ice margin is the same as it was at 3.5 ka. Thickening of Rutford Ice Stream reached ~900 m at the

LGM with thinning occurring between 14.5 and 6 ka (Fogwill et al., 2014a). Further south in Pirrit Hills, ice elevations reached 320 m above present and thinning occurred from 14 to 4 ka (Spector et al., 2019). In the Whitmore Mountains near the Weddell/Ross ice divide, the maximum ice thickness during the last glacial period were no more than 190 m when compared to the present (Spector et al., 2019). In situ ^{14}C and ^{10}Be data indicate the ice here was thicker than today for no more than 8 thousand years within the last 15 ka. Thickening at this inland site occurred well after the LGM in response to increase in snowfall (Spector et al., 2019), a result that agrees with earlier work in the interior of the WAIS (Ackert et al., 2007, 2013). At the ice divide between the Weddell Sea and Amundsen Sea drainage sectors, Ross et al. (2011) examined internal radio-echo layers, which show that this divide was remarkably stable during Holocene retreat of the ice margin.

In the southwestern Weddell Sea, cosmogenic ^{10}Be and ^{26}Al exposure ages indicate that LGM ice elevations in the Behrendt Mountains (75.5°S, 72.5°W) were at least 300 m higher than today (Bentley et al., 2006). Recent work on the Lassiter Coast (74.5°S, 62.5°W) demonstrates that the elevation of Johnston Glacier exceeded 385 m above present at the LGM (Johnson et al., 2019). Here, a mid-Holocene pulse of thinning of at least 250 m occurred from 7.5 to 6.0 ka according to in situ ^{14}C exposure ages from bedrock surfaces. The timing and magnitude of thinning are similar to those observed in the southern Ellsworth Mountains (Hein et al., 2016b) and Pensacola Mountains (Balco et al., 2016; Bentley et al., 2017).

Terrestrial data indicate greater ice thicknesses at the mouths of major Antarctic ice streams which result in surface gradients that are more compatible with the marine record indicating extensive grounded ice in Filchner Trough at the LGM (Anderson and Andrews, 1999; Anderson et al., 1980; Arndt et al., 2017; Bentley and Anderson, 1998; Elverhøi, 1981; Gales et al., 2013, 2014; Hillenbrand et al., 2012, 2014; Hodgson et al., 2018; Larter et al., 2012; Melles and Kuhn, 1993; Stolldorf et al., 2012). Recent swath bathymetry imagery, acoustic sub-bottom profiles and sediment core data from the outer Filchner Trough (75°50′S) provide evidence for a highly dynamic ice stream until the early Holocene (Arndt et al., 2017). Here, mega-scale glacial lineations, iceberg furrows and a series of GZWs were identified and their formation chronologically constrained. The geomorphology and available AMS ^{14}C dates on foraminifera suggest the grounded ice margin had advanced onto and retreated from the outer shelf before 27.5 cal. ka BP, several thousand years before the global LGM. The Filchner palaeo-ice stream then re-advanced to deposit GZWs at this site at least twice after 11.8 cal. ka BP, with final retreat before 8.7 cal. ka BP (Arndt et al., 2017), when glacimarine conditions established 220 km further upstream (Hillenbrand et al., 2014). This dynamic behaviour of the Filchner palaeo-ice stream may be linked to the reorganisation and re-routing of East and West Antarctic ice stream tributaries during the last glacial period, the post-LGM deglaciation and the Holocene (e.g., Arndt et al., 2017; Fogwill et al., 2014b; Kingslake et al., 2016; Larter et al., 2012; Rosier et al., 2018; Siegert et al., 2013, 2019; Whitehouse et al., 2017; Winter et al., 2015). The timing of early Holocene grounding line retreat in Filchner Trough is consistent with delayed early to mid-Holocene thinning observed at several locations across the southern Weddell Sea sector (Balco et al., 2016; Bentley et al., 2017; Hein et al., 2016a,b; Johnson et al., 2019; Nichols et al., 2019).

The glacial geomorphological footprint to the east of Filchner Trough reveals that the post-LGM retreat of the Filchner-palaeo ice stream resulted in its progressive southwards decoupling from outlet glaciers draining the EAIS along the eastern flank of the Weddell Sea embayment (Hodgson et al., 2018). In the northeastern embayment, a palaeo-ice stream that had formed in the area of the modern Stancomb-Wills Ice Shelf acted as the main conduit for ice drainage from the EAIS at the LGM (Arndt et al., 2020). GZWs document that this ice stream underwent stepwise retreat, with its grounding line having retreated from near the modern ice-shelf front by 10.5 cal. ka BP. Bedforms in front of the modern Brunt Ice Shelf further south hint at slow flow of grounded ice there during the last glacial period, while another glacial trough further west, called ‘Halley Trough’ (Gales et al., 2014), is assumed to have been covered by floating ice only during the LGM (Arndt et al., 2020).

Most geological records from the Weddell Sea sector indicate that ice margins had reached their present limits by the late Holocene. However, it is also suggested that grounding lines may have retreated significantly further upstream before re-advancing to their present locations as a consequence of glacial isostatic adjustment and ice shelf and ice rise buttressing (Bradley et al., 2015; Kingslake et al., 2016, 2018; Siegert et al., 2019; Wolstencroft et al., 2015). Radar investigations of the subglacial topography and internal ice sheet structures inform us that the Institute Ice Stream’s grounding line is positioned on the top of a steep and sizeable reverse bed slope, towards the $>$2 km deep Robin Subglacial Basin (Siegert et al., 2019). However, satellite altimetry reveals little change today, suggesting the ice stream is presently ‘stable’, despite it being on the threshold of marine ice sheet instability (Ross et al., 2012). Radar stratigraphy reveals that Bungenstock Ice Rise, bordering one side of the ice stream, comprises buckled and broken internal layering beneath horizontal and unbroken layers. The glaciological explanation is that the ice rise has been subject to major changes in ice dynamics, from fast flowing in the past to today’s very slow flow (Siegert et al., 2013). The date when this transition happened can be estimated from the age of the stratigraphic transition in the ice, which is around 5 ka. Hence, the region has experienced major ice dynamic change in the mid-Holocene (Siegert et al., 2019).

There are two explanations for this change. The first is that this entire sector of the ice sheet gently relaxed from its LGM position, halting the grounding line at its present location, with alteration in subglacial routing of water dictating ice-stream dynamic change. In this case, the buckled layers in Bungenstock Ice Rise are relics from a former ice stream that switched off ~5000 years ago. An alternative explanation is that, during post-LGM relaxation, the entire Robin Subglacial Basin deglaciated, and the release in the ice loading led to crustal uplift, which in turn caused floating ice across what is now Bungenstock Ice Rise to ground and build up. In this situation, the buckled layers are advected from an ice stream further up flow. At present, there is no conclusive evidence for either explanation (Siegert et al., 2019), though it is planned to undertake ice-core drilling combined with geophysical surveys in the region and utilise their results for constraining numerical models in order to understand how, and under which conditions, postglacial uplift can help to stabilise marine ice-sheet decay.

11.6 Discussion: pattern and timing of post-LGM ice retreat and thinning

The geological record provides convincing evidence that the Antarctic ice sheets were more expanded at the LGM and subsequently decreased in extent and thinned near their margins. The magnitude of ice retreat varies around the continent, ranging from relatively little marginal change at some terrestrial sites, such as the Larsemann Hills, to retreat of the grounding line by hundreds of kilometres in the large embayments currently occupied by the Ross and Filchner-Ronne ice shelves and along the Pacific margin of West Antarctica. At most of the marine sites studied, the evidence implies that the maximum ice extent at the LGM was relatively short-lived, while data from several terrestrial sites (e.g., Bunger Hills, Lützow-Holm Bay) suggest that the LGM was not necessarily the period of greatest ice extent during the last glacial cycle, and that ice sheet margins were more advanced prior to 35 ka.

Similarly, evidence for the timing of ice retreat following the LGM supports different retreat timings at different sites (Anderson, 1999; Livingstone et al., 2012; The RAISED Consortium, 2014). Some areas, such as the Antarctic Peninsula and the Amundsen Sea sector of the WAIS, appear to have responded relatively rapidly to global climate and sea level changes following the LGM. At other locations, including the Ross Sea, the Weddell Sea and the East Antarctic margin at Framnes Mountains, ice retreat appears to have begun relatively late and, in a few places, such as locations in Marie Byrd Land, may have continued to the present day. In the Ross Sea, ice streams fed by ice from West Antarctica interacted with glaciers from East Antarctica, leading to a complex retreat history that has only recently been recognised (Greenwood et al., 2018; Halberstadt et al., 2016; Prothro et al., 2018, 2020). While the evidence for this timetransgressive retreat is not definitive, the pattern may point to the differing sensitivities of each region to external forcing (e.g., Lowry et al., 2019).

Evidence for smaller ice volumes/ice extents during the mid-late Holocene relative to the present day is available at a number of sites. Sediments from the bed of epishelf Moutonée Lake indicate the free movement of icebergs, and therefore the partial or total collapse of the George VI Ice Shelf between Alexander Island and the Antarctic Peninsula, between 9.6 and 8 cal. ka BP (Bentley et al., 2005). Likewise, analyses of sediment cores recovered from the seabed of Prince Gustav Channel on the eastern side of the Antarctic Peninsula have shown that between 5 and 2 ^{14}C ka BP (corrected), clasts were sourced from a range of distal locations, indicating open marine conditions and the collapse of Prince Gustav Channel Ice Shelf (Pudsey and Evans, 2001). The mid-Holocene glacial minimum may not be confined to the Antarctic Peninsula. Goodwin (1996) provides evidence from a number of sources that Law Dome was at least 3–4 km smaller before ~4 ka, while data on penguin colonisation (Emslie et al., 2007) suggest that ice shelves along the western Ross Sea coast were reduced from ~4.0 to ~2.0 cal. ka BP.

Geological evidence suggests that the Larsen B Ice Shelf had been in place since 10.7 cal. ka BP before its collapse in CE 2002 (Domack et al., 2005; Rebesco et al., 2014). In East Antarctica, Verleyen et al. (2005) provide relative sea level (RSL)-based evidence for increased ice load near Larsemann Hills between ~7.1 and 2.5 cal. ka BP. Given the similarity of the RSL curve to that obtained from the Vestfold Hills (Zwartz et al., 1998b), this may have been more than a local feature. This fluctuation may correlate with glacial advances identified through striae patterns and weathering in the Vestfold Hills (Adamson and Pickard, 1986a,b) and the Rauer Group (White et al., 2009).

The idea that ocean forcing, rather than ice surface melting induced by atmospheric warming or global sea-level rise caused by post-LGM decay of Northern Hemisphere ice sheets, triggered rapid thinning and retreat of the Antarctic ice sheets subsequent to the LGM has stimulated a number of studies, which aimed at reconstructing advection of warm deep water onto the continental shelf. Following on from Hillenbrand et al. (2017) and Minzoni et al. (2017), who had reported ocean-forced ice sheet and ice-shelf retreat in the Amundsen Sea Embayment at the end of the LGM and during the Holocene, respectively, evidence from marine sediment records from the northeastern Antarctic Peninsula shelf show that ocean forcing strongly contributed to Holocene and recent ice-shelf collapses in this region (Etourneau et al., 2019). Similarly, the history of ice-sheet thinning and retreat in East Antarctica's Lützow-Holm Bay was also proposed to have resulted from warm deep-water intrusions (Kawamata et al., 2020). Further east in Edward VIII Gulf, however, elevated bed topography landward of deep troughs incised into the shelf apparently helped to stabilise the ice sheet during the Holocene, despite the presence of warm water on the continental shelf (Dove et al., 2020). Because most of the Antarctic continental margin remains poorly investigated and sampled, we are still far from understanding causes and feedbacks of ice-sheet/ocean interactions.

11.7 Summary

There is persuasive marine geological evidence from the relatively well-studied Ross Sea and Amundsen Sea embayments and the western Antarctic Peninsula shelf for an LGM ice sheet grounding line at, or very near to the edge of the continental shelf. A similar situation possibly existed on the eastern side of the Antarctic Peninsula and in the Weddell Sea embayment, although these regions have been less well studied to date. LGM thickening of the WAIS has been identified in several locations with the ice surface in the central regions likely to have been several hundred metres higher than today. Likewise, the APIS was up to 500 m thicker at central sites at that time.

The smaller number of studies undertaken on the EAIS have found wide variations in the extent of LGM ice advance across the continental shelf. It appears that the grounding line in East Antarctica advanced to the continental shelf break in some places, to a mid-shelf position in others, but not significantly at all elsewhere. Furthermore, there are several sites in East Antarctica, including the Bunger Hills, where deglaciation appears to have begun by $\sim$30 ka, well before the LGM.

The timing and rate of deglaciation following the LGM and during the Holocene appears to have varied greatly across the continent. The APIS and the Amundsen Sea sector of the WAIS may have been among the first regions to reach their pre-industrial ice-sheet configurations, while the Ross Sea sector along with many coastal areas in East Antarctica responded less rapidly to climate and sea-level change since the LGM.

At the end of the 20th Century, estimates of the reduction in the total volume of the Antarctic ice sheets since their maximum during the last glacial cycle ranged from 0.5 to 37 m SLE. Analysis of the geological evidence in the late 1990s and early 2000s considered the upper estimates improbable, with a consensus tending towards the upper end of the lower half of this range. Although there was no single agreed value, estimates based on geological evidence at that time (Bentley, 1999, 6.1−13.1 m; Denton and Hughes, 2002, 14 m) started to converge with those based on numerical ice sheet modelling (Ritz et al., 2001, 5.9 m; Huybrechts, 2002, 19.2 m; Philippon et al., 2006, 9.5−17.5 m) and those based on modelling of isostatic postglacial uplift (Nakada et al., 2000, 6.6−16.7 m; Peltier, 2004, 17.3 m) to narrow the likely range to 5.9−19.2 m SLE. The most recent numerical models, published after 2010, indicate an Antarctic contribution of 9.9 ± 1.7 m SLE to the global LGM sea-level lowstand of 120 m (see references in Simms et al., 2019), which is largely in line with constraints from geological data (The RAISED Consortium, 2014) and from a recent global reconstruction of LGM ice volume (Gowan et al., 2021).

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References

Ackert Jr., R.P., Barclay, D.J., Borns Jr., H.W., Calkin, P.E., Kurz, M.D., Fastook, J.L., et al., 1999. Measurements of past ice sheet elevations in interior West Antarctica. Science 286, 276–280. Available from: https://doi.org/10.1126/science.286.5438.276.

Ackert, R.P., Mukhopadhyay, S., Parizek, B.R., Borns, H.W., 2007. Ice elevation near the West Antarctic Ice Sheet divide during the last glaciation. Geophysical Research Letters 34, L21506. Available from: https://doi.org/10.1029/2007GL031412.

Ackert, R.P., Putnam, A.E., Mukhopadhyay, S., Pollard, D., DeConto, R.M., Kurz, M.D., et al., 2013. Controls on interior West Antarctic Ice Sheet elevations: inferences from geologic constraints and ice sheet modeling. Quaternary Science Reviews 65, 26–38. Available from: https://doi.org/10.1016/j.quascirev.2012.12.017.

Adamson, D.A., Mabin, M.C.G., Luly, J.G., 1997. Holocene isostasy and late Cenozoic development of landforms including Beaver and Radok Lake basins in the Amery Oasis, Prince Charles Mountains, Antarctica. Antarctic Science 9 (3), 299–306. Available from: https://doi.org/10.1017/S0954102097000382.

Adamson, D.A., Pickard, J., 1983. Late Quaternary ice movement across the Vestfold Hills, East Antarctica. In: Oliver, R.L., James, P.R., Jago, J.B. (Eds.), Antarctic Earth Science. Australian Academy of Science, Canberra, pp. 465–469.

Adamson, D.A., Pickard, J., 1986a. Cainozoic history of the Vestfold Hills. In: Pickard, J. (Ed.), Antarctic oasis. Academic Press, Sydney, pp. 63–97.

Adamson, D.A., Pickard, J., 1986b. Physiography and geomorphology of the Vestfold Hills, Antarctica. In: Pickard, J. (Ed.), Antarctic Oasis. Academic Press, Sydney, pp. 99–139.

Amblas, D., Urgeles, R., Canals, M., Calafat, A.M., Rebesco, M., Camerlenghi, A., et al., 2006. Relationship between continental rise development and palaeo-ice sheet dynamics, Northern Antarctic Peninsula Pacific margin. Quaternary Science Reviews 25, 933–944. Available from: https://doi.org/10.1016/j.quascirev.2005.07.012.

Anandakrishnan, S., Blankenship, D.D., Alley, R.B., Stoffa, P.L., 1998. Influence of subglacial geology on the position of a West Antarctic ice stream from seismic observations. Nature 394, 62–65. Available from: https://doi.org/10.1038/27889.

Anderson, J.B., 1999. Antarctic Marine Geology. Cambridge University Press, p. 289.

Anderson, J.B., Andrews, J.T., 1999. Radiocarbon constraints on ice sheet advance and retreat in the Weddell Sea, Antarctica. Geology 27, 179–182. Available from: https://doi.org/10.1130/0091-7613(1999)027%3C0179:RCOISA%3E2.3.CO;2.

Anderson, J.B., Conway, H., Bart, P.J., Witus, A.E., Greenwood, S.L., McKay, R.M., et al., 2014. Ross Sea paleo-ice sheet drainage and deglacial history during and since the LGM. Quaternary Science Reviews 100, 31–54. Available from: https://doi.org/10.1016/j.quascirev.2013.08.020.

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., Oakes-Fretwell, L., 2008. Geomorphology of the onset area of a palaeo-ice stream, Marguerite Bay, Antarctica Peninsula. Earth Surface Processes and Landforms 33, 503–512.

Anderson, J.B., Shipp, S.S., 2001. Evolution of the West Antarctic Ice Sheet. In: Alley, R.B., Bindschadler, R. (Eds.), The West Antarctic Ice Sheet: Behaviour and Environments, 77. American Geophysical Union, Washington, DC, pp. 45−57.

Anderson, J.B., Shipp, S.S., Lowe, A.L., Wellner, J.S., Mosola, A.B., 2002. The Antarctic Ice Sheet during the last glacial maximum and its subsequent retreat history: a review. Quaternary Science Reviews 21, 49−70. Available from: https://doi.org/10.1016/S0277-3791(01)00083-X.

Andrews, J.T., Domack, E.W., Cunningham, W.L., Leventer, A., Licht, K.J., Jull, A.J.T., et al., 1999. Problems and possible solutions concerning radiocarbon dating of surface marine sediments, Ross Sea, Antarctica. Quaternary Research 52, 206−216. Available from: https://doi.org/10.1006/qres.1999.2047.

Armand, L.K., 2000. An ocean of ice − advances in the estimation of past sea ice in the southern ocean. GSA Today 10, 1−7.

Arndt, J.E., Hillenbrand, C.-D., Grobe, H., Kuhn, G., Wacker, L., 2017. Evidence for a dynamic grounding-line in outer Filchner Trough, Antarctica, until the early Holocene. Geology 45 (11), 1035−1038. Available from: https://doi.org/10.1130/G39398.1.

Arndt, J.E., Larter, R.D., Hillenbrand, C.-D., Sørlie, S.H., Forwick, M., Smith, J.A., et al., 2020. Past ice sheet−seabed interactions in the northeastern Weddell Sea embayment, Antarctica. The Cryosphere 14, 2115−2135. Available from: https://doi.org/10.5194/tc-14-2115-2020.

Ashley, K.E., McKay, R., Etourneau, J., Jimenez-Espejo, F.J., Condron, A., Albot, A., et al., 2021. Mid-Holocene Antarctic sea-ice increase driven by marine ice sheet retreat. Climate of the Past 17, 1−19. Available from: https://doi.org/10.5194/cp-17-1-2021.

Austermann, J., Mitrovica, J.X., Latychev, K., Milne, G.A., 2013. Barbados-based estimate of ice volume at Last Glacial Maximum affected by subducted plate. Nature Geoscience 6, 553−557.

Balco, G., Schaefer, J.M., LARISSA Group, 2013. Exposure-age record of Holocene ice sheet and ice shelf change in the northeast Antarctic Peninsula. Quaternary Science Reviews 59, 101−111. Available from: https://doi.org/10.1016/j.quascirev.2012.10.022.

Balco, G., Todd, C., Huybers, K., Campbell, S., Vermuelen, M., Hegland, M., et al., 2016. Cosmogenic-nuclide exposure ages from the Pensacola Mountains adjacent to the foundation ice stream, Antarctica. American Journal of Science 316, 542−577. Available from: https://doi.org/10.2475/06.2016.02.

Bamber, J.L., Riva, R.E.M., Vermeersen, B.L.A., LeBrocq, A.M., 2009. Reassessment of the potential sea-level rise from a collapse of the West Antarctic Ice Sheet. Science 324, 901−903. Available from: https://doi.org/10.1126/science.1169335.

Banfield, L.A., Anderson, J.B., 1995. Seismic facies investigation of the Late Quarternary glacial history of Bransfield Basin, Antarctica. In: Cooper, A.K., Barker, P.F., Brancolini, G. (Eds.), Geology and Seismic Stratigraphy of the Antarctic Margin. Antarctic Research Series, 68. American Geophysical Union, pp. 123−140. Available from: https://doi.org/10.1029/AR068p0123.

Bard, E., Hamelin, B., Fairbanks, R.G., 1990. U-Th ages obtained by mass spectrometry in corals from Barbados: sea level during the past 130,000 years. Nature 346, 456−458. Available from: https://doi.org/10.1038/346456a0.

Barbara, L., Crosta, X., Leventer, A., Schmidt, S., Etourneau, J., Domack, E., et al., 2016. Environmental responses of the Northeast Antarctic Peninsula to the Holocene climate variability. Paleoceanography 31, 131−147. Available from: https://doi.org/10.1002/2015PA002785.

Barbara, L., Crosta, X., Massé, G., Ther, O., 2010. Deglacial environments in eastern Prydz Bay, East Antarctica. Quaternary Science Reviews 29, 2731−2740. Available from: https://doi.org/10.1016/j.quascirev.2010.06.027.

Barbara, L., Crosta, X., Schmidt, S., Massé, G., 2013. Diatoms and biomarkers evidence for major changes in sea ice conditions prior the instrumental period in Antarctic Peninsula. Quaternary Science Reviews 79, 99−110. Available from: https://doi.org/10.1016/j.quascirev.2013.07.021.

Baroni, C., Orombelli, G., 1994a. Abandoned penguin rookeries as Holocene paleoclimatic indicators in Antarctica. Geology 22, 23−26. Available from: https://doi.org/10.1130/0091-7613(1994)022(0023:APRAHP)2.3.CO;2.

Baroni, C., Orombelli, G., 1994b. Holocene glacier variations in the Terra Nova Bay area (Victoria Land, Antarctica). Antarctic Science 6, 497−505. Available from: https://doi.org/10.1130/0091-7613(1994)022(0023:APRAHP)2.3.CO;2.

Bart, P.J., Anderson, J.B., Nitsche, F., 2017a. Post-LGM grounding-line positions of the Bindschadler Ice Stream in Ross Sea. Journal of Geophysical Research: Earth Surface 122, 1827−1844. Available from: https://doi.org/10.1002/2017JF004259.

Bart, P.J., DeCesare, M., Rosenheim, B.E., Majewski, W., McGlannan, A., 2018. A centuries-long delay between a paleo-ice-shelf collapse and grounding-line retreat in the Whales Deep Basin, eastern Ross Sea, Antarctica. Scientific Reports 8, 12392. Available from: https://doi.org/10.1038/s41598-018-29911-8.

Bart, P.J., Krogmeier, B.J., Bart, M.P., Tulaczyk, S., 2017b. The paradox of a long grounding during West Antarctic Ice Sheet retreat in Ross Sea. Scientific Reports 7, 1262. Available from: https://doi.org/10.1038/s41598-017-01329-8.

Bart, P.J., Sjunneskog, C., Chow, J.M., 2011. Piston-core based biostratigraphic constraints on Pleistocene oscillations of the West Antarctic Ice Sheet in western Ross Sea between North Basin and AND-1B drill site. Marine Geology 289, 86−99. Available from: https://doi.org/10.1016/j.margeo.2011.09.005.

Bart, P., Tulaczyk, S., 2020. A significant acceleration of ice volume discharge preceded a major retreat of a West Antarctic paleo−ice stream. Geology 48, 313−317. Available from: https://doi.org/10.1130/G46916.1.

Bassett, S.E., Milne, G.A., Bentley, M.J., Huybrechts, P., 2007. Modelling Antarctic sea-level data to explore the possibility of a dominant Antarctic contribution to meltwater pulse IA. Quaternary Science Reviews 26, 2113−2127. Available from: https://doi.org/10.1016/j.quascirev.2007.06.011.

Beaman, R.J., Harris, P.T., 2003. Seafloor morphology and acoustic facies of the George V Land shelf. Deep-Sea Research II 50, 1343−1355.

Beaman, R.J., O'Brien, P.E., Post, A.L., De Santis, L., 2011. A new high-resolution bathymetry model for the Terre Adélie and George V continental margin, East Antarctica. Antarctic Science 23 (1), 95−103. Available from: https://doi.org/10.1017/S095410201000074X.

Bentley, M.J., 1999. Volume of Antarctic ice at the Last Glacial Maximum, and its impact on global sea level change. Quaternary Science Reviews 18, 1569−1595. Available from: https://doi.org/10.1016/S0277-3791(98)00118-8.

Bentley, M.J., Anderson, J.B., 1998. Glacial and marine geological evidence for the ice sheet configuration in the Weddell Sea Antarctic Peninsula region during the Last Glacial Maximum. Antarctic Science 10, 309−325. Available from: https://doi.org/10.1017/S0954102098000388.

Bentley, M.J., Fogwill, C.J., Kubik, P.W., Sugden, D.E., 2006. Geomorphological evidence and cosmogenic 10Be/26Al exposure ages for the Last Glacial Maximum and deglaciation of the Antarctic Peninsula Ice Sheet. Geological Society of America Bulletin 118, 1149−1159. Available from: https://doi.org/10.1130/B25735.1.

Bentley, M.J., Hein, A.S., Sugden, D.E., Whitehouse, P.L., Shanks, R., Xu, S., et al., 2017. Deglacial history of the Pensacola Mountains, Antarctica from glacial geomorphology and cosmogenic nuclide surface exposure dating. Quaternary Science Reviews 158, 58–76. Available from: https://doi.org/10.1016/j.quascirev.2016.09.028.

Bentley, M.J., Hodgson, D.A., Smith, J.A., Cofaigh, C.Ó., Domack, E.W., Larter, R.D., et al., 2009. Mechanisms of Holocene palaeoenvironmental change in the Antarctic Peninsula region. The Holocene 19, 51–66. Available from: https://doi.org/10.1177/0959683608096603.

Bentley, M.J., Hodgson, D.A., Sugden, D.E., Roberts, S.J., Smith, J.A., Leng, M.J., et al., 2005. Early Holocene retreat of the George VI Ice Shelf, Antarctic Peninsula. Geology 33, 173–176. Available from: https://doi.org/10.1130/G21203.1.

Bentley, M.J., Kubik, P.W., Sugden, D.E., 2000. Geomorphological evidence and cosmogenic ^{10}Be/^{26}Al exposure ages for the Last Glacial Maximum configuration of the Antarctic Peninsula ice sheet. In: Hjort, C. (Ed.), Glaciation of the Weddell Sea Basin. ANTIME Workshop, Abisko.

Bentley, M.J., Johnson, J.S., Hodgson, D.A., Dunai, T., Freeman, S.P.H.T., Cofaigh, C.Ó., 2011. Rapid deglaciation of Marguerite Bay, western Antarctic Peninsula in the Early Holocene. Quaternary Science Reviews 30, 3338–3349. Available from: https://doi.org/10.1016/j.quascirev.2011.09.002.

Bentley, M.J., Cofaigh, C.Ó., Anderson, J.B., Conway, H., et al., 2014. A community-based geological reconstruction of Antarctic Ice Sheet deglaciation since the Last Glacial Maximum. Quaternary Science Reviews 100, 1–9. Available from: https://doi.org/10.1016/j.quascirev.2014.06.025.

Berg, S., Melles, M., Gore, D.B., Verkulich, S., Pushina, Z.V., 2020. Postglacial evolution of marine and lacustrine water bodies in Bunger Hills. Antarctic Science 32, 107–129. Available from: https://doi.org/10.1017/S0954102019000476.

Berg, S., Wagner, B., Cremer, H., Leng, M.J., Melles, M., 2010. Late Quaternary environmental and climate history of Rauer Group, East Antarctica. Palaeogeography, Palaeoclimatology, Palaeoecology 297, 201–213. Available from: https://doi.org/10.1016/j.palaeo.2010.08.002.

Berg, S., White, D.A., Bennike, O., Fülöp, R.-H., Fink, D., 2016. Unglaciated areas in East Antarctica during the Last Glacial (Marine Isotope Stage 3) – new evidence from Rauer Group. Quaternary Science Reviews 153, 1–10. Available from: https://doi.org/10.1016/j.quascirev.2016.08.021.

Berkman, P., Forman, S.L.J., 1996. Pre-bomb radiocarbon and the reservoir correction for calcareous marine species in the Southern Ocean. Geophysical Research Letters 23, 363–366. Available from: https://doi.org/10.1029/96GL00151.

Borchers, S., Dietze, E., Kuhn, G., Esper, O., Voigt, I., Hartmann, K., et al., 2015. Holocene ice dynamics and bottom-water formation associated with Cape Darnley polynya activity recorded in Burton Basin, East Antarctica. Marine Geophysical Research 37, 49–70. Available from: https://doi.org/10.1007/s11001-015-9254-z.

Brachfeld, S., Domack, E.W., Kissel, C., Laj, C., Leventer, A., Ishman, S., et al., 2003. Holocene history of the Larsen-A Ice Shelf constrained by geomagnetic paleointensity dating. Geology 31, 749–752. Available from: https://doi.org/10.1130/G19643.1.

Bradley, S.L., Hindmarsh, R.C., Whitehouse, P.L., Bentley, M.J., King, M.A., 2015. Low post-glacial rebound rates in the Weddell Sea due to late Holocene ice-sheet readvance. Earth and Planetary Science Letters 413, 79–89. Available from: https://doi.org/10.1016/j.epsl.2014.12.039.

Briggs, R.D., Pollard, D., Tarasov, L., 2014. A data-constrained large ensemble analysis of Antarctic evolution since the Eemian. Quaternary Science Reviews 103, 91–115. Available from: https://doi.org/10.1016/j.quascirev.2014.09.003.

Broecker, W.S., Denton, G.H., 1990. The role of ocean-atmosphere reorganizations in glacial cycles. Quaternary Science Reviews 9 (4), 305−341. Available from: https://doi.org/10.1016/0277-3791(90)90026-7.

Brook, E.J., Kurz, M.D., Ackert, R.P., Raisbeck, G.M., Yiou, F., 1995. Cosmogenic nuclide exposure ages and glacial history of late Quaternary Ross Sea drift in McMurdo Sound, Antarctica. Earth and Planetary Science Letters 131 (1−2), 41−56. Available from: https://doi.org/10.1016/0012-821X(95)00006-X.

Budd, W.F., Smith, I.N., 1982. Large scale numerical modelling of the Antarctic Ice Sheet. Annals of Glaciology 3, 42−49.

Burgess, J.S., Spate, A.P., Shevlin, J., 1994. The onset of deglaciation in the Larsemann Hills, Eastern Antarctica. Antarctic Science 6 (4), 491−495.

Campo, J., Wellner, J.S., Lavoie, C., Domack, E., Yoo, K.-C., 2017. Glacial geomorphology of the northwestern Weddell Sea, eastern Antarctic Peninsula continental shelf: shifting ice flow patterns during deglaciation. Geomorphology 280, 89−107. Available from: https://doi.org/10.1016/j.geomorph.2016.11.022.

Canals, M., Casamor, J.L., Urgeles, R., Calafat, A.M., Domack, E.W., Baraza, J., et al., 2002. Seafloor evidence of a subglacial sedimentary system off the northern Antarctic Peninsula. Geology 30, 603−606. Available from: https://doi.org/10.1130/0091-7613(2002)030%3C0603:SEOASS%3E2.0.CO;2.

Canals, M., Urgeles, R., Calafat, A.M., 2000. Deep sea-floor evidence of past ice streams off the Antarctic Peninsula. Geology 28, 31−34. Available from: https://doi.org/10.1130/0091-7613(2000)028%3C0031:DSEOPI%3E2.0.CO;2.

Carson, C.J., Post, A.L., Smith, J., Walker, G., Waring, P., Bartley, R., et al., 2017. The seafloor geomorphology of the Windmill Islands, Wilkes Land, East Antarctica: evidence of Law Dome ice margin dynamics. Geomorphology 292 (2017), 1−15. Available from: https://doi.org/10.1016/j.geomorph.2017.04.031.

Christ, A.J., Bierman, P.R., 2020. The local Last Glacial Maximum in McMurdo Sound, Antarctica: implications for ice-sheet behavior in the Ross Sea Embayment. Geological Society of America Bulletin 132 (1−2), 31−47. Available from: https://doi.org/10.1130/B35139.1.

Çiner, A., Yildirim, C., Sarikaya, M.A., Seong, Y.B., Yu, B.Y., 2019. Cosmogenic ^{10}Be exposure dating of glacial erratics on Horseshoe Island in western Antarctic Peninsula confirms rapid deglaciation in the Early Holocene. Antarctic Science 31 (6), 319−331. Available from: https://doi.org/10.1017/S0954102019000439.

Clark, P.U., Tarasov, L., 2014. Closing the sea level budget at the last glacial maximum. Proceedings of the National Academy of Sciences 111, 15861−15862. Available from: https://doi.org/10.1073/pnas.1418970111.

CLIMAP, 1976. The surface of the Ice Age Earth. Science 191, 1131−1136.

Colhoun, E.A., Adamson, D.A., 1992. Raised beaches of the Bunger Hills. Australian National Antarctic Research Expeditions Report 136, 47.

Colhoun, E.A., Mabin, M.C.G., Adamson, D.A., Kirk, R.M., 1992. Antarctic ice volume and contribution to sea level fall at 20 000 yr BP from raised beaches. Nature 358, 316−319. Available from: https://doi.org/10.1038/358316a0.

Colleoni, F., De Santis, L., Siddoway, C.S., Bergamasco, A., Golledge, N., Lohmann, G., G., et al., 2018. Spatio-temporal variability of processes across Antarctic ice-bed-ocean interfaces. Nature Communications 8, 2289. Available from: https://doi.org/10.1038/s41467-018-04583-0.

Crosta, X., Crespin, J., Swingedouw, D., Marti, O., Masson-Delmotte, V., Etourneau, J., et al., 2018. Ocean as the main driver of Antarctic Ice Sheet retreat during the Holocene. Global and Planetary Change 166, 62–74. Available from: https://doi.org/10.1016/j.gloplacha.2018.04.007.

Crosta, X., Etourneau, J., Orme, L.C., Dalaiden, Q., Campagne, P., Swingedouw, D., et al., 2021. Multi-decadal trends in Antarctic sea-ice extent driven by ENSO–SAM over the last 2,000 years. Nature Geoscience. Available from: https://doi.org/10.1038/s41561-021-00697-1.

Cuffey, K.M., Marshall, S.J., 2000. Substantial contribution to sea-level rise during the last interglacial from the Greenland ice sheet. Nature 404, 591–594. Available from: https://doi.org/10.1038/35007053.

Dahl-Jensen, D., Albert, M., Aldahan, A., et al., 2013. Eemian interglacial reconstructed from a Greenland folded ice core. Nature 493, 489–494. Available from: https://doi.org/10.1038/nature11789.

Davies, B., Hambrey, M.J., Glasser, N.F., Holt, T., Rodes, A., Smellie, J.L., et al., 2017. Ice-dammed lateral lake and epishelf lake insights into Holocene dynamics of Marguerite Trough Ice Stream and George VI Ice Shelf, Alexander Island, Antarctic Peninsula. Quaternary Science Reviews 177, 189–219. Available from: https://doi.org/10.1016/j.quascirev.2017.10.016.

Davies, B.J., Glasser, N.F., Carrivick, J.L., Hambrey, M.J., Smellie, J.L., Nývlt, D., 2013. Antarctic landscape evolution and ice-sheet behaviour in a semi-arid polar environment: James Ross Island, NE Antarctic Peninsula. Palaeoenvironments and Earth Surface Processes. Geological Society of London Special Publication 381, 353–395. Available from: https://doi.org/10.1144/SP381.1.

Davies, B.J., Hambrey, M.J., Smellie, J.L., Carrivick, J.L., Glasser, N.F., 2012. Antarctic Peninsula Ice Sheet evolution during the Cenozoic Era. Quaternary Science Reviews 31, 30–66. Available from: https://doi.org/10.1016/j.quascirev.2014.06.023.

DeConto, R.M., Pollard, D., 2016. Contribution of Antarctica to past and future sea-level rise. Nature 531 (7596), 591–597. Available from: https://doi.org/10.1038/nature17145.

Denis, D., Crosta, X., Schmidt, S., Carson, D.S., Ganeshram, R.S., Renssen, H., et al., 2009. Holocene glacier and deep water dynamics, Adelie Land region, East Antarctica. Quaternary Science Reviews 28, 1291–1303. Available from: https://doi.org/10.1016/j.quascirev.2008.12.024.

Denton, G.H., Bockheim, J.G., Rutford, R.H., Andersen, B.G., 1992. Glacial history of the Ellsworth Mountains, West Antarctica. In: Webers, G.F., Craddock, C., Splettstoesser, J.F. (Eds.), Geology and Palaeontology of the Ellsworth Mountains, West Antarctica. Geological Society of America, Boulder, CO.

Denton, G.H., Hughes, T.P., 2002. Reconstructing the Antarctic Ice Sheet at the Last Glacial Maximum. Quaternary Science Reviews 21, 193–202. Available from: https://doi.org/10.1016/S0277-3791(01)00090-7.

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. Clarendon Press, Oxford, pp. 365–433.

Depoorter, M.A., Bamber, J.L., Griggs, J.A., Lenaerts, J.T.M., Ligtenberg, S.R.M., van den Broeke, M.R., et al., 2013. Calving fluxes and basal melt rates of Antarctic ice shelves. Nature 502, 89–92. Available from: https://doi.org/10.1038/nature12567.

Di Roberto, A., Colizza, E., Del Carlo, P., Petrelli, M., Finocchiaro, F., Kuhn, G., 2019. First marine cryptotephra in Antarctica found in sediments of the western Ross Sea correlates with englacial tephras and climate records. Scientific Reports 9, 10628. Available from: https://doi.org/10.1038/s41598-019-47188-3.

Dickens, W.A., Kuhn, G., Leng, M.J., Graham, A.G.C., Dowdeswell, J.A., Meredith, M.P., et al., 2019. Enhanced glacial discharge from the eastern Antarctic Peninsula since the 1700s associated with a positive Southern Annular Mode. Scientific Reports 9, 14606. Available from: https://doi.org/10.1038/s41598-019-50897-4.

Domack, E.W., Amblas, D., Gilbert, R., Brachfeld, S., Camerlenghi, A., Rebesco, M., et al., 2006. Subglacial morphology and glacial evolution of the Palmer Deep outlet system, Antarctic Peninsula. Geomorphology 75, 125−142. Available from: https://doi.org/10.1016/j.geomorph.2004.06.013.

Domack, E.W., Duran, D., Leventer, A., Ishman, S., Doane, S., McCallum, S., et al., 2005. Stability of the Larsen-B Ice Shelf on the Antarctic Peninsula during the Holocene epoch. Nature 436, 681−685. Available from: https://doi.org/10.1038/nature03908.

Domack, E.W., Jacobsen, E.A., Shipp, S.S., Anderson, J.B., 1999. Late Pleistocene-Holocene retreat of the West Antarctic Ice-Sheet system in the Ross Sea: part 2 − sedimentologic and stratigraphic signature. Geological Society of America Bulletin 111, 1517−1536. Available from: https://doi.org/10.1130/0016-7606(1999)111%3C1517:LPHROT%3E2.3.CO;2.

Domack, E.W., Jull, A.J.T., Nakao, S., 1991. Advance of East Antarctic outlet glaciers during the hypsithermal; implications for the volume state of the Antarctic Ice Sheet under global warming. Geology 19, 1059−1062. Available from: https://doi.org/10.1130/0091-7613(1991)019%3C1059:AOEAOG%3E2.3.CO;2.

Domack, E.W., Leventer, A., Dunbar, R., Taylor, F., Brachfeld, S., Sjunneskog, C., et al., 2001. Chronology of the Palmer Deep site, Antarctic Peninsula: a Holocene palaeoenvironmental reference for the circum-Antarctic. The Holocene 11, 1−9. Available from: https://doi.org/10.1191/095968301673881493.

Domack, E.W., O'Brien, P., Harris, P.T., Taylor, F., Quilty, P.G., De Santis, L., et al., 1998. Late Quaternary sediment facies in Prydz Bay, East Antarctica and their relationship to glacial advance onto the continental shelf. Antarctic Science 10 (3), 236−246. Available from: https://doi.org/10.1017/S0954102098000339.

Dove, I.A., Leventer, A., Metcalf, M.J., Brachfeld, S.A., Dunbar, R.B., Manley, P., et al., 2020. Marine geological investigation of Edward VIII Gulf, Kemp Coast, East Antarctica. Antarctic Science 32, 210−222. Available from: https://doi.org/10.1017/S0954102020000097.

Dowdeswell, J.A., Batchelor, C.L., Montelli, A., Ottesen, D., Christie, F.D.W., Dowdeswell, E. K., et al., 2020. Delicate seafloor landforms reveal past Antarctic grounding-line retreat of kilometers per year. Science 368 (6494), 1020−1024. Available from: https://doi.org/10.1126/science.aaz3059.

Dowdeswell, J.A., Cofaigh, C.Ó., Noormets, R., Larter, R.D., Hillenbrand, C.-D., Benetti, S., et al., 2008b. A major trough-mouth fan on the continental margin of the Bellingshausen Sea, West Antarctica: The Belgica Fan. Marine Geology 252, 129−140. Available from: https://doi.org/10.1016/j.margeo.2008.03.017.

Dowdeswell, J.A., Cofaigh, C.Ó., Pudsey, C.J., 2004. Thickness and extent of the subglacial till layer beneath an Antarctic paleo-ice stream. Geology 32, 13−16. Available from: https://doi.org/10.1130/G19864.1.

Dowdeswell, J.A., Evans, J., Cofaigh, C.Ó., Anderson, J.B., 2006. Morphology and sedimentary processes on the continental slope off Pine Island Bay, Amundsen Sea, West Antarctica. Geological Society of America Bulletin 118 (5/6), 606−619. Available from: https://doi.org/10.1130/B25791.1.

Dowdeswell, J.A., Ottesen, D., Evans, J., Cofaigh, C.Ó., Anderson, J.B., 2008a. Submarine glacial landforms and rates of ice-stream collapse. Geology 36, 819−822. Available from: https://doi.org/10.1130/G24808A.1.

Dutton, A., Carlson, A.E., Long, A.J., Milne, G.A., Clark, P.U., DeConto, R., et al., 2015. Sea-level rise due to polar ice-sheet mass loss during past warm periods. Science 349 (6244), . Available from: https://doi.org/10.1126/science.aaa4019aaa4019-1.

Elverhøi, A., 1981. Evidence for a late Wisconsin glaciation of the Weddell Sea. Nature 293, 641–642. Available from: https://doi.org/10.1038/293641a0.

Emslie, S.D., Coats, L.L., Licht, K.J., 2007. A 45,000 yr record of Adélie penguins and climate change in the Ross Sea, Antarctica. Geology 35 (1), 61–64. Available from: https://doi.org/10.1130/G23011A.1.

Etourneau, J., Collins, L.G., Willmott, V., Kim, J.-H., Barbara, L., Leventer, A., et al., 2013. Holocene climate variations in the western Antarctic Peninsula: evidence for sea ice extent predominantly controlled by changes in insolation and ENSO variability. Climate of the Past 9, 1431–1446. Available from: https://doi.org/10.5194/cp-9-1431-2013.

Etourneau, J., Sgubin, G., Crosta, X., Swingedouw, D., Willmott, V., Barbara, L., et al., 2019. Ocean temperature impact on ice shelf extent in the eastern Antarctic Peninsula. Nature Communications 10, 304. Available from: https://doi.org/10.1038/s41467-018-08195-6.

Evans, J., Dowdeswell, J.A., Cofaigh, C.Ó., 2004. Late Quaternary submarine bedforms and ice-sheet flow in Gerlache Strait and on the adjacent continental shelf, Antarctic Peninsula. Journal of Quaternary Science 19 (4), 397–407. Available from: https://doi.org/10.1002/jqs.831.

Evans, J., Dowdeswell, J.A., Cofaigh, C.Ó., Benham, T.J., Anderson, J.B., 2006. Extent and dynamics of the West Antarctic Ice Sheet on the outer continental shelf of Pine Island Bay during the last glaciation. Marine Geology 230, 53–72. Available from: https://doi.org/10.1016/j.margeo.2006.04.001.

Evans, J., Pudsey, C.J., Cofaigh, C.Ó., Morris, P., Domack, E.W., 2005. Late Quaternary glacial history, flow dynamics and sedimentation along the eastern margin of the Antarctic Peninsula Ice Sheet. Quaternary Science Reviews 24 (5–6), 741–774. Available from: https://doi.org/10.1016/j.quascirev.2004.10.007.

Fabel, D., Stone, J., Fifield, L.K., Cresswell, R.G., 1997. Deglaciation of the Vestfold Hills, East Antarctica: preliminary evidence from exposure dating of three subglacial erratics. In: Ricci, C.A. (Ed.), The Antarctic Region: Geological Evolution and Processes. Terra Antartica Publications, Siena, pp. 829–834.

Farmer, G.L., Licht, K., Swope, R.J., Andrews, J., 2006. Isotopic constraints on the provenance of fine-grained sediment in LGM tills from the Ross Embayment, Antarctica. Earth and Planetary Science Letters 249, 90–107. Available from: https://doi.org/10.1016/j.epsl.2006.06.044.

Fernandez, R., Gulick, S., Domack, E., Montelli, A., Leventer, A., Shevenell, A., et al., 2018. Past ice stream and ice sheet changes on the continental shelf off the Sabrina Coast, East Antarctica. Geomorphology 317, 10–22. Available from: https://doi.org/10.1016/j.geomorph.2018.05.020.

Florindo, F., Siegert, M.J. (Eds.), 2008. Antarctic Climate Evolution. Elsevier, 606 pp. ISBN: 9780444528476.

Fogwill, C.J., Bentley, M.J., Sugden, D.E., Kerr, A.R., Kubik, P.W., 2004. Cosmogenic nuclides ^{10}Be and ^{26}Al imply limited Antarctic Ice Sheet thickening and low erosion in the Shackleton Range for >1 m.y. Geology 32, 265–268. Available from: https://doi.org/10.1130/G19795.1.

Fogwill, C.J., Turney, C.S.M., Golledge, N.R., Rood, D.H., Hippe, K., Wacker, L., et al., 2014b. Drivers of abrupt Holocene shifts in West Antarctic ice stream direction determined from combined ice sheet modelling and geologic signatures. Antarctic Science 26 (6), 674–686. Available from: https://doi.org/10.1017/S0954102014000613.

Fogwill, C.J., Turney, C.S.M., Meissner, K.J., Golledge, N.R., Spence, P., Roberts, J.L., et al., 2014a. Testing the sensitivity of the East Antarctic Ice Sheet to Southern Ocean dynamics: past changes and future implications. Journal of Quaternary Science 29, 91–98. Available from: https://doi.org/10.1002/jqs.2683.

Fretwell, P., et al., 2013. Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. The Cryosphere 7, 375–393. Available from: https://doi.org/10.5194/tc-7-375-2013.

Gales, J.A., Larter, R.D., Mitchell, N.C., Dowdeswell, J.A., 2013. Geomorphic signature of Antarctic submarine gullies: implications for continental slope processes. Marine Geology 337, 112–124. Available from: https://doi.org/10.1016/j.margeo.2013.02.003.

Gales, J.A., Leat, P.T., Larter, R.D., Kuhn, G., Hillenbrand, C.-D., Graham, A.G.C., et al., 2014. Large-scale submarine landslides, channel and gully systems on the southern Weddell Sea margin, Antarctica. Marine Geology 348, 73–87. Available from: https://doi.org/10.1016/j.margeo.2013.12.002.

Gales, J., Rebesco, M., De Santis, L., Bergamasco, A., Colleoni, F., Kim, S., et al. 2021. Role of dense shelf water in the development of Antarctic submarine canyon morphology. Geomorphology 372, 107453. Available from: https://doi.org/10.1016/j.geomorph.2020.107453.

Gao, Y., Yang, L., Wang, J., Xie, Z., Wang, Y., Sun, L., 2018. Penguin colonization following the last glacial-interglacial transition in the Vestfold Hills, East Antarctica. Palaeogeography, Palaeoclimatology, Palaeoecology 490, 629–639. Available from: https://doi.org/10.1016/j.palaeo.2017.11.053.

Gersonde, R., Crosta, X., Abelmann, A., Armand, L., 2005. Sea-surface temperature and sea ice distribution of the Southern Ocean at the EPILOG Last Glacial Maximum – circum-Antarctic view based on siliceous microfossil records. Quaternary Science Reviews 24, 869–896. Available from: https://doi.org/10.1016/j.quascirev.2004.07.015.

Gibson, J.A.E., Paterson, K.S., White, C.A., Swadling, K.M., 2009. Evidence for the continued existence of Abraxas Lake, Vestfold Hills, East Antarctica during the Last Glacial Maximum. Antarctic Science 21 (3), 269–278. Available from: https://doi.org/10.1017/S0954102009001801.

Glasser, N.F., Davies, B.J., Carrivick, J.L., Ròdes, A., Hambrey, M.J., Smellie, J.L., et al., 2014. Ice-stream initiation, duration and thinning on James Ross Island, northern Antarctic Peninsula. Quaternary Science Reviews 86, 78–88. Available from: https://doi.org/10.1016/j.quascirev.2013.11.012.

Goehring, B.M., Balco, G., Todd, C., Moening-Swanson, I., Nichols, K., 2019. Late-glacial grounding line retreat in the northern Ross Sea, Antarctica. Geology 47, 291–294. Available from: https://doi.org/10.1130/G45413.1.

Golledge, N.R., Levy, R.H., McKay, R.M., Fogwill, C.J., White, D.A., Graham, A.G.C., et al., 2013. Glaciology and geological signature of the Last Glacial Maximum Antarctic Ice Sheet. Quaternary Science Reviews 78, 225–247. Available from: https://doi.org/10.1016/j.quascirev.2013.08.011.

Golledge, N.R., Menviel, L., Carter, L., Fogwill, C.J., England, M.H., Cortese, G., et al., 2014. Antarctic contribution to meltwater pulse 1A from reduced Southern Ocean overturning. Nature Communications 5 (5107), 1–10. Available from: https://doi.org/10.1038/ncomms6107.

Goodwin, I.D., 1993. Holocene deglaciation, sea-level change, and the emergence of the Windmill Islands, Budd Coast, Antarctica. Quaternary Research 40, 55–69. Available from: https://doi.org/10.1006/qres.1993.1057.

Goodwin, I.D., 1996. A mid to late Holocene readvance of the Law Dome ice margin, Budd Coast, East Antarctica. Antarctic Science 8, 395–406. Available from: https://doi.org/10.1017/S0954102096000570.

Goodwin, I.D., Zweck, C., 2000. Glacio-isostasy and glacial ice load at Law Dome, Wilkes Land, East Antarctica. Quaternary Research 53, 285–293.

Gore, D.B., 1997a. Last glaciation of Vestfold Hills: extension of the East Antarctic Ice Sheet or lateral expansion of Sørsdal Glacier? Polar Record 33, 5–12.

Gore, D.B., 1997b. Blanketing snow and ice; constraints on radiocarbon dating deglaciation in East Antarctic oases. Antarctic Science 9, 336–348. Available from: https://doi.org/10.1017/S0954102097000412.

Gore, D.B., Rhodes, E.J., Augustinus, P.C., Leishman, M.R., Colhoun, E.A., Rees-Jones, J., 2001. Bunger Hills, East Antarctica: ice free at the Last Glacial Maximum. Geology 29, 1103–1106. Available from: https://doi.org/10.1130/0091-7613(2001)029%3C1103:BHEAIF%3E2.0.CO;2.

Gosse, J.C., Phillips, F.M., 2001. Terrestrial in situ cosmogenic nuclides: theory and application. Quaternary Science Reviews 20, 1475–1560. Available from: https://doi.org/10.1016/S0277-3791(00)00171-2.

Gowan, E.J., Zhang, X., Khosravi, S., Rovere, A., Stocchi, P., Hughes, A.L.C., et al., 2021. A new global ice sheet reconstruction for the past 80 000 years. Nature Communications 12, 1199. Available from: https://doi.org/10.1038/s41467-021-21469-w.

Graham, A.G.C., Larter, R.D., Gohl, K., Dowdeswell, J.A., Hillenbrand, C.-D., Smith, J.A., et al., 2010. Flow and retreat of the Late Quaternary Pine Island-Thwaites palaeo-ice stream, West Antarctica. Journal of Geophysical Research: Earth Surface 115, F03025. Available from: https://doi.org/10.1029/2009JF001482.

Graham, A.G.C., Larter, R.D., Gohl, K., Hillenbrand, C.-D., Smith, J.A., Kuhn, G., 2009. Bedform signature of a West Antarctic palaeo-ice stream reveals a multi-temporal record of flow and substrate control. Quaternary Science Reviews 28, 2774–2793. Available from: https://doi.org/10.1016/j.quascirev.2009.07.003.

Graham, A.G.C., Nitsche, F.O., Larter, R.D., 2011. An improved bathymetry compilation for the Bellingshausen Sea, Antarctica, to inform ice-sheet and ocean models. The Cryosphere 5, 95–106. Available from: https://doi.org/10.5194/tc-5-95-2011.

Graham, A.G.C., Smith, J.A., 2012. Palaeoglaciology of the Alexander Island ice cap, western Antarctic Peninsula, reconstructed from marine geophysical and core data. Quaternary Science Reviews 35, 63–81. Available from: https://doi.org/10.1016/j.quascirev.2012.01.008.

Greenwood, S.L., Gyllencreutz, R., Jakobsson, M., Anderson, J.B., 2012. Ice-flow switching and East/West Antarctic Ice Sheet roles in glaciation of the western Ross Sea. Geological Society of America Bulletin 124, 1736–1749. Available from: https://doi.org/10.1130/B30643.1.

Greenwood, S.L., Simkins, L.M., Halberstadt, A.R.W., Prothro, L.O., Anderson, J.B., 2018. Holocene reconfiguration and readvance of the East Antarctic Ice Sheet. Nature Communications 9, 3176. Available from: https://doi.org/10.1038/s41467-018-05625-3.

Halberstadt, A.R.W., Simkins, L.M., Greenwood, S.L., Anderson, J.B., 2016. Past ice-sheet behaviour: retreat scenarios and changing controls in the Ross Sea, Antarctica. The Cryosphere 10, 1003–1020. Available from: https://doi.org/10.5194/tc-10-1003-2016.

Hall, B.L., Hoelzel, A.R., Baroni, C., Denton, G.H., Le Boeuf, B.J., Overturf, B., et al., 2006. Holocene elephant seal distribution implies warmer-than-present climate in the Ross Sea. Proceedings of the National Academy of Sciences 103 (27), 10213–10217. Available from: https://doi.org/10.1073/pnas.0604002103.

Hall, B., Denton, G., Heath, S., Jackson, M., Koffman, T., 2015. Accumulation and marine forcing of ice dynamics in the western Ross Sea during the last deglaciation. Nature Geoscience 8, 625–628. Available from: https://doi.org/10.1038/ngeo2478.

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. Available from: https://doi.org/10.1016/0025-3227(92)90009-7.

Harris, P.T., O'Brien, P., 1998. Bottom currents, sedimentation and ice-sheet retreat facies successions on the Mac.Robertson shelf, East Antarctica. Marine Geology 151, 47–72. Available from: https://doi.org/10.1016/S0025-3227(98)00047-4.

Hein, A., Woodward, J., Marrero, S.M., Dunning, S.A., Steig, E.J., Freeman, S.P.H.T., et al., 2016a. Evidence for the stability of the West Antarctic Ice Sheet divide for 1.4 million years. Nature Communications 7, 10325. Available from: https://doi.org/10.1038/ncomms10325.

Hein, A.S., Fogwill, C.J., Sugden, D.E., Xu, S., 2011. Glacial/interglacial ice-stream stability in the Weddell Sea embayment, Antarctica. Earth and Planetary Science Letters 307, 211–221. Available from: https://doi.org/10.1016/j.epsl.2011.04.037.

Hein, A.S., Fogwill, C.J., Sugden, D.E., Xu, S., 2014. Geological scatter of cosmogenic-nuclide exposure ages in the Shackleton Range, Antarctica: implications for glacial history. Quaternary Geochronology 19, 52–66. Available from: https://doi.org/10.1016/j.quageo.2013.03.008.

Hein, A.S., Marrero, S.M., Woodward, J., Dunning, S.A., Winter, K., Westoby, M.J., et al., 2016b. Mid-Holocene pulse of thinning in the Weddell Sea sector of the West Antarctic Ice Sheet. Nature Communications 7, 12511. Available from: https://doi.org/10.1038/ncomms12511.

Hemer, M., Harris, P., 2003. Sediment core from beneath the Amery Ice Shelf, East Antarctica, suggests mid-Holocene ice-shelf retreat. Geology 31, 127–130. Available from: https://doi.org/10.1130/0091-7613(2003)031%3C0127:SCFBTA%3E2.0.CO;2.

Hemer, M.A., Post, A.L., O'Brien, P.E., Craven, M., Truswell, E.M., Roberts, D., et al., 2007. Sedimentological signatures of the sub-Amery Ice Shelf circulation. Antarctic Science 19, 497–506. Available from: https://doi.org/10.1017/S0954102007000697.

Hendy, C.H., Hall, B.L., 2006. The radiocarbon reservoir effect in proglacial lakes: examples from Antarctica. Earth and Planetary Science Letters 241, 413–421. Available from: https://doi.org/10.1016/j.epsl.2005.11.045.

Heroy, D.C., Anderson, J.B., 2005. Ice-sheet extent of the Antarctic Peninsula region during the Last Glacial Maximum (LGM)-insights from glacial geomorphology. Geological Society of America Bulletin 117 (11/12), 1497–1512. Available from: https://doi.org/10.1130/B25694.1.

Heroy, D.C., Anderson, J.B., 2007. Radiocarbon constraints on Antarctic Peninsula Ice Sheet retreat following the Last Glacial Maximum (LGM). Quaternary Science Reviews 26, 3286–3297. Available from: https://doi.org/10.1016/j.quascirev.2007.07.012.

Hillenbrand, C.-D., Bentley, M.J., Stolldorf, T.D., Hein, A.S., Kuhn, G., Graham, A.G.C., et al., 2014. Reconstruction of changes in the Weddell Sea sector of the Antarctic Ice Sheet since the Last Glacial Maximum. Quaternary Science Reviews 100, 111–136. Available from: https://doi.org/10.1016/j.quascirev.2013.07.020.

Hillenbrand, C.-D., Kuhn, G., Smith, J.A., Gohl, K., Graham, A.G.C., Larter, R.D., et al., 2013. Grounding-line retreat of the West Antarctic Ice Sheet from inner Pine Island Bay. Geology 41, 35–38. Available from: https://doi.org/10.1130/G33469.1.

Hillenbrand, C.-D., Larter, R.D., Dowdeswell, J.A., Ehrmann, W., Cofaigh, C.Ó., Benetti, S., et al., 2010a. The sedimentary legacy of a palaeo-ice stream on the shelf of the southern Bellingshausen Sea: clues to West Antarctic glacial history during the Late Quaternary. Quaternary Science Reviews 29 (19–20), 2741–2763. Available from: https://doi.org/10.1016/j.quascirev.2010.06.028.

Hillenbrand, C.-D., Melles, M., Kuhn, G., Larter, R.D., 2012. Marine geological constraints for the grounding-line position of the Antarctic Ice Sheet on the southern Weddell Sea shelf at the Last Glacial Maximum. Quaternary Science Reviews 32, 25−47. Available from: https://doi.org/10.1016/j.quascirev.2011.11.017.

Hillenbrand, C.-D., Smith, J.A., Hodell, D.A., Greaves, M., Poole, C.R., Kender, S., et al., 2017. West Antarctic Ice Sheet retreat driven by Holocene warm water incursions. Nature 547, 43−48. Available from: https://doi.org/10.1038/nature22995.

Hillenbrand, C.-D., Smith, J.A., Kuhn, G., Esper, O., Gersonde, R., Larter, R.D., et al., 2010b. Age assignment of a diatomaceous ooze deposited in the western Amundsen Sea Embayment after the Last Glacial Maximum. Journal of Quaternary Science 25, 280−295. Available from: https://doi.org/10.1002/jqs.1308.

Hiller, A., Hermichen, W.-D., Wand, U., 1995. Radiocarbon dated subfossil stomach oil deposits from petrel nesting sites: novel paleoenvironmental records from continental Antarctica. Radiocarbon 37, 171−180. Available from: https://doi.org/10.1017/S0033822200030617.

Hodgson, D.A., Bentley, M.J., Schnabel, C., Cziferszky, A., Fretwell, P., Convey, P., et al., 2012. Glacial geomorphology and cosmogenic ^{10}Be and ^{26}Al exposure ages in the northern Dufek Massif, Weddell Sea Embayment, Antarctica. Antarctic Science 24, 377−394. Available from: https://doi.org/10.1017/S0954102012000016.

Hodgson, D.A., Hogan, K., Smith, J.M., Smith, J.A., Hillenbrand, C.-D., Graham, A.G.C., et al., 2018. Deglaciation and future stability of the Coats Land ice margin, Antarctica. The Cryosphere 12, 2383−2399. Available from: https://doi.org/10.5194/tc-12-2383-2018.

Hodgson, D.A., Noon, P.E., Vyverman, W., Bryant, C.L., Gore, D.B., Appleby, P., et al., 2001. Were the Larsemann Hills ice-free through the Last Glacial Maximum? Antarctic Science 13, 440−454. Available from: https://doi.org/10.1017/S0954102001000608.

Hodgson, D.A., Roberts, S.J., Smith, J.A., Verleyen, E., Sterken, M., Labarque, M., et al., 2013. Late Quaternary environmental changes in Marguerite Bay, Antarctic Peninsula, inferred from lake sediments and raised beaches. Quaternary Science Reviews 68, 216−236. Available from: https://doi.org/10.1016/j.quascirev.2011.10.011.

Hodgson, D.A., Verleyen, E., Sabbe, K., Squier, A.H., Keely, B.J., Leng, M.J., et al., 2005. Late Quaternary climate-driven environmental change in the Larsemann Hills, East Antarctica, multi-proxy evidence from a lake sediment core. Quaternary Research 64, 83−99. Available from: https://doi.org/10.1016/j.yqres.2005.04.002.

Hodgson, D.A., Verleyen, E., Squier, A.H., Sabbe, K., Keely, B.J., Saunders, K.M., et al., 2006. Interglacial environments of coastal east Antarctica: comparison of MIS 1 (Holocene) and MIS 5e (Last Interglacial) lake-sediment records. Quaternary Science Reviews 25, 179−197. Available from: https://doi.org/10.1016/j.quascirev.2005.03.004.

Hodgson, D.A., Verleyen, E., Vyverman, W., Sabbe, K., Leng, M.J., Pickering, M., et al., 2009. A geological constraint on relative sea level in Marine Isotope Stage 3 in the Larsemann Hills, Lambert Glacier region, East Antarctica (31 366−33 228 cal yr BP). Quaternary Science Reviews 28, 2689−2696. Available from: https://doi.org/10.1016/j.quascirev.2009.06.006.

Hogan, K.A., Larter, R.D., Graham, A.G.C., Arthern, R., Kirkham, J.D., Minzoni, R.T., et al., 2020. Revealing the former bed of Thwaites Glacier using sea-floor bathymetry: implications for warm-water routing and bed controls on ice flow and buttressing. The Cryosphere 14, 2883−2908. Available from: https://doi.org/10.5194/tc-14-2883-2020.

Hughes, T., 1977. West Antarctic Ice Streams. Reviews of Geophysics and Space Physics 15 (1), 1−45. Available from: https://doi.org/10.1029/RG015i001p00001.

Huybrechts, P., 2002. Sea level changes at the LGM from ice-dynamic reconstructions of the Greenland and Antarctic Ice Sheets during the glacial cycles. Quaternary Science Reviews 21, 203–231. Available from: https://doi.org/10.1016/S0277-3791(01)00082-8.

Igarashi, A., Harada, N., Moriwaki, K., 1995. Marine fossils of 30–40 ka in raised beach deposits, and late Pleistocene glacial history around Lützow-Holm Bay, East Antarctica. Proceedings of the NIPR Symposium, Antarctic Geoscience 8, 219–229.

Igarashi, A., H. Miura, C. Hart, 1998. Amino-acid racemization dates of fossil molluscs from raised beach deposits on East Ongul Island and northern part of Langhovde, Lützow-Holm Bay region, East Antarctica. In: The 18th Symposium on Antarctic Geosciences, Program and Abstracts. NIPR, pp. 59–61.

Igarashi, A., Numanami, H., Tsuchiya, Y., Fukuchi, M., 2001. Bathymetric distribution of fossil foraminifera within marine sediment cores from the eastern part of Lützow-Holm Bay, East Antarctica, and its paleoceanographic implications. Marine Micropaleontology 42, 125–162. Available from: https://doi.org/10.1016/S0377-8398(01)00004-4.

Ingólfsson, O., Hjort, C., Humlum, O., 2003. Glacial and climate history of the Antarctic Peninsula since the Last Glacial Maximum. Arctic Antarctic and Alpine Research 35, 175–186.

Ingólfsson, Ó., 2004. Quaternary glacial and climate history of Antarctica. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations – Extent and Chronology Part III. Elsevier, pp. 3–43. Available from: https://doi.org/10.1016/S1571-0866(04)80109-X.

Jakobsson, M., Anderson, J.B., Nitsche, F., Dowdeswell, J.A., Gyllencreutz, R., Kirchner, N., et al., 2011. Geological record of ice shelf break-up and grounding line retreat, Pine Island Bay, West Antarctica. Geology 39, 691–694. Available from: https://doi.org/10.1130/G32153.1.

Jakobsson, M., Anderson, J.B., Nitsche, F., Gyllencreutz, R., Kirshner, A., Kirchner, N., et al., 2012. Ice sheet retreat dynamics inferred from glacial morphology of the central Pine Island Bay Trough, West Antarctica. Quaternary Science Reviews 38, 1–10. Available from: https://doi.org/10.1016/j.quascirev.2011.12.017.

Jamieson, S.S.R., Stokes, C.R., Ross, N., Rippin, D.M., Bingham, R.G., Wilson, D.S., et al., 2014. The glacial geomorphology of the Antarctic Ice Sheet bed. Antarctic Science 26, 724–741. Available from: https://doi.org/10.1017/S0954102014000212.

Jeong, A., Lee, J.I., Seong, Y.B., Balco, G., Yoo, K.C., Yoon, H.I., et al., 2018. Late Quaternary deglacial history across the Larsen B embayment, Antarctica. Quaternary Science Reviews 189, 134–148. Available from: https://doi.org/10.1016/j.quascirev.2018.04.011.

Johnson, J.S., Bentley, M.J., Gohl, K., 2008. First exposure ages from the Amundsen Sea Embayment, West Antarctica: the Late Quaternary context for recent thinning of Pine Island, Smith, and Pope Glaciers. Geology 36 (3), 223–226. Available from: https://doi.org/10.1130/G24207A.1.

Johnson, J.S., Bentley, M.J., Roberts, S.J., Binney, S.A., Freeman, S.P., 2011. Holocene deglacial history of the northeast Antarctic Peninsula – a review and new chronological constraints. Quaternary Science Reviews 30, 3791–3802. Available from: https://doi.org/10.1016/j.quascirev.2011.10.011.

Johnson, J.S., Bentley, M.J., Smith, J.A., Finkel, R.C., Rood, D.H., Gohl, K., et al., 2014. Rapid thinning of Pine Island glacier in the Early Holocene. Science 343, 999–1001. Available from: https://doi.org/10.1126/science.1247385.

Johnson, J.S., Everest, J.D., Leat, P.T., Golledge, N.R., Rood, D.H., Stuart, F.M., 2012. The deglacial history of NW Alexander Island, Antarctica, from surface exposure dating. Quaternary Research 77, 273–280. Available from: https://doi.org/10.1016/j.yqres.2011.11.012.

Johnson, J.S., Nichols, K.A., Goehring, B.M., Balco, G., Schaefer, J.M., 2019. Abrupt mid-Holocene ice loss in the western Weddell Sea Embayment of Antarctica. Earth and Planetary Science Letters 518, 127–135. Available from: https://doi.org/10.1016/j.epsl.2019.05.002.

Johnson, J.S., Roberts, S.J., Rood, D.H., Pollard, D., Schaefer, J.M., Whitehouse, P.L., et al., 2020. Deglaciation of Pope Glacier implies widespread early Holocene ice sheet thinning in the Amundsen Sea sector of Antarctica. Earth and Planetary Science Letters 548, 116501. Available from: https://doi.org/10.1016/j.epsl.2020.116501.

Johnson, J.S., Smellie, J.L., Nelson, A.E., Stuart, F.M., 2009. History of the Antarctic Peninsula Ice Sheet since the early Pliocene-Evidence from cosmogenic dating of Pliocene lavas on James Ross Island, Antarctica. Global and Planetary Change 69, 205–213. Available from: https://doi.org/10.1016/j.gloplacha.2009.09.001.

Johnson, J.S., Smith, J.A., Schaefer, J.M., Young, N.E., Goehring, B.M., Hillenbrand, C.-D., et al., 2017. The last glaciation of Bear Peninsula, central Amundsen Sea Embayment of Antarctica: constraints on timing and duration revealed by in situ cosmogenic ^{14}C and ^{10}Be dating. Quaternary Science Reviews 178, 77–88. Available from: https://doi.org/10.1016/j.quascirev.2017.11.003.

Jones, R.S., Mackintosh, A.N., Norton, K.P., Golledge, N.R., Fowill, C.J., Kubik, P.W., et al., 2015. Rapid Holocene thinning of an East Antarctic outlet glacier driven by marine ice sheet instability. Nature Communications 6, 8910. Available from: https://doi.org/10.1038/ncomms9910.

Kawamata, M., Suganuma, Y., Doi, K., Misawa, K., Hirabayashi, M., Hattori, A., et al., 2020. Abrupt Holocene ice-sheet thinning along the southern Soya Coast, Lützow-Holm Bay, East Antarctica, revealed by glacial geomorphology and surface exposure dating. Quaternary Science Reviews 247, 106540. Available from: https://doi.org/10.1016/j.quascirev.2020.106540.

Kiernan, K., Gore, D.B., Fink, D., McConnell, A., Sigurdsson, I.A., White, D.A., 2009. Deglaciation and weathering of Larsemann Hills, East Antarctica. Antarctic Science 21 (4), 373–382. Available from: https://doi.org/10.1017/S0954102009002028.

Kiernan, K., McConnell, A., Colhoun, E., Lawson, E., 2003. Radiocarbon dating of mumiyo from the Vestfold Hills, East Antarctica. Papers & Proceedings of the Royal Society of Tasmania 136, 141–144.

Kilfeather, A.A., Cofaigh, C.Ó., Lloyd, J.M., Dowdeswell, J.A., Xu, S., Moreton, S.G., 2011. Ice-stream retreat and ice-shelf history in Marguerite Trough, Antarctic Peninsula: sedimentological and foraminiferal signatures. Geological Society of America Bulletin 123, 997–1015. Available from: https://doi.org/10.1130/B30282.1.

King, C., Hall, B., Hillebrand, T., Stone, J., 2020. Delayed maximum and recession of an East Antarctic outlet glacier. Geology 48 (6), 630–634. Available from: https://doi.org/10.1130/G47297.1.

Kingslake, J., Martín, C., Arthern, R.J., Corr, H.F.J., King, E.C., 2016. Ice-flow reorganization in West Antarctica 2.5 kyr ago dated using radar-derived englacial flow velocities. Geophysical Research Letters 43, 9103–9112. Available from: https://doi.org/10.1002/2016GL070278.

Kingslake, J., Scherer, R.P., Albrecht, T., Coenen, J., Powell, R.D., Reese, R., et al., 2018. Extensive retreat and re-advance of the West Antarctic Ice Sheet during the Holocene. Nature 558 (7710), 430–434. Available from: https://doi.org/10.1038/s41586-018-0208-x.

Kim, S., Yoo, K.-C., Lee, J.I., Khim, B.-K., Bak, Y.-S., Lee, M.K., et al., 2018. Holocene paleoceanography of Bigo Bay, west Antarctic Peninsula: connections between surface water productivity and nutrient utilization and its implication for surface-deep water mass exchange. Quaternary Science Reviews 192, 59–70. Available from: https://doi.org/10.1016/j.quascirev.2018.05.028.

Kirkham, J.D., Hogan, K.A., Larter, R.D., Arnold, N.S., Nitsche, F.O., Golledge, N.R., et al., 2019. Past water flow beneath Pine Island and Thwaites glaciers, West Antarctica. The Cryosphere 13, 1959–1981. Available from: https://doi.org/10.5194/tc-13-1959-2019.

Kirkup, H., Melles, M., Gore, D.B., 2002. Late Quaternary environment of the southern Windmill Islands, East Antarctica. Antarctic Science 14, 385–394. Available from: https://doi.org/10.1017/S0954102002000202.

Kirshner, A., Anderson, J.B., Jakobsson, M., O'Regan, M., Majewski, W., Nitsche, F., 2012. Post-LGM deglaciation in Pine Island Bay, West Antarctica. Quaternary Science Reviews 38, 11–26. Available from: https://doi.org/10.1016/j.quascirev.2012.01.017.

Klages, J.P., Kuhn, G., Graham, A.G.C., Hillenbrand, C.-D., Smith, J.A., Nitsche, F.O., et al., 2015. Palaeo-ice stream pathways and retreat style in the easternmost Amundsen Sea Embayment, West Antarctica, revealed by combined multibeam bathymetric and seismic data. Geomorphology 245, 207–222. Available from: https://doi.org/10.1016/j.geomorph.2015.05.020.

Klages, J.P., Kuhn, G., Hillenbrand, C.-D., Graham, A.G.C., Smith, J.A., Larter, R.D., et al., 2014. Retreat of the West Antarctic Ice Sheet from the western Amundsen Sea shelf at a pre- or early LGM stage. Quaternary Science Reviews 91, 1–15. Available from: https://doi.org/10.1016/j.quascirev.2014.02.017.

Klages, J.P., Kuhn, G., Hillenbrand, C.-D., Smith, J.A., Graham, A.G.C., Nitsche, F.O., F.O., et al., 2017. Limited grounding-line advance onto the West Antarctic continental shelf in the easternmost Amundsen Sea Embayment during the last glacial period. PLoS One 12 (7), e0181593. Available from: https://doi.org/10.1371/journal.pone.0181593.

Kopp, R., Simons, F., Mitrovica, J., et al., 2009. Probabilistic assessment of sea level during the last interglacial stage. Nature 462, 863–867. Available from: https://doi.org/10.1038/nature08686.

Krause, W.E., Krbetschek, M.R., Stolz, W., 1997. Dating of Quaternary lake sediments from the Schirmacher Oasis (East Antarctica) by infra-red stimulated luminescence (IRSL) detected at the wavelength of 560 nm. Quaternary Science Reviews 16 (3–5), 387–392. Available from: https://doi.org/10.1016/S0277-3791(96)00090-X.

Kuhn, G., Hillenbrand, C.-D., Kasten, S., Smith, J.A., Nitsche, F.O., Frederichs, T., et al., 2017. Evidence for a palaeo-subglacial lake on the Antarctic continental shelf. Nature Communications 8, 15591. Available from: https://doi.org/10.1038/ncomms15591.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., Sambridge, M., 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. Proceedings of the National Academy of Sciences 111, 15296–15303. Available from: https://doi.org/10.1073/pnas.1411762111.

Lamping, N., Müller, J., Esper, O., Hillenbrand, C.-D., Smith, J.A., Kuhn, G., 2020. Highly branched isoprenoids reveal onset of deglaciation followed by dynamic sea-ice conditions in the western Amundsen Sea, Antarctica. Quaternary Science Reviews 228, 106103. Available from: https://doi.org/10.1016/j.quascirev.2019.106103.

Larter, R.D., Anderson, J.B., Graham, A.G.C., Gohl, K., Hillenbrand, C.-D., Jakobsson, M., et al., 2014. Reconstruction of changes in the Amundsen Sea and Bellingshausen Sea sector of the West Antarctic Ice Sheet since the Last Glacial Maximum. Quaternary Science Reviews 100, 55–86. Available from: https://doi.org/10.1016/j.quascirev.2013.10.016.

Larter, R.D., Graham, A.G.C., Gohl, K., Kuhn, G., Hillenbrand, C.-D., Smith, J.A., et al., 2009. Subglacial bedforms reveal complex basal regime in a zone of paleo-ice stream convergence, Amundsen Sea embayment, West Antarctica. Geology 37, 411–414. Available from: https://doi.org/10.1130/G25505A.1.

Larter, R.D., Graham, A.G.C., Hillenbrand, C.-D., Smith, J.A., Gales, J.A., 2012. Late Quaternary grounded ice extent in the Filchner Trough, Weddell Sea, Antarctica: new marine geophysical evidence. Quaternary Science Reviews 53, 111–122. Available from: https://doi.org/10.1016/j.quascirev.2012.08.006.

Larter, R.D., Hogan, K.A., Hillenbrand, C.-D., Smith, J.A., Batchelor, C.L., Cartigny, M., et al., 2019. Subglacial hydrological control on flow of an Antarctic Peninsula palaeo-ice stream. The Cryosphere 13, 1583–1596. Available from: https://doi.org/10.5194/tc-13-1583-2019.

Larter, R.D., Vanneste, L.E., 1995. Relict subglacial deltas on the Antarctic Peninsula outer shelf. Geology 23, 33–36. Available from: https://doi.org/10.1130/0091-7613(1995)023%3C0033:RSDOTA%3E2.3.CO;2.

Lavoie, C., Domack, E.W., Pettit, E.C., Scambos, T.A., Larter, R.D., Schenke, H.-W., et al., 2015. Configuration of the Northern Antarctic Peninsula Ice Sheet at LGM based on a new synthesis of seabed imagery. The Cryosphere 9, 613–629. Available from: https://doi.org/10.5194/tc-9-613-2015.

Lee, J.I., McKay, R.M., Golledge, N.R., Yoon, H.I., Yoo, K.-C., Kim, H.J., et al., 2017. Widespread persistence of expanded East Antarctic glaciers in the southwest Ross Sea during the last deglaciation. Geology 45 (5), 403–406. Available from: https://doi.org/10.1130/G38715.1.

Leventer, A., Domack, E.W., Dunbar, R., Pike, J., Stickley, C., Maddison, E., et al., 2006. Marine sediment record from the East Antarctic margin reveals dynamics of ice sheet recession. GSA Today 16, 4–10. Available from: https://www.geosociety.org/gsatoday/archive/16/12/pdf/i1052-5173-16-12-4.pdf.

Licht, K.J., 2004. The Ross Sea's contribution to eustatic sea level during meltwater pulse 1A. Sedimentary Geology 165, 343–353. Available from: https://doi.org/10.1016/j.sedgeo.2003.11.020.

Licht, K.J., Dunbar, N.W., Andrews, J.T., Jennings, A.E., 1999. Distinguishing subglacial till and glacial marine diamictons in the western Ross Sea, Antarctica: implications for a last glacial maximum grounding line. Geological Society of America Bulletin 111 (1), 91–103. Available from: https://doi.org/10.1130/0016-7606(1999)111%3C0091:DSTAGM%3E2.3.CO;2.

Licht, K.J., Hennessy, A.J., Welke, B.M., 2014. The U/Pb detrital zircon signature of West Antarctic ice stream tills in the Ross Embayment, with implications for LGM ice flow reconstructions. Antarctic Science 26, 687–697. Available from: https://doi.org/10.1017/S0954102014000315.

Licht, K.J., Jennings, A.E., Andrews, J.T., Williams, K.M., 1996. Chronology of late Wisconsin ice retreat from the western Ross Sea, Antarctica. Geology 24 (3), 223–226. Available from: https://doi.org/10.1130/0091-7613(1996)024%3C0223:COLWIR%3E2.3.CO;2.

Licht, K.J., Lederer, J.R., Swope, R.J., 2005. Provenance of LGM glacial till (sand fraction) across the Ross embayment, Antarctica. Quaternary Science Reviews 24, 1499–1520. Available from: https://doi.org/10.1016/j.quascirev.2004.10.017.

Licht, K.J., Palmer, E.F., 2013. Erosion and transport by Byrd Glacier, Antarctica during the last glacial maximum. Quaternary Science Reviews 62, 32–48. Available from: https://doi.org/10.1016/j.quascirev.2012.11.017.

Lilly, K., 2008. Three million years of East Antarctic Ice Sheet history from in situ cosmogenic nuclides in the Lambert-Amery Basin. PhD thesis, Australian National University, 183 pp. Available from: <https://openresearch-repository.anu.edu.au/handle/1885/149854>.

Lilly, K., Fink, D., Fabel, D., Lambeck, K., 2010. Pleistocene dynamics of the interior East Antarctic Ice Sheet. Geology 38 (8), 703–706. Available from: https://doi.org/10.1130/G31172x.1.

Lindow, J., Castex, M., Wittmann, H., Johnson, J.S., Lisker, F., Gohl, K., et al., 2014. Glacial retreat in the Amundsen Sea sector, West Antarctica – first cosmogenic evidence from central Pine Island Bay and the Kohler Range. Quaternary Science Reviews 98, 166–173. Available from: https://doi.org/10.1016/j.quascirev.2014.05.010.

Livingstone, S.J., Cofaigh, C.Ó., Stokes, C.R., Hillenbrand, C.-D., Vieli, A., Jamieson, S.S.R., 2012. Antarctic palaeo-ice streams. Earth-Science Reviews 111, 90–128. Available from: https://doi.org/10.1016/j.earscirev.2011.10.003.

Livingstone, S.J., Cofaigh, C.Ó., Stokes, C.R., Hillenbrand, C.-D., Vieli, A., Jamieson, S.S.R., 2013. Glacial geomorphology of Marguerite Bay palaeo-ice stream, western Antarctic Peninsula. Journal of Maps 9, 558–572. Available from: https://doi.org/10.1080/17445647.2013.829411.

Lowe, A.L., Anderson, J.B., 2002. Reconstruction of the West Antarctic Ice Sheet in Pine Island Bay during the Last Glacial Maximum and its subsequent retreat history. Quaternary Science Reviews 21, 1879–1897. Available from: https://doi.org/10.1016/S0277-3791(02)00006-9.

Lowe, A.L., Anderson, J.B., 2003. Evidence for abundant subglacial meltwater beneath the paleo-ice sheet in Pine Island Bay, Antarctica. Journal of Glaciology 49, 125–138. Available from: https://doi.org/10.3189/172756503781830971.

Lowry, D.P., Golledge, N.R., Bertler, N.A.N., Selwyn Jones, R., McKay, R., 2019. Deglacial grounding-line retreat in the Ross Embayment, Antarctica, controlled by ocean and atmosphere forcing. Science Advances 5 (8), eaav8754. Available from: https://doi.org/10.1126/sciadv.aav8754.

Mackintosh, A., Golledge, N., Domack, E., Dunbar, R., Leventer, A., White, D., et al., 2011. Retreat of the East Antarctic Ice Sheet during the last glacial termination. Nature Geoscience 4, 195–202. Available from: https://doi.org/10.3189/172756503781830971.

Mackintosh, A., Verleyan, E., O'Brien, P.E., White, D.A., Jones, R.S., McKay, R., et al., 2014. Retreat history of the East Antarctic Ice Sheet since the Last Glacial Maximum. Quaternary Science Reviews 100, 10–30. Available from: https://doi.org/10.1016/j.quascirev.2013.07.024.

Mackintosh, A., White, D., Fink, D., Gore, D.B., Pickard, J., Fanning, P.C., 2007. Exposure ages from mountain dipsticks in Mac.Robertson Land, East Antarctica, indicate little change in ice sheet thickness since the Last Glacial Maximum. Geology 35, 551–554. Available from: https://doi.org/10.1130/G23503A.1.

Maddison, E., Pike, J., Leventer, A., Dunbar, R., Brachfeld, S., Domack, E., et al., 2006. Post-glacial seasonal diatom record of the Mertz Glacial Polynya, East Antarctica. Marine Micropaleontology 60, 66–88. Available from: https://doi.org/10.1016/j.marmicro.2006.03.001.

Maemoku, H., Miura, H., Saigusa, S., Moriwaki, K., 1997. Stratigraphy of the Late Quaternary raised beach deposits in the northern part of Langhovde, Lützow-Holm Bay, East Antarctica. Proceedings of NIPR Symposium. Antarctic Geoscience 10, 178–186.

McGlannan, A.J., Bart, P.J., Chow, J.M., DeCesare, M., 2017. On the influence of post- LGM ice shelf loss and grounding zone sedimentation on West Antarctic Ice Sheet stability. Marine Geology 392, 151–169. Available from: https://doi.org/10.1016/j.margeo.2017.08.005.

McKay, R.M., Dunbar, G.B., Naish, T.R., Barrett, P.J., Carter, L., Harper, M., 2008. Retreat history of the Ross ice sheet (shelf) since the last glacial maximum from deep-basin sediment cores around Ross Island. Palaeogeography, Palaeoclimatology, Palaeoecology 260 (1), 245–261. Available from: https://doi.org/10.1016/j.palaeo.2007.08.015.

McKay, R., Golledge, N.R., Maas, S., Naish, T., Levy, R., Dunbar, G., et al., 2016. Antarctic marine ice-sheet retreat in the Ross Sea during the early Holocene. Geology 44, 7−10. Available from: https://doi.org/10.1130/G37315.1.

McMillan, M., 2018. The current health of polar ice sheets and implications for sea level. In: Nuttall, M., Christensen, T.R., Siegert, M.J. (Eds.), Routledge Handbook of the Polar Regions. Routledge, pp. 185−197.

McMullen, K., Domack, E.W., Leventer, A., Olson, C., Dunbar, R., Brachfeld, S., 2006. Glacial morphology and sediment formation in the Mertz Trough, East Antarctica. Palaeogeography, Palaeoclimatology, Palaeoecology 231, 169−180. Available from: https://doi.org/10.1016/j.palaeo.2005.08.004.

Melis, R., Capotondi, L., Torricella, F., Ferretti, P., Geniram, A., Hong, J.K., et al., 2021. Last Glacial Maximum to Holocene paleoceanography of the northwestern Ross Sea inferred from sediment core geochemistry and micropaleontology at Hallett Ridge. Journal of Micropalaeontology 40, 15−35. Available from: https://doi.org/10.5194/jm-40-15-2021.

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 (4), 739−760. Available from: https://doi.org/10.1016/0967-0637(93)90069-F.

Melis, R., Salvi, G., 2020. Foraminifer and Ostracod occurrence in a cool-water carbonate factory of the Cape Adare (Ross Sea, Antarctica): a key lecture for the climatic and oceanographic variations in the last 30,000 years. Geosciences 10, 413. Available from: https://doi.org/10.3390/geosciences10100413.

Mercer, J.H., 1978. West Antarctic Ice Sheet and CO_2 greenhouse effect: a threat of disaster. Nature 271, 321−325. Available from: https://doi.org/10.1038/271321a0.

Mezgec, K., Stenni, B., Crosta, X., Masson-Delmotte, V., Baroni, C., Braida, M., et al., 2017. Holocene sea ice variability driven by wind and polynya efficiency in the Ross Sea. Nature Communications 8, 1334. Available from: https://doi.org/10.1038/s41467-017-01455-x.

Miles, B.W.J., Stokes, C.R., Vieli, A., Cox, N.J., 2013. Rapid, climate-driven changes in outlet glaciers on the Pacific coast of East Antarctica. Nature 500, 563−566. Available from: https://doi.org/10.1038/nature12382.

Minzoni, R.T., Majewski, W., Anderson, J.B., Yokoyama, Y., Fernandez, R., Jakobsson, M., 2017. Oceanographic influences on the stability of the Cosgrove Ice Shelf, Antarctica. The Holocene 27 (11), 1645−1658. Available from: https://doi.org/10.1016/j.quascirev.2004.10.006.

Miura, H., Maemoku, H., Seto, K., Moriwaki, K., 1998. Late Quaternary East Antarctic melting event in the Soya coast region based on stratigraphy and oxygen isotopic ratio of fossil molluscs. Polar Geoscience 11, 260−274.

Morlighem, M., et al., 2020. Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic Ice Sheet. Nature Geoscience 13, 132−137. Available from: https://doi.org/10.1038/s41561-019-0510-8.

Morse, D.L., Waddington, E.D., Steig, E.J., 1998. Ice age storm trajectories inferred from radar stratigraphy at Taylor Dome, Antarctica. Geophysical Research Letters 25, 3383−3386. Available from: https://doi.org/10.1029/98GL52486.

Mosola, A.B., Anderson, J.B., 2006. Expansion and rapid retreat of the West Antarctic Ice Sheet in eastern Ross Sea: possible consequence of over-extended ice streams? Quaternary Science Reviews 25, 2177−2196. Available from: https://doi.org/10.1016/j.quascirev.2005.12.013.

Mulvaney, R., Abram, N.J., Hindmarsh, R.C.A., Arrowsmith, C., Fleet, L., Triest, J., et al., 2012. Recent Antarctic Peninsula warming relative to Holocene climate and ice-shelf history. Nature 489, 141−144. Available from: https://doi.org/10.1038/nature11391.

Nakada, M., Kimura, R., Okuno, J., Moriwaki, K., Miura, H., Maemoku, H., 2000. Late Pleistocene and Holocene melting history of the Antarctic Ice Sheet derived from sea level variations. Marine Geology 167, 85–103. Available from: https://doi.org/10.1016/S0025-3227(00)00018-9.

Nakada, M., Lambeck, K., 1988. The melting history of the late Pleistocene Antarctic Ice Sheet. Nature 333, 36–40. Available from: https://doi.org/10.1038/333036a0.

Nichols, K.A., Goehring, B.M., Balco, G., Johnson, J.S., Hein, A.S., Todd, C., 2019. New Last Glacial Maximum ice thickness constraints for the Weddell Sea Embayment, Antarctica. The Cryosphere 13, 2935–2951. Available from: https://doi.org/10.5194/tc-13-2935-2019.

Nitsche, F.O., Gohl, K., Larter, R.D., Hillenbrand, C.-D., Kuhn, G., Smith, J.A., et al., 2013. Paleo-ice flow and subglacial meltwater dynamics in Pine Island Bay, West Antarctica. The Cryosphere 7, 249–262. Available from: https://doi.org/10.5194/tc-7-249-2013.

Nitsche, F.O., Jacobs, S.S., Larter, R.D., Gohl, K., 2007. Bathymetry of the Amundsen Sea continental shelf: implications for geology, oceanography and glaciology. Geochemistry, Geophysics, Geosystems 8, Q10009. Available from: https://doi.org/10.1029/2007GC001694.

Noble, T.L., Rohling, E.J., Aitken, A.R.A., Bostock, H.C., Chase, Z., Gomez, N., N., et al., 2020. The sensitivity of the Antarctic Ice Sheet to a changing climate: past, present, and future. Reviews of Geophysics 58. Available from: https://doi.org/10.1029/2019RG000663.

O'Brien, P.E., De Santis, L., Harris, P.T., Domack, E., Quilty, P.G., 1999. Ice shelf grounding zone features of western Prydz Bay, Antarctica: sedimentary processes from seismic and sidescan images. Antarctic Science 11, 78–91. Available from: https://doi.org/10.1017/S0954102099000115.

O'Brien, P., Smith, J., Stark, J.S., Johnstone, G., Riddle, M., Franklin, D., 2015. Submarine geomorphology and sea floor processes along the coast of Vestfold Hills, East Antarctica, from multibeam bathymetry and video data. Antarctic Science 27, 566–586. Available from: https://doi.org/10.1017/S0954102015000371.

Ó Cofaigh, C., Davies, B.J., Livingstone, S.J., Smith, J.A., Johnson, J.S., Hocking, E.P., et al., 2014. Reconstruction of ice-sheet changes in the Antarctic Peninsula since the Last Glacial Maximum. Quaternary Science Reviews 100, 87–110. Available from: https://doi.org/10.1016/j.quascirev.2014.06.023.

Ó Cofaigh, C., Dowdeswell, J.A., Allen, C.S., Hiemstra, J.F., Pudsey, C.J., Evans, J., et al., 2005a. Flow dynamics and till genesis associated with a marine-based Antarctic palaeo-ice stream. Quaternary Science Reviews 24, 709–740. Available from: https://doi.org/10.1016/j.quascirev.2004.10.006.

Ó Cofaigh, C., Larter, R.D., Dowdeswell, J.A., Hillenbrand, C.-D., Pudsey, C.J., Evans, J., et al., 2005b. Flow of the West Antarctic Ice Sheet on the continental margin of the Bellingshausen Sea at the Last Glacial Maximum. Journal of Geophysical Research 110 (B11103). Available from: https://doi.org/10.1029/2005JB003619.

Ó Cofaigh, C., Pudsey, C.J., Dowdeswell, J.A., Morris, P., 2002. Evolution of subglacial bedforms along a paleo-ice stream, Antarctic Peninsula continental shelf. Geophysical Research Letters 29 (8), 1–4. Available from: https://doi.org/10.1029/2001GL014488.

Overpeck, J.T., Otto-Bliesner, B.L., Miller, G.H., Muhs, D.R., Alley, R.B., Kiehl, J.T., 2006. Paleoclimatic evidence for future ice-sheet instability and rapid sea-level rise. Science 311, 1747–1750. Available from: https://doi.org/10.1126/science.1256697.

Peck, V.L., Allen, C.S., Kender, S., McClymont, E.L., Hodgson, D.A., 2015. Oceanographic variability on the West Antarctic Peninsula during the Holocene and the influence of upper circumpolar deep water. Quaternary Science Reviews 119, 54–65. Available from: https://doi.org/10.1016/j.quascirev.2015.04.002.

Peltier, W.R., 2004. Global glacial isostasy and the surface of the ice-age earth: the ICE-56 (VM2) Model and GRACE. Annual Reviews of Earth and Planetary Science 39, 114–149. Available from: https://doi.org/10.1146/annurev.earth.32.082503.144359.

Perotti, M., Andreucci, B., Talarico, F., Zattin, M., Langone, A., 2017. Multianalytical provenance analysis of Eastern Ross Sea LGM till sediments (Antarctica): petrography, geochronology, and thermochronology detrital data. Geochemistry Geophysics Geosystems 18, 2275–2304. Available from: https://doi.org/10.1002/2016GC006728.

Philippon, G., Ramstein, G., Charbit, S., Kageyama, M., Ritz, C., Dumas, C., 2006. Evolution of the Antarctic ice sheet throughout the last deglaciation: a study with a new coupled climate-north and south hemisphere ice sheet model. Earth and Planetary Science Letters 248, 750–758. Available from: https://doi.org/10.1016/j.epsl.2006.06.017.

Pike, J., Swann, G.E.A., Leng, M.J., Snelling, A.M., 2013. Glacial discharge along the west Antarctic Peninsula during the Holocene. Nature Geoscience 6, 199–202. Available from: https://doi.org/10.1038/ngeo1703.

Pollard, D., DeConto, R.M., 2009. Modelling West Antarctic Ice Sheet growth and collapse through the past five million years. Nature 458, 329–332. Available from: https://doi.org/10.1038/nature07809.

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. Available from: https://doi.org/10.1029/AR057p0063.

Post, A.L., O'Brien, P.E., Edwards, S., Carroll, A.G., Malakoff, K., Armand, L.K., 2020. Upper slope processes and seafloor ecosystems on the Sabrina continental slope, East Antarctica. Marine Geology 422, 106091. Available from: https://doi.org/10.1016/j.margeo.2019.106091.

Pritchard, H., Arthern, R., Vaughan, D., Edwards, L.A., 2009. Extensive dynamic thinning on the margins of the Greenland and Antarctic Ice Sheets. Nature 461, 971–975. Available from: https://doi.org/10.1038/nature08471.

Prothro, L.O., Majewski, W., Yokoyama, Y., Simkins, L.M., Anderson, J.B., Yamane, M., et al., 2020. Timing and pathways of East Antarctic Ice Sheet retreat. Quaternary Science Reviews 230, 106166. Available from: https://doi.org/10.1016/j.quascirev.2020.106166.

Prothro, L.O., Simkins, L.M., Majewski, W., Anderson, J.B., 2018. Glacial retreat patterns and processes determined from integrated sedimentology and geomorphology records. Marine Geology 395, 104–119. Available from: https://doi.org/10.1016/j.margeo.2017.09.012.

Pudsey, C.J., Barker, P.F., Larter, R.D., 1994. Ice sheets retreat from the Antarctic Peninsula shelf. Continental Shelf Research 14, 1647–1675. Available from: https://doi.org/10.1016/0278-4343(94)90041-8.

Pudsey, C.J., Evans, J., 2001. First survey of Antarctic sub-ice shelf sediments reveals Mid-Holocene ice shelf retreat. Geology 29 (9), 787–790. Available from: https://doi.org/10.1130/0091-7613(2001)029%3C0787:FSOASI%3E2.0.CO;2.

Pudsey, C.J., Evans, J., Domack, E.W., Morris, P., Del Valle, R.A., 2001. Bathymetry and acoustic facies beneath the former Larsen-A and Prince Gustav ice shelves, north-west Weddell Sea. Antarctic Science 13, 312–322. Available from: https://doi.org/10.1017/S095410200100044X.

Pudsey, C.J., Murray, J.W., Appleby, P., Evans, J., 2006. Ice shelf history from petrographic and foraminiferal evidence, northeast Antarctic Peninsula. Quaternary Science Reviews 25, 2357–2379. Available from: https://doi.org/10.1016/j.quascirev.2006.01.029.

Rebesco, M., Domack, E., Zgur, F., Lavoie, C., Leventer, A., Brachfeld, S., et al., 2014. Boundary condition of grounding lines prior to collapse, Larsen-B Ice Shelf, Antarctica. Science 345, 1354–1358. Available from: https://doi.org/10.1126/science.1256697.

Rignot, E., Jacobs, S.S., 2002. Rapid bottom melting widespread near Antarctic Ice sheet grounding lines. Science 296 (5575), 2020–2023. Available from: https://doi.org/10.1126/science.1070942.

Rignot, E., Jacobs, S., Mouginot, J., Scheuchl, B., 2013. Ice-shelf melting around Antarctica. Science 341, 266–270. Available from: https://doi.org/10.1126/science.1235798.

Rignot, E., Mouginot, J., Scheuchl, B., van den Broeke, M., van Wessem, M.J., Morlighem, M., 2019. Four decades of Antarctic Ice Sheet mass balance from 1979–2017. Proceedings of the National Academy of Sciences 116, 1095–1103. Available from: https://doi.org/10.1073/pnas.1812883116.

Ritz, C., Rommelaere, V., Dumas, C., 2001. Modelling the evolution of Antarctic Ice Sheet over the last 420,000 years: implications for altitude changes in the Vostok region. Journal of Geophysical Research 106, 31943–31964. Available from: https://doi.org/10.1029/2001JD900232.

Roberts, S.J., Hodgson, D.A., Bentley, M.J., Sanderson, D.C.W., Milne, G., Smith, J.A., et al., 2009. Holocene relative sea-level change and deglaciation on Alexander Island, Antarctic Peninsula, from elevated lake deltas. Geomorphology 112, 122–134. Available from: https://doi.org/10.1016/j.geomorph.2009.05.011.

Rosenheim, B.E., Day, M.B., Domack, E., Schrum, H., Benthien, A., Hayes, J.M., 2008. Antarctic sediment chronology by programmed-temperature pyrolysis: methodology and data treatment. Geochemistry, Geophysics, Geosystems 9 (4), 1–16. Available from: https://doi.org/10.1029/2007GC001816.

Rosenheim, B.E., Santoro, J.A., Gunter, M., Domack, E.W., 2013. Improving Antarctic sediment ^{14}C dating using ramped pyrolysis: an example from the Hugo Island trough. Radiocarbon 55 (1), 115–126. Available from: https://doi.org/10.2458/azu_js_rc.v55i1.16234.

Rosier, S.H.R., Hofstede, C., Brisbourne, A.M., Hattermann, T., Nicholls, K.W., Davis, P.E.D., et al., 2018. A new bathymetry for the southeastern Filchner-Ronne Ice Shelf: implications for modern oceanographic processes and glacial history. Journal of Geophysical Research: Oceans 123, 4610–4623. Available from: https://doi.org/10.1029/2018JC013982.

Ross, N., Siegert, M.J., Woodward, J., Smith, A.M., Corr, H.F.J., Bentley, M.J., et al., 2011. Holocene stability of the Pine Island Glacier-Weddell Sea ice divide, West Antarctica. Geology 39, 935–938. Available from: https://doi.org/10.1130/G31920.1.

Ross, N., Bingham, R.G., Corr, H., Ferraccioli, F., Jordan, T.A., Le Brocq, A., et al. 2012. Steep reverse bed slope at the grounding line of the Weddell Sea sector in West Antarctica. Nature Geoscience 5, 393–396. Available from: https://doi.org/10.1038/ngeo1468.

Scherer, R.P., Aldahan, A., Tulaczyk, S., Possnert, G., Engelhardt, H., Kamb, B., 1998. Pleistocene collapse of the West Antarctic Ice Sheet. Science 281, 82–85. Available from: https://doi.org/10.1126/science.281.5373.82.

Shackleton, N.J., 2000. The 100,000-year ice age cycle identified and found to lag temperature, carbon dioxide, and orbital eccentricity. Science 289 (5486), 1897–1902. Available from: https://doi.org/10.1126/science.289.5486.1897.

Shackleton, N.J., Sanchez-Goni, M.F., Pailler, D., Lancelot, Y., 2003. Marine isotope substage 5e and the Eemian interglacial. Global and Planetary Change 36, 151–155. Available from: https://doi.org/10.1016/S0921-8181(02)00181-9.

Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., et al., 2018. Mass balance of the Antarctic Ice Sheet from 1992 to 2017. Nature 558, 219–222. Available from: https://doi.org/10.1038/s41586-018-0179-y.

Shevenell, A.E., Ingalls, A.E., Domack, E.W., Kelly, C., 2011. Holocene Southern Ocean surface temperature variability west of the Antarctic Peninsula. Nature 470, 250–254. Available from: https://doi.org/10.1038/nature09751.

Shipp, S.S., Anderson, J.B., Domack, E.W., 1999. Late Pleistocene-Holocene retreat of the West Antarctic Ice Sheet system in the Ross Sea: part 1 − geophysical results. Geological Society of America Bulletin 111, 1486−1516. Available from: https://doi.org/10.1130/0016-7606(1999)111(1486:LPHROT)2.3.CO;2.

Shipp, S.S., Wellner, J.A., Anderson, J.B., 2002. Retreat signature of a polar ice stream: subglacial geomorphic features and sediments from the Ross Sea, Antarctica. In: Dowdeswell, J. A., Cofaigh, C.Ó. (Eds.), Glacier-Influenced Sedimentation on High-Latitude Continental Margins, 203. Geological Society of London Special Publication, pp. 277−304. Available from: https://doi.org/10.1144/GSL.SP.2002.203.01.15.

Siegert, M.J., 2001. Ice Sheets and Late Quaternary Environmental Change. John Wiley, Chichester, p. 231, ISBN: 978-0-471-98570-9.

Siegert, M.J., 2003. Glacial-Interglacial variations in central East Antarctic ice accumulation rates. Quaternary Science Reviews 22, 741−750. Available from: https://doi.org/10.1016/S0277-3791(02)00191-9.

Siegert, M.J., Alley, R.B., Rignot, E., Englander, J., Corell, R., 2020. 21st century sea-level rise could exceed IPCC predictions for strong-warming futures. One Earth 3, 691−703. Available from: https://doi.org/10.1016/j.oneear.2020.11.002.

Siegert, M.J., Kingslake, J., Ross, N., Whitehouse, P.L., Woodward, J., Jamieson, S.S.R., et al., 2019. Late Holocene glacial history of the Weddell Sea sector of the West Antarctic Ice Sheet. Reviews of Geophysics 57, 1197−1223. Available from: https://doi.org/10.1029/2019RG000651.

Siegert, M.J., Leysinger Vieli, G.J.M.C., 2007. Late glacial history of the Ross Sea sector of the West Antarctic Ice Sheet: evidence from englacial layering at Talos Dome, East Antarctica. Journal of Environmental and Engineering Geophysics 12, 63−67. Available from: https://doi.org/10.2113/JEEG12.1.63.

Siegert, M.J., Ross, N., Corr, H., Kingslake, J., Hindmarsh, R., 2013. Late Holocene ice-flow reconfiguration in the Weddell Sea sector of West Antarctica. Quaternary Science Reviews 78, 98−107. Available from: https://doi.org/10.1016/j.quascirev.2013.08.003.

Siegert, M.J., Ross, N., Li, J., Schroeder, D., Rippin, D., Ashmore, D., et al., 2016. Controls on the onset and flow of Institute Ice Stream, West Antarctica. Annals of Glaciology 57, 19−24. Available from: https://doi.org/10.1017/aog.2016.17.

Siegert, M.J., Golledge, N.R., 2021. Advances in numerical modelling of the Antarctic ice sheet. In: Florindo, F., et al. (Eds.), Antarctic Climate Evolution, second edition. Elsevier (this volume).

Simkins, L.M., Anderson, J.B., Greenwood, S.L., Gonnermann, H.M., Prothro, L.O., Halberstadt, A.R.W., et al., 2017. Anatomy of a meltwater drainage system beneath the ancestral East Antarctic Ice Sheet. Nature Geoscience 10 (9), 691−697. Available from: https://doi.org/10.1038/ngeo3012.

Simms, A.R., Lisiecki, L., Gebbie, G., Whitehouse, P.L., Clark, J.F., 2019. Balancing the last glacial maximum (LGM) sea-level budget. Quaternary Science Reviews 205, 143−153. Available from: https://doi.org/10.1016/j.quascirev.2018.12.018.

Smith, J.A., Andersen, T.J., Shortt, M., Gaffney, A.M., Truffer, M., Stanton, T.P., et al., 2017. Sub-ice-shelf sediments record history of twentieth-century retreat of Pine Island Glacier. Nature 541, 77−80. Available from: https://doi.org/10.1038/nature20136.

Smith, J.A., Bentley, M.J., Hodgson, D.A., Roberts, S.J., Leng, M.J., Lloyd, J.M., et al., 2007. Oceanic and atmospheric forcing of early Holocene ice shelf retreat, George VI Ice Shelf, Antarctica Peninsula. Quaternary Science Reviews 26, 500−516. Available from: https://doi.org/10.1016/j.quascirev.2006.05.006.

Smith, J.A., Hillenbrand, C.-D., Kuhn, G., Klages, J.P., Graham, A.G.C., Larter, R.D., et al., 2014. New constraints on the timing of West Antarctic Ice Sheet retreat in the eastern

Amundsen Sea since the Last Glacial Maximum. Global and Planetary Change 122, 224−237. Available from: https://doi.org/10.1016/j.gloplacha.2014.07.015.

Smith, J.A., Hillenbrand, C.-D., Kuhn, G., Larter, R.D., Graham, A.G.C., Ehrmann, W., et al., 2011. Deglacial history of the West Antarctic Ice Sheet in the western Amundsen Sea Embayment. Quaternary Science Reviews 30, 488−505. Available from: https://doi.org/10.1016/j.quascirev.2010.11.020.

Smith, J.A., Hillenbrand, C.-D., Larter, R.D., Graham, A.G.C., Kuhn, G., 2009. The sediment infill of subglacial meltwater channels on the West Antarctic continental shelf. Quaternary Research 71, 190−200. Available from: https://doi.org/10.1016/j.yqres.2008.11.005.

Spector, P., Stone, J., Cowdery, S.G., Hall, B., Conway, H., Bromley, G., 2017. Rapid early-Holocene deglaciation in the Ross Sea, Antarctica. Geophysical Research Letters 44, 7817−7825. Available from: https://doi.org/10.1002/2017GL074216.

Spector, P., Stone, J., Goehring, B., 2019. Thickness of the divide and flank of the West Antarctic Ice Sheet through the last deglaciation. The Cryosphere 13, 3061−3075. Available from: https://doi.org/10.5194/tc-13-3061-2019.

Stirling, C.H., Esat, T.M., Lambeck, K., McCulloch, M.T., 1998. Timing and duration of the last interglacial: evidence for a restricted interval of widespread coral reef growth. Earth and Planetary Science Letters 160, 745−762. Available from: https://doi.org/10.1016/S0012-821X(98)00125-3.

Stolldorf, T., Schenke, H.-W., Anderson, J.B., 2012. LGM ice sheet extent in the Weddell Sea: evidence for diachronous behavior of Antarctic Ice Sheets. Quaternary Science Reviews 48, 20−31. Available from: https://doi.org/10.1016/j.quascirev.2012.05.017.

Stone, J.O., Balco, G.A., Sugden, D.E., Caffee, M.W., Sass, L.C.I., Cowdery, S.G., et al., 2003. Holocene deglaciation of Marie Byrd Land, West Antarctica. Science 299, 99−102. Available from: https://doi.org/10.1126/science.1077998.

Studinger, M., Bell, R.E., Blankenship, D.D., Finn, C.A., Arko, R.A., Morse, D.L., et al., 2001. Subglacial sediments: a regional geological template for ice flow in Antarctica. Geophysical Research Letters 28, 3493−3496. Available from: https://doi.org/10.1029/2000GL011788.

Subt, C., Fangman, K.A., Wellner, J.S., Rosenheim, B.E., 2016. Sediment chronology in Antarctic deglacial sediments: reconciling organic carbon ^{14}C ages to carbonate ^{14}C ages using Ramped PyrOx. The Holocene 26, 265−273. Available from: https://doi.org/10.1177/0959683615608688.

Subt, C., Yoon, H.I., Yoo, K.C., Lee, J.I., Leventer, A., Domack, E.W., et al., 2017. Sub-ice shelf sediment geochronology utilizing novel radiocarbon methodology for highly detrital sediments. Geochemistry, Geophysics, Geosystems 18, 1404−1418. Available from: https://doi.org/10.1002/2016GC006578.

Sugden, D.E., Bentley, M.J., Cofaigh, C.Ó., 2006. Geological and geomorphological insights into Antarctic Ice Sheet evolution. Philosophical Transactions of the Royal Society A 364, 1607−1625. Available from: https://doi.org/10.1098/rsta.2006.1791.

Sugden, D.E., Jamieson, S.S.R., 2018. The pre-glacial landscape of Antarctica. Scottish Geographical Journal 134, 203−223. Available from: https://doi.org/10.1080/14702541.2018.1535090.

Sugden, D.E.A.S., Hein, J., Woodward, S.M., Marrero, Á., Rodés, S.A., Dunning, F.M., et al., 2017. The million-year evolution of the glacial trimline in the southernmost Ellsworth Mountains, Antarctica. Earth and Planetary Science Letters 469, 42−52. Available from: https://doi.org/10.1016/j.epsl.2017.04.006.

Takada, M., Miura, M., Zwartz, D., 1998. Radiocarbon and thermoluminescence ages in the Mt Riiser-Larsen area, Enderby Land, East Antarctica. Polar Geoscience 11, 239−248.

Takada, M., Tani, A., Miura, H., Moriwaki, K., Nagatomo, T., 2003. ESR dating of fossil shells in the Lützow-Holm Bay region, East Antarctica. Quaternary Science Reviews 22 (10−13), 1323−1328. Available from: https://doi.org/10.1016/S0277-3791(03)00040-4.

Tarasov, L., Peltier, W.R., 2003. Greenland glacial hstory, borehole constraints and Eemian extent. Journal of Geophysical Research 108 (B3), 2143. Available from: https://doi.org/10.1029/2001JB001731.

Taylor, F., McMinn, A., 2002. Late Quaternary diatom assemblages from Prydz Bay, Eastern Antarctica. Quaternary Research 57 (1), 151−161. Available from: https://doi.org/10.1006/qres.2001.2279.

Taylor, J., Siegert, M.J., Payne, A.J., Hambrey, M.J., O'Brien, P.E., Cooper, A.K., et al., 2004. Topographic controls on post-Oligocene changes in ice-sheet dynamics, Prydz Bay region, East Antarctica. Geology 32, 197−200. Available from: https://doi.org/10.1130/G20275.1.

The RAISED Consortium, 2014. A community-based geological reconstruction of Antarctic Ice Sheet deglaciation since the Last Glacial Maximum. Quaternary Science Reviews 100, 1−9. Available from: https://doi.org/10.1016/j.quascirev.2014.06.025.

Tingey, R.J., McDougall, I., Gleadow, A.J.W., 1983. The age and mode of formation of Gaussberg. Antarctica. Journal of the Geological Society of Australia 30, 241−246. Available from: https://doi.org/10.1080/00167618308729251.

Tinto, K.J., et al., 2019. Ross Ice Shelf response to climate driven by the tectonic imprint on seafloor bathymetry. Nature Geoscience 12, 441−449. Available from: https://doi.org/10.1038/s41561-019-0370-2.

Todd, C., Stone, J., Conway, H., Hall, B., Bromley, G., 2010. Late Quaternary evolutionof Reedy Glacier, Antarctica. Quaternary Science Reviews 29, 1328−1341. Available from: https://doi.org/10.1016/j.quascirev.2010.02.001.

Turner, J., Orr, A., Gudmundsson, G.H., Jenkins, A., Bingham, R.G., Hillenbrand, C.-D., et al., 2017. Atmosphere-ocean-ice interactions in the Amundsen Sea Embayment, West Antarctica. Reviews of Geophysics 55, 235−276. Available from: https://doi.org/10.1002/2016RG000532.

Vaughan, D.G., Marshall, G., Connolley, W.M., Parkinson, C., Mulvaney, R., Hodgson, D.A., et al., 2003. Recent rapid regional climate warming on the Antarctic Peninsula. Climatic Change 60, 243−274. Available from: https://doi.org/10.1023/A:1026021217991.

Verleyen, E., Hodgson, D.A., Milne, G.A., Sabbe, K., Vyverman, W., 2005. Relative sea-level history from the Lambert Glacier region, East Antarctica, and its relation to deglaciation and Holocene glacier readvance. Quaternary Research 63, 45−52. Available from: https://doi.org/10.1016/j.yqres.2004.09.005.

Voosen, P., 2018. Antarctic ice melt 125,000 years ago offers warning. Science 362, 1339. Available from: https://doi.org/10.1126/science.362.6421.1339.

Waddington, E.D., Conway, H., Steig, E.J., Alley, R.B., Brook, E.J., Taylor, K.C., et al., 2005. Decoding the dipstick: thickness of Siple Dome, West Antarctica, at the Last Glacial Maximum. Geology 33, 281−284. Available from: https://doi.org/10.1130/G21165.1.

Wagner, B., Cremer, H., Hultzsch, N., Gore, D.B., Melles, M., 2004. Late Pleistocene and Holocene history of Lake Terrasovoje, Amery Oasis, East Antarctica, and its climatic and environmental implications. Journal of Paleolimnology 32, 321−339. Available from: https://doi.org/10.1007/s10933-004-0143-8.

Wagner, B., Hultzsch, N., Melles, M., Gore, D.B., 2007. Indications of Holocene sea-level rise in Beaver Lake, East Antarctica. Antarctic Science 19, 125−128. Available from: https://doi.org/10.1017/S095410200700017X.

Wellner, J.S., Lowe, A.L., Shipp, S.S., Anderson, J.B., 2001. Distribution of glacial geomorphic features on the Antarctic continental shelf and correlation with substrate: implications for ice behaviour. Journal of Glaciology 47, 397−411. Available from: https://doi.org/10.3189/172756501781832043.

White, D.A., Bennike, O., Berg, S., Harley, S.L., Fink, D., Kiernan, K., et al., 2009. Geomorphology and glacial history of Rauer Group, East Antarctica. Quaternary Research 72, 80−90. Available from: https://doi.org/10.1016/j.yqres.2009.04.001.

White, D.A., Fink, D., 2014. Late Quaternary glacial history constrains glacio-isostatic rebound in Enderby Land East Antarctica. Journal of Geophysical Research 119, 401−413. Available from: https://doi.org/10.1002/2013JF002870.

White, D.A., Fink, D., Gore, D.B., 2011. Cosmogenic nuclide evidence for enhanced sensitivity of an East Antarctic ice stream to change during the last deglaciation. Geology 39 (1), 23−26. Available from: https://doi.org/10.1130/G31591.1.

White, D.A., Hermichen, W.-D., 2007. Glacial and periglacial history of the southern Prince Charles Mountains, East Antarctica. Terra Antartica 14, 5−12.

Whitehouse, P.L., 2018. Post last glacial maximum processes in the polar regions. In: Nuttall, M., Christensen, T.R., Siegert, M.J. (Eds.), Routledge Handbook of the Polar Regions. Routledge, pp. 209−223. Chapter 16.

Whitehouse, P.L., Bentley, M.J., Le Brocq, A.M., 2012. A deglacial model for Antarctica: geological constraints and glaciological modelling as a basis for a new model of Antarctic glacial isostatic adjustment. Quaternary Science Reviews 32, 1−24. Available from: https://doi.org/10.1016/j.quascirev.2011.11.016.

Whitehouse, P.L., Bentley, M.J., Vieli, A., Jamieson, S.S.R., Hein, A.S., Sugden, D.E., 2017. Controls on Last Glacial Maximum ice extent in the Weddell Sea embayment, Antarctica. Journal of Geophysical Research 122, 371−397. Available from: https://doi.org/10.1002/2016JF004121.

Willmott, V., Domack, E.W., Canals, M., Brachfeld, S., 2006. A high resolution relative paleointensity record from the Gerlache-Boyd paleo-ice stream region, northern Antarctic Peninsula. Quaternary Science Reviews 66, 1−11. Available from: https://doi.org/10.1016/j.yqres.2006.01.006.

Wilson, D.J., Bertram, R.A., Needham, E.F., et al., 2018. Ice loss from the East Antarctic Ice Sheet during late Pleistocene interglacials. Nature 561, 383−386. Available from: https://doi.org/10.1038/s41586-018-0501-8.

Wilson, D.J., et al., 2021. In: Florindo, F. (Ed.), et al., Antarctic Climate Evolution, second ed. Elsevier, (this volume).

Winter, K., Woodward, J., Ross, N., Dunning, S.A., Corr, H.F.J., Bingham, R.G., et al., 2015. Airborne radar evidence for tributary flow switching in the Institute Ice Stream upper catchment, West Antarctica: implications for ice sheet configuration and dynamics. Journal of Geophysical Research 120, 1611−1625. Available from: https://doi.org/10.1002/2015JF003518.

Wise, M.G., Dowdeswell, J.A., Jakobsson, M., Larter, R.D., 2017. Evidence of marine ice-cliff instability in Pine Island Bay from iceberg-keel plough marks. Nature 550 (7677), 506−510. Available from: https://doi.org/10.1038/nature24458.

Witus, A.E., Branecky, C.M., Anderson, J.B., Szczuciński, W., Schroeder, D.M., Blankenship, D.D., et al., 2014. Meltwater intensive retreat in polar environments and investigation of associated sediments: example from Pine Island Bay, West Antarctica. Quaternary Science Reviews 85, 99−118. Available from: https://doi.org/10.1016/j.quascirev.2013.11.021.

Wolstencroft, M., King, M.A., Whitehouse, P.L., Bentley, M.J., Nield, G.A., King, E.C., et al., 2015. Uplift rates from a new high-density GPS network in Palmer Land indicate significant late Holocene ice loss in the southwestern Weddell Sea. Geophysical Journal International 203, 737−754. Available from: https://doi.org/10.1093/gji/ggv327.

Wright, A., White, D., Gore, D., Siegert, M.J., 2008. Antarctica at the LGM. In: Florindo, F., Siegert, M.J. (Eds.), Antarctic Climate Evolution. Developments in Earth & Environmental Sciences, 8. Elsevier, pp. 531−570. Available from: https://doi.org/10.1016/S1571-9197(08)00012-8.

Yamane, M., Yokoyama, Y., Miura, H., Maemoku, H., Iwasaki, S., Matsuzaki, H., 2011. The last deglacial history of Lützow-Holm Bay, East Antarctica. Journal of Quaternary Science 26, 3–6. Available from: https://doi.org/10.1002/jqs.1465.

Yamane, M., Yokoyama, Y., Miyairi, Y., Suga, H., Matsuzaki, H., Dunbar, R.B., et al., 2014. Compound-specific ^{14}C dating of IODP Expedition 318 Core U1357A obtained off the Wilkes Land Coast, Antarctica. Radiocarbon 56 (3), 1009–1017. Available from: https://doi.org/10.2458/56.17773.

Yau, A.M., Bender, M.L., Robinson, A., Brook, E.J., 2016. Reconstructing the last interglacial at Summit, Greenland: insights from GISP2. Proceedings of the National Academy of Sciences 113 (35), 9710–9715. Available from: https://doi.org/10.1073/pnas.1524766113.

Yokoyama, Y., Anderson, J.B., Yamane, M., Simkins, L.M., Miyairi, Y., Yamazaki, T., et al., 2016. Widespread collapse of the Ross Ice Shelf during the late Holocene. Proceedings of the National Academy of Sciences 113, 2354–2359. Available from: https://doi.org/10.1073/pnas.1516908113.

Yoshida, Y., Moriwaki, K., 1979. Some considerations on elevated coastal features and their dates around Syowa Station, Antarctica. Memoirs of the National Institute of Polar Research, Special Issue 13, 220–226.

Zwartz, D., Bird, M., Stone, J., Lambeck, K., 1998b. Holocene sea-level change and ice-sheet history in the Vestfold Hills, East Antarctica. Earth and Planetary Science Letters 155 (1–2), 131–145. Available from: https://doi.org/10.1016/S0012-821X(97)00204-5.

Zwartz, D.P., Miura, H., Takada, M., Moriwaki, K., 1998a. Holocene lake sediments and sea-level change at Mt. Riiser-Larsen. Polar Geoscience 11, 249–259. Available from: https://doi.org/10.1016/S0012-821X(97)00204-5.