Reconstruction of changes in the Weddell Sea sector of the Antarctic Ice Sheet since the Last Glacial Maximum

Claus-Dieter Hillenbrand[1,*], Michael J. Bentley[2,*], Travis D. Stolldorf[3], Andrew S. Hein[4], Gerhard Kuhn[5], Alastair G. C. Graham[6], Christopher J. Fogwill[7], Yngve Kristoffersen[8], James. A. Smith[1], John B. Anderson[3], Robert D. Larter[1], Martin Melles[9], Dominic A. Hodgson[1], Robert Mulvaney[1] & David E. Sugden[4]

[1]*British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK*

[2]*Department of Geography, Durham University, South Road, Durham DH1 3LE, UK*

[3]*Department of Earth Sciences, Rice University, 6100 Main Street, Houston, TX 77005, USA*

[4]*School of GeoSciences, University of Edinburgh, Drummond Street, Edinburgh, EH8 9XP, UK*

[5]*Alfred-Wegener-Institut Hemholtz-Zentrum für Polar- und Meeresforschung, Am Alten Hafen 26, D-27568 Bremerhaven, Germany*

[6]*College of Life and Environmental Sciences, University of Exeter, Exeter EX4 4RJ, UK*

[7]*Climate Change Research Centre, University of New South Wales, Sydney, Australia*

[8]*Department of Earth Science, University of Bergen, Allegate 41, Bergen, N-5014, Norway*

[9]*Institute of Geology and Mineralogy, University of Cologne, Zülpicher Strasse 49a, D-50674 Cologne, Germany*

*These authors contributed equally to this work.

Manuscript submitted to *Quaternary Science Reviews*, Special Issue on *Antarctic Ice Sheet History*

Abstract

The Weddell Sea sector is one of the main formation sites for Antarctic bottom water and an outlet for about one fifth of Antarctica's continental ice volume. Over the last few decades, studies on glacial-geological records in this sector have provided conflicting reconstructions of changes in ice-sheet extent and ice-sheet thickness since the Last Glacial Maximum (LGM at ca. 23-19 calibrated kiloyears before present, cal ka BP). Terrestrial geomorphological records and exposure ages obtained from rocks in the hinterland of the Weddell Sea, ice-sheet thickness constraints from ice cores and some radiocarbon dates on offshore sediments were interpreted to indicate no significant ice thickening and locally restricted grounding-line advance at the LGM. Other marine geological and geophysical studies concluded that subglacial bedforms mapped on the Weddell Sea continental shelf, subglacial deposits and sediments over-compacted by overriding ice recovered in cores, and the few available radiocarbon ages from marine sediments are consistent with major ice-sheet advance at the LGM. Reflecting the geological interpretations, different ice-sheet models have reconstructed conflicting LGM ice-sheet configurations for the Weddell Sea sector. Consequently, the estimated contributions of ice-sheet build-up in the Weddell Sea sector to the LGM sea-level low-stand of ~130 metres vary considerably.

In this paper, we summarise and review the geological records of past ice-sheet margins and past ice-sheet elevations in the Weddell Sea sector. We compile marine and terrestrial chronological data constraining former ice-sheet size, thereby

highlighting different levels of certainty, and present two alternative scenarios of the LGM ice-sheet configuration, including time-slice reconstructions for post-LGM grounding-line retreat. Moreover, we discuss consistencies and possible reasons for inconsistencies between the various reconstructions and propose objectives for future research. The aim of our study is to provide two alternative interpretations of glacial-geological datasets on Antarctic ice-sheet history for the Weddell Sea sector, which can be utilised to test and improve numerical ice-sheet models.

Keywords: Antarctica; cosmogenic nuclide surface exposure age dating; deglaciation; geomorphology; glacial history; ice sheet; ice shelf; Last Glacial Maximum; radiocarbon dating; sea level; Weddell Sea.

1. Introduction

The Weddell Sea region in the Atlantic sector of Antarctica (Fig. 1) plays a key role for the global thermohaline circulation by ventilating the abyssal World Ocean in the Southern Hemisphere (Rahmstorf 2002). Interaction between sea ice, ice shelves and seawater on the continental shelf of the Weddell Sea Embayment (WSE) produces dense cool precursor water masses for Antarctic Bottom Water (AABW) which fills the deep Southern Ocean and spreads equatorwards into the deep-sea basins of the Atlantic, Indian and Pacific oceans: in the Atlantic sector AABW reaches as far as ~5°S latitude (e.g., Orsi et al. 1999, Nicholls et al. 2009). At present, about 40-70% of AABW is formed in the Weddell Sea, which therefore represents an important 'AABW factory' (Naveira Garabato et al. 2002, Fukamachi et al. 2010, Meredith 2013). Glaciers, ice streams and ice shelves flowing into the WSE drain more than 22% of the combined area of the West Antarctic Ice Sheet (WAIS), the East Antarctic Ice Sheet (EAIS) and the Antarctic Peninsula Ice Sheet (APIS) (e.g., Joughin et al. 2006). Thus, as in other sectors of Antarctica, dynamical changes in the ice drainage basins surrounding the WSE have the potential to make major contributions to future sea-level rise (IPCC 2007). The southern part of the embayment is covered by the Filchner-Ronne Ice Shelf, one of the two major ice shelves in Antarctica, which has been identified as potentially critical to future WAIS stability (Hellmer et al. 2012).

Recently published data on subglacial topography have revealed that in the hinterland of the WSE (i) the WAIS is grounded at about 1000-1200 metres below sea level on a bed with locally reverse slopes, (ii) the WAIS has a thickness close to floatation, and (iii) a large subglacial basin is located immediately upstream of the grounding line (Ross et al. 2012). Such a configuration is thought to make the ice sheet prone to rapid grounding-line retreat and ice-sheet draw-down (e.g., Weertman 1974, Schoof 2007, Vaughan & Arthern 2007, Katz & Worster 2010, Joughin & Alley 2011), which could be triggered by grounding-line destabilisation in response to increased oceanic melting during the latter half of the 20th century (Hellmer et al. 2012). The presence of a smooth, flat bed upstream of the grounding line has been cited as evidence of previous deglaciation (Ross et al. 2012). Whilst much recent work has focussed on the Amundsen Sea sector of the WAIS, the recent findings have drawn attention to the Weddell Sea sector as another potentially important unstable part of the Antarctic ice sheets.

Furthermore, East Antarctica, including the eastern WSE, has been identified as a key region for better understanding glacial-isostatic adjustment (GIA) following the LGM (King et al. 2012, Shepherd et al. 2012). Estimates of mass balance based on satellite gravimetry (and to a lesser extent satellite altimetry) require a correction for crustal and mantle movements following ice (un-)loading; the uncertainty in such mass balance estimates is now dominated by the relatively poor knowledge of East Antarctic GIA (King et al. 2012).

Reconstructions of the dynamical changes affecting the Weddell Sea sector during the last glacial cycle may give important clues about the future fate of its drainage basins. Such palaeo-studies have the potential to answer three fundamental questions hampering our understanding of Antarctica's glacial history: 1) Did the grounding line in the WSE advance to the shelf break during the LGM at ~23,000 to 19,000 cal yrs BP (e.g. Gersonde et al. 2005) and thereby shut down the modern type of AABW production in this sector? 2) How much did ice-sheet build-up in this sector contribute to the LGM sea-level low-stand of ~130 metres below present, and how much did post-LGM ice-sheet draw-down contribute to global meltwater pulses at 19.1 cal ka BP (e.g. Clark et al. 2004) and 14.6 cal ka BP (e.g. Clark et al. 2002)? 3) What was the ice-sheet history in the WSE and especially in its eastern part that contributed to modern day glacial-isostatic adjustment? Unfortunately, the available geological data constraining the LGM and post-LGM history of the Weddell Sea sector are so sparse that it can arguably be considered as one of the least well-studied sectors of Antarctica (e.g., Sugden et al. 2006, Wright et al. 2008). The main reasons for this lack of data are (i) the logistically very challenging access to the remote outcrops of rocks and till in the WSE hinterland, which are far away from any research station, and (ii) the nearly perennial sea-ice coverage, which has significantly restricted the access of research vessels to the southern WSE shelf, especially since the calving of huge icebergs from the Filchner Ice Shelf in 1986 (Grosfeld et al. 2001), with one of these icebergs remaining grounded on the shelf even today. Thus, at the time of the last major review of Weddell Sea glaciation (Bentley & Anderson 1998) there was only fragmentary marine and terrestrial geological evidence to draw upon, much of it undated. As a consequence of the scarcity of data, LGM ice-sheet configurations reconstructed from numerical models show major discrepancies in the WSE, with some models indicating a thick ice sheet covering the entire continental shelf (e.g., Huybrechts 2002, Bassett et al. 2007, Pollard & DeConto 2009, Golledge et al. 2012) and others suggesting a thin ice-sheet extending across only shallower parts of the shelf (Bentley et al. 2010, Le Brocq et al. 2011, Whitehouse et al. 2012). Consequently, the estimated sea-level equivalent volume of LGM ice-sheet build-up in the Weddell Sea sector varies between 1.4 to 3 metres and 13.1 to 14.1 metres (Bassett et al. 2007, Le Brocq et al. 2011).

Despite these challenges, significant progress has been made over the last decade (and especially during the last few years) in mapping terrestrial palaeo-ice sheet surfaces and collecting rock samples for exposure age dating by analysing cosmogenic nuclides (e.g. Fogwill et al. 2004, Bentley et al. 2010, Hein et al. 2011, Hodgson et al. 2012) and in mapping glacial bedforms on the continental shelf for reconstructing past ice-sheet extent (Larter et al. 2012, Stolldorf et al. 2012). Furthermore, compilations of older datasets together with new results from sedimentological and chronological analyses on marine sediment cores recovered in the late 1960s, early 1970s and 1980s have recently been published (Hillenbrand et al. 2012, Stolldorf et al. 2012). Additional important information about the LGM ice-sheet configuration was obtained from the Berkner Island ice core drilled from 2002 to 2005 (Mulvaney et al. 2007).

All these recent studies have substantially increased the available palaeo-dataset and stimulated this paper. The main aim of our reconstruction is to provide a timely summary of current knowledge about the LGM to Holocene glacial history of the Weddell Sea sector. Together with the reconstructions of the other Antarctic sectors synthesised in this special issue by the community of palaeo-researchers, our study will provide comprehensive and integrated glacial-geological datasets on Antarctic ice-sheet history. The aim is that the datasets can be used to test and refine numerical ice-sheet models and to improve their reliability in predicting future sea-level rise from ice-sheet melting in response to global warming.

In the WSE there is still an apparent discrepancy between different lines of evidence for the extent of the ice sheet at the LGM (e.g. Bentley et al. 2010, Hillenbrand et al. 2012). The discrepancy has not yet been resolved and so this paper presents two alternative reconstructions for the LGM ice-sheet configuration in the Weddell Sea sector. We go on to discuss how these two reconstructions might (at least partly) be reconciled, and suggest priorities for future field, analytical and modelling work.

2. Study area

The Weddell Sea sector as defined for this reconstruction extends from ~60°W to 0°W and from the South Pole to the continental shelf edge offshore from the large Ronne and Filchner ice shelves and the relatively small Brunt, Stancombe-Wills, Riiser-Larsen, Quar, Ekstrøm, Jelbart and Fimbul ice shelves, respectively (Fig. 1). The Ronne and Filchner ice shelves are separated by Berkner Island and fed by ice streams draining the APIS and the WAIS into the Ronne Ice Shelf (from west to east: Evans Ice Stream, Carlson Inlet, Rutford, Institute, Möller and Foundation ice streams) and draining the EAIS into the Filchner Ice Shelf (Support Force, Recovery and Slessor glaciers, Bailey Ice Stream) (Fig. 1; Swithinbank et al. 1988, Vaughan et al. 1995, Joughin et al. 2006). Mountain outcrops extend all along the eastern Palmer Land coast (Antarctic Peninsula), but around the rest of the WSE are restricted to high elevation regions in the Ellsworth Mountains (SW-hinterland of the Ronne Ice Shelf), the Pensacola Mountains (S-hinterland of the Filchner Ice Shelf), the Shackleton Range and Theron Mountains in Coats Land (east of the Filchner Ice Shelf) and Maudheimvidda in western Dronning Maud Land (Fig. 1).

North of the Ronne and Filchner ice shelves the continental shelf is ~450 km wide and on average ~400-500 metres deep (Schenke et al. 1998). The shallowest water depth (≤250 metres) is recorded in the vicinity of Berkner Island (Haase 1986), and the deepest part of the shelf edge lies at ~600-630 metres water depth between ca. 32°W and 34°W (Gales et al. 2012). In the region from ~25°W to 0°W the distance between ice-shelf front and shelf break varies between 0 km and 80 km, with the water depths predominantly ranging from 300 to 400 metres. Filchner Trough (also called Crary Trough, with its subglacial landward continuation usually referred to as Thiel Trough), Hughes Trough and Ronne Trough are bathymetric depressions that extend across the continental shelf offshore from the Filchner and Ronne ice shelves (Fig. 1; Schenke et al. 1998, Stolldorf et al. 2012). All three troughs have pronounced landward dipping bathymetric profiles, which are typical for cross-shelf troughs eroded by Antarctic palaeo-ice streams, with the over-deepening of the inner shelf mainly resulting from subglacial erosion during repeated ice sheet advances over successive glacial cycles (e.g. Anderson 1999, Livingstone et al. 2012). Filchner Trough is located offshore from the Filchner Ice Shelf, up to ~1200 metres deep near the ice front (Schenke et al. 1998, Larter et al. 2012) and associated with a trough-mouth fan (Crary Fan) on the adjacent continental slope (e.g. Kuvaas & Kristoffersen 1991). Hughes Trough extends north of the central Ronne Ice Shelf and has a more subtle bathymetric expression with its floor lying at water depths shallower than 500 metres (Haase 1986, Stolldorf et al. 2012). Ronne Trough, which is located offshore from the westernmost Ronne Ice Shelf, is up to ~650 metres deep (Fig. 1; Haase 1986, Mackensen 2001, Nicholls et al. 2003, 2009, Hillenbrand et al. 2012). Data on subglacial topography indicate that all three palaeo-ice stream troughs are the submarine northward expressions of subglacial troughs which deepen further inshore beneath the WAIS and EAIS, respectively (see Fig. 11; Vaughan et al. 1995, Nicholls et al. 2009, Ross et al. 2012, Fretwell et al. 2013).

3. Methods

3.1. Marine studies

Ice-sheet extent on the Antarctic continental shelf is usually reconstructed from subglacial bedforms mapped by multi-beam swath bathymetry or sidescan sonar imaging, glacial erosional unconformities observed in (shallow) seismic or acoustic subbottom profiles, and occurrence of subglacial diamictons (i.e. tills) recovered in marine sediment cores (e.g. Domack et al. 1999, Shipp et al. 1999, Pudsey et al. 2001, Anderson et al. 2001, 2002, Heroy & Anderson 2005, Ó Cofaigh et al. 2005a, 2005b, Wellner et al. 2006, Graham et al. 2009, Hillenbrand et al. 2010, Mackintosh et al. 2011, Smith et al. 2011, Jakobsson et al. 2012, Kirshner et al. 2012, Livingstone et al. 2012). In the Weddell Sea sector, several seismic, 3.5 kHz, TOPAS, PARASOUND and sparker surveys were conducted but only a few narrow strips of the shelf were mapped with high-resolution bathymetry (Fig. 2). While the distribution and geometry of subglacial bedforms, such as moraines, glacial lineations and drumlins, give unequivocal evidence for former ice-sheet grounding and ice-flow directions on the shelf, their preservation allows only crude age estimations, unless chronological information from sediment cores is available. Likewise, any interpretations of prominent (sub-)seafloor reflectors visible in seismic profiles as glacial erosional unconformities or seabed outcrops of subglacial till still require confirmation by sediment coring, and such reflectors alone do not provide chronological information about past grounding events.

Marine sediment cores have been recovered mainly from the southern and eastern parts of the Weddell Sea sector, while only sparse sedimentological information from a few short cores is available for the rest of the study area (Supplementary Table 1, Fig. 3). A particular problem in identifying palaeo-grounding events in sediment cores is the clear distinction of subglacial and glaciomarine facies (e.g. Anderson et al. 1980, Elverhøi 1984, Domack et al. 1999, Licht et al. 1996, 1999, Evans & Pudsey

2002, Hillenbrand et al. 2005). For example, new sedimentological and micropalaeontological data on diamictons recovered from the WSE shelf that had previously been classified as subglacial tills (Anderson et al. 1980, 1983), led to a reinterpretation of some of the diamictons as glaciomarine sediments (Stolldorf et al. 2012). Another challenge for the sedimentological identification of past grounding events on the WSE shelf is that here, in contrast to other sectors from the Antarctic continental shelf (e.g. Licht et al. 1996, 1999, Domack et al. 1999, Heroy & Anderson 2005, Ó Cofaigh et al. 2005, Mosola & Anderson 2006, Hillenbrand et al. 2010, Kilfeather et al. 2011, Smith et al. 2011, Kirshner et al. 2012), several cores contain glaciomarine sediments with low water content, high shear strength and high density, which may indicate their post-depositional over-consolidation by a grounded ice sheet (e.g. Haase 1986, Elverhøi 1981, 1984, Elverhøi & Roaldset 1983, Melles 1987, Melles & Kuhn 1993, Hillenbrand et al. 2012).

The main dating method applied to shelf sediments in the Weddell Sea sector is radiocarbon (^{14}C) dating of calcareous microfossils, including radiometric ^{14}C dating and since the mid 1980s the much more sensitive Accelerator Mass Spectrometry (AMS) ^{14}C dating, which requires only ≤10 milligram of calcareous material. Radiocarbon dating of biogenic carbonate does not suffer from the large uncertainties affecting ^{14}C dating of particulate organic matter (e.g. Andrews et al. 1999, Licht & Andrews 2002, Anderson & Mosola 2006, Rosenheim et al. 2008). However, calcareous microfossils are very rare in Antarctic shelf sediments and, as a consequence, only a few of the cores recovered from the WSE shelf have been dated (Supplementary Table 2, Fig. 4). Where calcareous microfossils had been sampled from glaciomarine sediments above subglacial till, their ^{14}C dates were usually interpreted as minimum ages for grounded ice-sheet retreat (e.g. Anderson &

Andrews 1999). Most of the dated cores have provided just a single ^{14}C age (e.g. Kristoffersen et al. 2000b) or ^{14}C ages for horizons significantly above the transition of subglacial to glaciomarine sediments (e.g. Elverhøi 1981). Several cores are characterised by down-core reversals of ^{14}C dates that may result from post-depositional sediment reworking and disturbance caused by iceberg scouring, current winnowing or debris flow redeposition (e.g. Anderson & Andrews 1999, Kristoffersen et al. 2000a). Gravitational mass wasting is widespread on the continental slope of the Weddell Sea (e.g. Michels et al. 2002, Gales et al. 2012). Cores from further down the slope and the continental rise frequently recovered debris flow deposits, turbidites and contourites, i.e. sediments largely consisting of reworked material (e.g. Melles & Kuhn 1993, Kuhn & Weber 1993, Grobe & Mackensen 1992, Anderson & Andrews 1999). Therefore, we exclusively consider ^{14}C ages of cores collected from the continental shelf and the uppermost slope (i.e. shallower than 1000 metres water depth) in this study.

Taking into account the problems of down-core age reversals and possible presence of subglacially compacted, originally glaciomarine sediments on the WSE shelf, the interpretation of the oldest or even the youngest ^{14}C date in a sediment core as a minimum age for the last retreat of grounded ice is not straightforward. These limitations, together with uncertainties about the increase of the marine reservoir effect (MRE) in the Southern Ocean during the last glacial period (e.g., Sikes et al. 2000, Van Beek et al. 2002, Robinson & van de Flierdt 2009, Skinner et al. 2010), make it particularly challenging to reconstruct the timing of the last ice-sheet advance and retreat in the Weddell Sea sector from shelf sediments.

The marine ^{14}C dates mentioned under 'Datasets' (section 4) are reported as in the original references, but the ^{14}C ages used for the 'Time-slice reconstructions' (section 5) and referred to in the 'Discussion' (section 6) were all calibrated with the CALIB Radiocarbon Calibration Program version 6.1.0. We used an MRE correction of 1300±70 years (Berkman & Forman 1996), the uncertainty range of which overlaps with that of the core-top age of 1215±30 ^{14}C yrs BP obtained from site PS1418 on the upper slope just to the west of Crary Fan (Fig. 4, Supplementary Table 2), and the Marine09 calibration dataset (Reimer et al. 2009). Average calibrated ^{14}C ages are given for samples with replicate ^{14}C dates (Stolldorf et al. 2012), and corrected ^{14}C ages are given for ^{14}C dates that could not be calibrated. Uncorrected and corrected radiocarbon dates are given in ^{14}C ka BP (or ^{14}C yrs BP) and calibrated ^{14}C dates are given in cal ka BP (or cal yrs BP). All conventional and calibrated ^{14}C dates are listed in Supplementary Table 2.

3.2. Terrestrial studies

At the time of the last major review of ice-sheet extent and chronology in the WSE during the last glacial cycle (Bentley & Anderson 1998) the mapped evidence of the onshore ice-sheet configuration, which included features marking the altitudinal extent of the former ice-sheet surface (e.g., erosional trimlines, moraines) and former flow direction indicators (e.g., striations, roches moutonnees), was limited and the dating control of these features was poor. Since then there has been a substantial increase in onshore glacial geological investigations around the embayment. The majority of studies have applied geomorphological mapping and cosmogenic surface exposure dating to mountain groups and nunataks located around the rim of the WSE, notably in the SE Antarctic Peninsula, Ellsworth Mountains, Pensacola Mountains, and Shackleton Range. These studies have provided important geomorphological constraints on former ice thickness configurations, including evidence from trimlines, sediment drifts, striated bedrock, and deposition of erratic clasts on exposed nunatak flanks. The latter have been particularly important because they have formed the primary target for dating former changes in ice-sheet elevation: erratics at a range of altitudes have now been dated at several locations extending around much of the WSE (e.g. Fogwill et al. 2004, Bentley et al. 2006, 2010, Hein et al. 2011, 2013, Hodgson et al. 2012). We report the exposure dates in ka, corresponding to cal ka BP of the marine radiocarbon ages. A compilation of all the exposure dates from the hinterland of the Weddell Sea sector is provided in Supplementary Table 3.

There have also been other approaches to reconstructing former ice thickness. Two deep ice cores have been drilled in the WSE, or close to it, namely the Berkner Island core (Mulvaney et al. 2007) and the EPICA-Dronning Maud Land (EDML) core (EPICA community members 2006) (Fig. 1). As with other ice cores the isotopic proxy records and gas bubble proxies can potentially be used to infer former ice sheet surface elevations.

Biological indicators of former ice absence (deglaciation) include accumulations of snow petrel stomach oil. Petrels rapidly colonise newly deglaciated areas of rock in East Antarctica, driven by competition for nesting sites, even up to 300 km from the coast. At their nest sites the petrels regurgitate stomach oil as a defence mechanism; this accumulates as a waxy grey coating, termed ‘mumiyo’, on the rocks, 100-500 mm thick, with a stratified internal structure. Radiocarbon ages show an increase with depth (Ryan et al. 1992) confirming that it is deposited by progressive accumulation of regurgitated oil, at a rate of 9-100 mm/kyr. Dating of the base of these deposits has been shown to provide a *minimum* age for local deglaciation, and has been used in combination with cosmogenic isotopes to determine ice sheet thickness changes (e.g. in the Framnes Mountains in East

Antarctica, Mackintosh et al. 2011). By using a sequence of dates on a single mumiyo deposit it is also possible to demonstrate continuous petrel occupation (i.e. ice absence) over millennia, or identify significant hiatuses (indicating that ice thickening may have occurred). Such deposits have been dated at a number of sites, but from the hinterland of the Weddell Sea only ^{14}C dates on mumiyo deposits collected from the Shackleton Range (Hiller et al. 1988, 1995), western Dronning Maud Land (Thor & Low 2011) and central Dronning Maud Land (Steele & Hiller 1997) have been published. Nevertheless, it seems breeding sites of petrels are a near-ubiquitous feature of nunataks within a suitable range (up to ca. 450 km) of feeding grounds. In line with the marine ^{14}C ages, we report all terrestrial ^{14}C dates mentioned under 'Datasets' (section 4) as in the original references. A compilation of the terrestrial ^{14}C dates from the hinterland of the Weddell Sea sector is provided in Supplementary Table 4.

In almost all cases the primary focus of onshore studies has been the maximum configuration of ice at the local LGM in the region. Less is known about the post-LGM ice-sheet history but in some studies the deglacial portion of the last glaciation has also been constrained by thinning histories derived from dating material on nunatak 'dipsticks' (e.g. Todd & Stone 2004, Bentley et al. 2010).

Other terrestrial studies in the Weddell Sea sector, such as radar and seismic investigations of the ice sheet, have also contributed to palaeo-ice sheet reconstructions. These datasets have helped to identify past changes in ice-flow directions (Campbell et al. 2013), reconstruct former ice-divide migration (Ross et al. 2011) and calculate palaeo-accumulation rates (Huybrechts et al. 2009).

4. Datasets

In the following, we summarise the datasets, outputs and interpretations of the marine and terrestrial studies that are relevant to reconstruct the LGM to Holocene glacial history of the Weddell Sea sector, thereby identifying their key constraints.

4.1. Weddell Sea marine studies

4.1.1. U.S. expeditions

Piston and gravity cores were recovered from the continental shelf of the Weddell Sea sector during the 'International Weddell Sea Oceanographic Expeditions' (IWSOE) aboard the USCGC *Glacier* from 1968 to 1970 and during cruise IO1578 aboard the ARA *Islas Orcadas* in 1978 (Supplementary Table 1, Fig. 3). Glaciomarine and subglacial facies on several of these cores were analysed by Anderson et al. (1980, 1982, 1983, 1991), but the first AMS ^{14}C ages obtained from glaciomarine sediments in the cores were not published until the late 1990s (Bentley & Anderson 1998, Anderson & Andrews 1999). According to these early studies, glaciomarine muds and glaciomarine diamictons overly subglacial till in Filchner Trough and seaward from the Riiser-Larsen to Fimbul ice shelves. The seabed of the eastern flank of Filchner Trough and its western flank (inner to mid shelf) consists of coarse-grained residual glaciomarine sediments and exposed basement rocks, while the rest of the WSE shelf comprises glaciomarine muds and diamictons (Bentley & Anderson 1998). On the basis of the few available ^{14}C dates, Anderson and Andrews (1999) concluded that the last grounding event of the EAIS on the Weddell Sea shelf must predate ~26 ^{14}C ka BP (cf. Anderson et al. 2002).

Recently, Stolldorf et al. (2012) carried out more detailed grain-size analyses on some of the IWSOE and IO1578 cores and obtained numerous AMS ^{14}C dates from glaciomarine sediments, predominantly in cores from the eastern flank of Filchner Trough and the seabed offshore from the Brunt, Riiser-Larsen and Quar ice shelves.

The authors reinterpreted some of the diamictons previously classified as subglacial tills as glaciomarine sediments (Fig. 3). This conclusion is consistent with the observation that the benthic foraminifera assemblages in those diamictons are identical with foraminifera assemblages characterising various glaciomarine environments in the Weddell Sea today and show no sign of subglacial reworking (Anderson 1972a, 1972b). Stolldorf et al. (2012) concluded from the range of the AMS ^{14}C dates that the EAIS did not ground on the shelf to the east of Filchner Trough after 30,476 cal yrs BP (Fig. 5). A single AMS ^{14}C date from the western flank of the inner shelf part of Filchner Trough (core G10) yielded an age of 48,212 cal yrs BP, while the only date from within Filchner Trough (core G7) provided an age of 8521 cal yrs BP. The older of two dates in core 2-19-1, which is located on the outermost shelf just to the west of Filchner Trough, gave an age of 17,884 cal yrs BP (Figs. 4, 5; Anderson & Andrews 1999, Stolldorf et al. 2012).

4.1.2. Norwegian expeditions

During the 'Norwegian Antarctic Research Expedition' (NARE) cruises with R/V *Polarsirkel* from 1976 to 1979, seismic profiles and sediment cores were collected from Filchner Trough, its eastern flank and offshore from the ice shelves extending eastward to the Fimbul Ice Shelf (Supplementary Table 1, Fig. 3; Elverhøi 1981, 1984, Elverhøi & Maisey, 1983, Elverhøi & Roaldset 1983, Haugland 1982, Haugland et al. 1985). The seismic profiles revealed a thin sediment drape overlying an unconformity extending from the Brunt to the Riiser-Larsen ice shelves and were interpreted to indicate repeated advance and retreat of grounded ice across the continental shelf during the Late Pleistocene (Elverhøi & Maisey 1983, Elverhøi 1984, Haugland et al. 1985). Profiles from Filchner Trough were interpreted as showing outcrops of Proterozoic crystalline basement along its eastern flank

(Elverhøi & Maisey 1983, Haugland et al. 1985). Near the ice-shelf front, westward dipping units of stratified to massive sedimentary rocks, which are separated by erosional unconformities and assumed to be of Jurassic to Cainozoic age, onlap the acoustic basement and form the trough floor (Elverhøi & Maisey 1983, Haugland et al. 1985). Subsequent analysis of palynomorphs in subglacial and glaciomarine sediments recovered in IWSOE cores from this area suggested an Early to Late Cretaceous age for these westward dipping strata (Anderson et al. 1991). On the inner and mid-shelf part of Filchner Trough, an angular unconformity separates the dipping strata from a thin veneer of late Pleistocene to Holocene sediments on the trough floor and thick semi-consolidated flat-lying glacigenic sediments on the western trough flank (Elverhøi & Maisey 1983, Haugland et al. 1985). At the transition from the middle to the outer shelf, these flat-lying strata, which are assumed to be of late Neogene to Quaternary age, extend onto the trough floor and are underlain by a second unit of flat-lying glacigenic sediments of assumed early Neogene age. The upper unit displays a wedge-shaped geometry on the outer shelf part of Filchner Trough (Elverhøi & Maisey 1983). The shelf in the vicinity of the Filchner Trough mouth and Crary Fan is characterised by pronounced glacial progradation (Haugland 1982, Haugland et al. 1985, Kuvaas & Kristoffersen 1991, Bart et al. 1999).

According to the lithological analyses on the NARE sediment cores (Elverhøi 1981, 1984, Elverhøi & Maisey, 1983, Elverhøi & Roaldset 1983), the seabed of the Weddell Sea sector is characterised by the presence of a stiff pebbly mud interpreted as subglacial till or glaciomarine sediment that was subsequently compacted by grounded ice. This over-consolidated pebbly mud is locally overlain by a soft pebbly mud interpreted as glaciomarine sediment (for locations of subglacial, over-consolidated and normally consolidated sediments, see Fig. 3). Two radiometric ^{14}C dates obtained from glaciomarine sediments in core 212 on the outermost shelf to the west of Filchner Trough and core 214 from the uppermost continental slope yielded uncorrected radiocarbon ages of 31,290 ^{14}C yrs BP and >35,100 ^{14}C yrs BP, respectively (Supplementary Table 2, Figs. 4-6; Elverhøi 1981). However, the sediments in core 212 were subsequently considered to be disturbed by iceberg scouring and those in core 214 to be affected by current winnowing, and therefore these ^{14}C ages may not constrain the time of the last ice-sheet retreat (Bentley & Anderson 1998, Anderson & Andrews 1999). Another single ^{14}C radiometric date obtained from a glaciomarine diamicton in core 206 offshore from the Fimbul Ice Shelf provided an uncorrected radiocarbon age of just 3950 ^{14}C yrs BP, and three more ^{14}C dates from core 234 at the uppermost slope offshore from the Riiser-Larsen Ice shelf gave uncorrected ages ranging from 21,240 to 37,830 ^{14}C yrs BP in normal stratigraphic order (Supplementary Table 2, Figs. 4-6; Elverhøi 1981, 1984, Elverhøi & Roaldset 1983).

During NARE 84/85 with K/V *Andenes* additional side-scan sonar and shallow seismic data as well as several gravity and vibro-cores were collected north of the Kvitkuven Ice Rise, Riiser-Larsen Ice Shelf (Orheim 1985, Lien et al. 1989). The same area was targeted with a detailed seismic survey during the Nordic Antarctic Research Expedition 1995/1996 aboard the Finnish R/V *Aranda* (Kristoffersen et al. 2000b), during which a 14.05 metre long core with a recovery of 18% was drilled (core KK9601; Kristoffersen et al. 2000a). The seismic profiles revealed not only significant shelf progradation caused by repeated advances of a grounded EAIS to the shelf break during the Plio-/Pleistocene, but also that the shelf progradation west of Kvitkuven Ice Rise started earlier than further east (Kristoffersen et al. 2000b).

The side-scan sonar data showed iceberg scour marks (Lien et al. 1989), while the seismic survey mapped two submarine moraine ridge complexes on the shelf that are orientated parallel to the shelf edge (Fig. 2; Kristoffersen et al. 2000b). The sediment cores recovered glaciomarine sediments, with only two cores retrieving over-consolidated diamictons at their bases (Fig. 3; Orheim 1985, Lien et al. 1989). A single AMS ^{14}C date was obtained from a normally consolidated diamicton in core AN85-10 that was recovered from between the two moraine ridges (Fig. 4). Its uncorrected radiocarbon age of 18,950 ^{14}C yrs BP was interpreted to indicate that either grounded ice had retreated from an earlier outer shelf position to the core site by this time or that the inner moraine ridge marks the maximum ice-sheet extent at the LGM (Supplementary Table 2, Fig. 6; Kristoffersen et al. 2000b). Core KK9601 was drilled landward from the inner moraine ridge and recovered glaciomarine muds, sands and diamictons that overlie a subglacial diamicton at its base (Kristoffersen et al. 2000a). Two AMS ^{14}C dates obtained from glaciomarine diamicton just above the till provided uncorrected radiocarbon ages of 30,040 and 37,750 ^{14}C yrs BP, respectively, while six more dates obtained from the overlying sediments range from 3870 to 11,440 ^{14}C yrs BP but not in stratigraphic order (Supplementary Table 2; Figs. 4-6). These ages were interpreted to indicate (i) an initial phase of EAIS advance and retreat before ~38 ^{14}C ka BP, (ii) a second phase of grounded EAIS advance after ~30 ^{14}C ka BP and retreat before ~11 ^{14}C ka BP, and (iii) a short phase of local ice advance or iceberg ploughing during the Holocene (Kristoffersen et al. 2000a).

4.1.3. German expeditions

During numerous German expeditions by the Alfred Wegener Institute for Polar and Marine Research (AWI) with R/V *Polarstern* in the 1980s and early 1990s, seismic profiles, acoustic subbottom profiles and sediment cores (Supplementary Table 1) were collected along the Ronne Ice Shelf front (Haase 1986, Wessels 1989, Crawford et al. 1996, Jokat et al. 1997, Hillenbrand et al. 2012), within Filchner Trough and from its flanks (Melles 1987, 1991, Fütterer & Melles 1990, Miller et al. 1990, Jokat et al. 1997, Melles & Kuhn 1993) and offshore from the Brunt, Riiser-Larsen and Ekstrøm ice shelves (Miller et al. 1990, Grobe & Mackensen 1992, Kuhn & Weber 1993, Michels et al. 2002).

High-resolution seismic profiles collected along the front of the Filchner-Ronne Ice Shelf in the season 1994/1995 indicate a westward transition of the westward dipping Jurassic to Cainozoic sedimentary strata described by Elverhøi & Maisey (1983) and Haugland et al. (1985) into flat-lying strata north of the central Ronne Ice Shelf and into a folded sequence north of the western Ronne Ice Shelf (Jokat et al. 1997). Recently, Stolldorf et al. (2012) presented the first multi-beam data from the Weddell Sea sector, which had been collected just north of the Filchner-Ronne Ice Shelf on R/V *Polarstern* cruise ANT-XII/3 in 1995. The seabed images revealed mega-scale lineations (MSGLs) on the inner shelf parts of Ronne Trough and Hughes Trough and more subtle subglacial lineations on the inner shelf part of Filchner Trough (Fig. 2). Based on the pristine preservation of the MSGLs, the authors proposed an LGM age for the last grounding event offshore from Ronne Ice Shelf.

The sediments recovered along the Ronne Ice Shelf front consist mainly of glaciomarine deposits with subglacial till reported only from site PS1197 in Hughes Trough and site PS1423 at the western flank of Ronne Trough (Fig. 3; Haase 1986, Wessels 1989, Crawford et al. 1996). An acoustically transparent layer in a subbottom profile from the inner shelf part of Ronne Trough suggests the presence of a soft till layer (Hillenbrand et al. 2012), which is consistent with the recent discovery of MSGLs on the trough floor there (Stolldorf et al. 2012). Along the ice-shelf front acoustic profiles extending from Ronne Trough to Filchner Trough revealed few details (Haase 1986, Fütterer & Melles 1990), but several of the glaciomarine sequences recovered from Hughes Trough and its flanks are over-compacted, possibly as a result of ice-sheet loading at the LGM (Fig. 3; Haase 1986, Wessels 1989, Hillenbrand et al. 2012). Two AMS ^{14}C dates from a normally consolidated glaciomarine diamicton at site PS1423, which was interpreted as an iceberg-rafted sediment deposited at a former ice-shelf calving line, provide the only age constraints for cores collected along the Ronne Ice Shelf front and yielded uncorrected radiocarbon ages of 3250 and 5910 ^{14}C yrs BP, respectively (Supplementary Table 2, Figs. 4-6; Hedges et al. 1995, Crawford et al. 1996).

Cores from the deepest part of Filchner Trough often recovered tills, while cores recovered from the outer shelf frequently recovered over-consolidated glaciomarine sediments (Fig. 3; Melles 1987, 1991, Fütterer & Melles 1990, Melles & Kuhn 1993, Hillenbrand et al. 2012). Although this over-compaction was attributed to iceberg ploughing at some core sites (Melles 1991, Melles & Kuhn 1993), an LGM advance of a grounded ice sheet through Filchner Trough to the shelf break was considered as the most likely explanation for the distribution of over-consolidated glaciomarine sediments and tills in this area (Melles 1987, 1991, Fütterer & Melles 1990, Melles & Kuhn 1993, Hillenbrand et al. 2012). This suggestion is supported by sedimentary sequences recovered on the adjacent continental slope, which indicate that during the last glacial period (i) glaciogenic detritus originating from the continental shelf was transported down-slope by mass movements and bottom-water flow, and (ii) catabatic winds blowing off an expanded ice sheet formed a polynya above the uppermost slope (Melles 1991, Ehrmann et al. 1992, Melles & Kuhn 1993). The conclusion of LGM ice-sheet grounding seems also to be consistent with: (i) the observation of 'hard' reflectors in acoustic subbottom profiles from the outer shelf, which are high-amplitude reflectors without reflections beneath them, suggesting that they are the acoustic expressions of glacial unconformities and surfaces of tills, respectively (Melles & Kuhn 1993), and (ii) the recent discovery of subglacial bedforms within Filchner Trough (Larter et al. 2012, Stolldorf et al. 2012). Only eight ^{14}C dates were obtained from glaciomarine sediments recovered by R/V *Polarstern* from the continental shelf and the uppermost slope in the vicinity of Filchner Trough. The corresponding ages range from 1215 to 8790 ^{14}C yrs BP (Supplementary Table 2, Figs. 4-6; Hillenbrand et al. 2012). Down-core abundance of planktonic and benthic foraminifera was sufficient at three sites from the outer WSE shelf (PS1420, PS1609, PS1611) for analysing stable oxygen isotopes ($\delta^{18}O$) (Melles 1991). However, the suitability of these data for applying $\delta^{18}O$ stratigraphy by identifying $\delta^{18}O$ shifts related to glacial-interglacial transitions remains uncertain (Hillenbrand et al. 2012).

A hard seabed reflector was recorded in subbottom profiles offshore from the Brunt and Riiser-Larsen ice shelves but it remained unclear if this acoustic character resulted from coarse grain-size, over-compaction or a combination of both (Kuhn & Weber 1993, Michels et al. 2002). The shelf cores collected offshore from the eastern Riiser-Larsen Ice Shelf and the Ekstrøm Ice Shelf contain exclusively glaciomarine sediments, for which a Holocene age was assumed (Grobe & Mackensen 1992, Michels et al. 2002).

4.1.4. British expeditions

Multibeam swath bathymetry data and acoustic subbottom profiles (TOPAS) were collected in the Filchner Trough area by the British Antarctic Survey (BAS) during RRS *James Clark Ross* cruises JR97 in 2005 and JR244 in 2011 (Gales et al. 2012, Larter et al. 2012). On the inner shelf, these data revealed the presence of subglacial lineations in the axis of the trough and of drumlins on the lower part of its eastern flank (Fig. 2). Subglacial lineations that are locally eroded into an acoustically transparent layer were mapped in the mid-shelf part of Filchner Trough, and a grounding-zone wedge located landward of linear iceberg furrows was mapped on the outer shelf (Fig. 2). These bedform assemblages were interpreted as the results of a Late Pleistocene ice-sheet advance through Filchner Trough, and an LGM age was proposed for their formation (Larter et al. 2012).

4.1.5. Summary of marine studies

The available seismic, swath bathymetry and sediment core data indicate ice-sheet grounding on the continental shelf of the Weddell Sea sector during the past, with ice grounding even in the deepest parts of the palaeo-ice stream troughs (Stolldorf et al. 2012) and grounded ice in Filchner Trough advancing onto the outer shelf to within at least 40 km of the shelf break (Larter et al. 2012). The pristine preservation of the mapped subglacial bedforms (Fig. 2) suggests that the last ice-sheet grounding directly north of Ronne Ice Shelf and within Filchner Trough occurred during the Late Pleistocene. However, the few available ^{14}C dates poorly constrain the timing of this grounding event, and therefore it remains unclear whether it happened at the LGM. When only shelf sites are considered and the date from core 212 is ignored (because of possible disturbance of its stratigraphy), all but one of the oldest ages obtained from cores recovered north of the Ronne Ice Shelf and within Filchner Trough are consistent with LGM grounding (Figs. 5, 6; Hillenbrand et al. 2012, Stolldorf et al. 2012). However, these few dates are all minimum limiting ages and so do not rule out the grounding event being older. In contrast, the oldest ages obtained from cores on the uppermost continental slope and on the shelf to the east of Filchner Trough can be interpreted to indicate grounded ice-sheet retreat before 34 cal ka BP or even before 50 ^{14}C ka BP (Figs. 5, 6). It has to be taken into account, however, that (i) the sediments from the flanks of Filchner Trough and the upper continental slope are prone to reworking by debris flows because of a steep seafloor gradient, and (ii) those from the eastern Filchner Trough flank are prone to iceberg scouring because the corresponding core sites are located at water depths shallower than 550 metres and thus above the mean keel depth of icebergs calving from the Filchner Ice Shelf (Dowdeswell & Bamber 2007). Therefore, the dates from all those cores may be dismissed as unreliable for constraining the age of the last grounding-line retreat, which may be supported by down-core age reversals observed in some of the cores (cf. Anderson & Andrews 1999). In addition, very old ^{14}C ages of near-surface sediments in conjunction with down-core dates in normal stratigraphic order at sites to the east of Filchner Trough indicate that sediments younger than ~30 cal ka BP are missing at these locations (e.g. core 2-20-1; Fig. 4, Supplementary Table 2), which might be explained by subglacial erosion at the LGM.

Five ^{14}C dates spanning 15,876 to 27,119 cal yrs BP in normal stratigraphic order in core 3-17-1 offshore from the Quar Ice Shelf strongly suggest that the EAIS had retreated before ca. 27.3 cal ka BP in this part of the Weddell Sea sector (Supplementary Table 2, Figs. 4, 5; cf. Anderson & Andrews 1999, Stolldorf et al. 2012). This scenario would not necessarily contradict a later, limited readvance north of the Riiser-Larsen Ice Shelf (Kristoffersen et al. 2000a, 2000b). On the WSE shelf west of Filchner Trough, the time of the last WAIS retreat is only constrained by ^{14}C dates from five cores on the outermost shelf and upper slope seaward of the eastern Ronne Ice Shelf and from core PS1423 on the inner shelf part of Ronne Trough (Supplementary Table 2, Figs. 4, 6). Thus, the assumption of an LGM age for the last ice-sheet advance in this area is based on (i) very few dates (Hillenbrand et al 2012) and (ii) analogy with the glacial history of other WAIS drainage sectors (Stolldorf et al. 2012).

All ^{14}C ages available from the Weddell Sea sector extend back to 54 ^{14}C ka BP and seem to hint at a possible hiatus spanning the time interval from ~46.5 to ~41.5 cal ka BP (Supplementary Table 2, Fig. 5a). It has to be pointed out, however, that radiocarbon dates on calcareous (micro-)fossils exceeding ca. 35 ^{14}C ka BP are inherently unreliable because of diagenetic alteration, and that the true ages may be much older (Hughen 2007). For example, electron spin resonance (ESR) dating of mollusc shells from raised beach deposits in Lützow-Holm Bay in East Antarctica, which had provided uncorrected AMS ^{14}C ages spanning from 34.7 to 42.8 ^{14}C ka BP, demonstrated that these molluscs had been deposited between 50 and 228 ka (Takada et al. 2003). On the Weddell Sea shelf, marine radiocarbon dates younger than 35 ^{14}C ka BP do show considerable regional variability, which could be significant. So far, none of the cores from the shelf north of the Ronne Ice Shelf, within Filchner Trough, on the eastern flank of Filchner Trough and offshore from the Riiser-Larsen Ice Shelf (Fig. 4) provided ages falling into the intervals from ~34.0 to ~18.5 cal ka BP, ~31.0 to ~14.0 cal ka BP and ~33.0 to ~21.5 cal ka BP, respectively (Fig. 5b). These apparent hiatuses, which are the most extended in the three areas and include the time span of the LGM from 23 to 19 cal ka BP, may be interpreted as evidence that those parts of the WSE shelf were affected by subglacial erosion or non-deposition at the LGM. In contrast, the dates obtained from cores located offshore from the Brunt and Quar ice shelves (sites 3-7-1 and 3-17-1; Fig. 4) do not indicate any pronounced hiatus after ~33 and ~28 cal ka BP, respectively (Fig. 5a).

At the moment, we cannot preclude the possibility that the apparent hiatus from ~31.0 to ~21.5 cal ka BP observed north of the Filchner-Ronne and Riiser-Larsen ice shelves is an artefact resulting from the low number of available ^{14}C ages. Even if this hiatus is real, however, it does not necessarily imply an advance of grounded ice across the Weddell Sea shelf during that time because coverage with an ice shelf or perennial sea ice alone may have prevented the deposition of microfossils. Moreover, even the studies favouring grounded WAIS and EAIS advance across the southern WSE shelf at the LGM argue that the grounded ice had a very low profile, i.e. the grounding event itself was merely a slight 'touchdown' of an advancing ice shelf, and that the grounding may have been brief and in the order of a few thousand years (Hillenbrand et al. 2012, Larter et al. 2012).

4.2. Weddell Sea terrestrial studies

The subglacial topography of the WSE has been partly mapped by airborne radio echo sounding and seismic profiles (the latter especially over the Filchner-Ronne Ice Shelf) by several nations. These surveys have been compiled into the Bedmap2 dataset (Fretwell et al. 2013). Terrestrial studies have focussed on five nunatak groups around the WSE rim and we describe results from these areas in turn. The terrestrial data are consistent in suggesting that ice-sheet thickening around the WSE rim during the LGM was of the order of only a few hundred metres, and in some areas may have been zero. This view of minor LGM thickening is critical in determining the reconstruction of post-LGM ice in the WSE, and so we spend some time discussing the assumptions that underpin it.

4.2.1. SE Antarctic Peninsula

The western Weddell Sea is fed partly by ice from the SE Antarctic Peninsula. Early glacial geological work (Carrara 1979, 1981, Waitt 1983) suggested that the area had been over-ridden by an expanded ice sheet but the timing remained unknown. Further mapping and reconnaissance-level dating of this expanded ice sheet by Bentley et al. (2006) suggested that during the LGM the ice sheet thickened by over 300-540 metres in the southernmost part of the Antarctic Peninsula and by 500 metres further north. Striation data in Palmer Land show that when the APIS thickened, it did not merge to form a single dome, but rather, two or more of the present-day ice domes expanded and became thicker, and drove ice-sheet flow oblique to present trends (Bentley et al. 2006). Thinning of this ice sheet on the east side of the peninsula was underway by the Early Holocene such that it was <300 metres thicker than present in the Behrendt Mountains by 7.2 ka (Bentley et al. 2006). Other attempts to date deglacial thinning were confounded by very high proportions of reworked erratic clasts that yielded complex ages and which were in some cases as old as 1.2 Ma (Bentley et al. 2006).

4.2.2. Ellsworth Mountains

Evidence for a formerly thicker ice sheet was mapped in detail by Denton et al. (1992). Although their evidence of past thickening was undated they provided a detailed map of former erosional and glacial drift evidence of the upper limits of ice sheet glaciation. Much of this effort focussed on a high (800-1000 metres above present ice) glacier trimline, which is especially well-preserved in the Sentinel Range and also observed elsewhere in the Ellsworth Mountains. The altitudinal relationship between this erosional trimline and the present ice sheet surface throughout the region may suggest long-term stability of ice divide location even during ice-sheet expansion (Denton et al. 1992). This conclusion would be consistent with the interpretation of radio-echo-sounding and GPS data collected between Pine Island Glacier and Institute Ice Stream that document a stable position of the ice divide between the Amundsen Sea and the Weddell Sea drainage sectors of the WAIS for at least the last 7 ka and possibly for the last 10 to 20 ka, or even longer (Ross et al. 2011).

Bentley et al. (2010) subsequently mapped a second trimline, which is significantly below the trimline reported by Denton et al. (1992) and exposed as a drift limit in the Heritage Range, southern Ellsworth Mountains. This lower drift limit drapes nunatak flanks in Marble Hills, Patriot Hills and Independence Hills and was deposited by ice that reached 230-480 metres above present-day levels. Material below the limit is relatively fresh and lithologically diverse whilst the sparse patches of drift above the limit are highly weathered and have a much more restricted range of lithologies. Based on weathering and dating of erratics this lower drift limit was interpreted by Bentley et al. (2010) as the LGM upper surface of the ice sheet in this region (cf. Fogwill et al. 2012). Cosmogenic surface exposure dating showed that a moraine ridge forming the upper edge of this lower drift was abandoned by the ice sheet at or around 15 ka and that ice thinning to present levels occurred progressively through the Holocene. The data were inadequate to determine whether thinning continued through to the present-day or whether present ice elevations were achieved sometime earlier in the late Holocene: exposure ages of erratics at the present-day margin yield youngest ages of 2 ka (Marble Hills) or 490 yrs (Patriot Hills). Above the moraine delineating the top of the lower drift, erratics yielded only older ages, some of which appeared to imply continuous exposure for several 100 ka (Todd & Stone 2004, Bentley et al. 2010, Fogwill et al. 2012).

The underpinning assumptions of the chronology were subsequently debated (Clark 2011, Bentley et al. 2011a). Specifically Clark (2011) questioned whether there was a (short-lived) ice sheet thickening above the lower trimline during the LGM. Bentley et al. (2011a) argued that this would require that the ice sheet did so without leaving behind fresh erratics, and that it would require an explanation for the weathering contrast above and below the lower drift limit, and why the depositional regime shifted from almost no deposition to extensive supraglacial deposition below a critical altitude. So, although the problems of using negative evidence were acknowledged, and that such a scenario could not be conclusively ruled out, Bentley et al. (2011a) argued that the most parsimonious explanation is that the lower trimline is the LGM limit and not an intermediate limit. One implication of this is that discovery of any young (e.g. Holocene) ages above the lower trimline would invalidate the Bentley et al. (2010) model.

In an attempt to constrain the postglacial crustal rebound in Antarctica, Argus et al. (2011) analysed GPS data from stations around the Antarctic coast, the WSE and in the Ellsworth Mountains that had been recorded between 1996 and 2011. The authors found that the Ellsworth Mountains are currently rising at a rate of ca. 5±4 mm/yr (95% confidence limits) and concluded that significant ice loss there must have ended by 4 ka.

4.2.3. Pensacola Mountains

Boyer (1979) made geomorphological observations in the Dufek Massif (northern Pensacola Mountains) that showed a complex glacial history of regional ice sheet over-riding and local outlet glacier advance. As with other early work the available techniques meant that the author was unable to date the evidence of glacial fluctuations. The first cosmogenic surface exposure dating of Dufek Massif was carried out by Hodgson et al. (2012). This study revealed evidence of a long glacial history, mostly prior to the timescale relevant to this paper. However, mapping of boulder ice-sheet moraines in Davis Valley and cosmogenic surface exposure dating of erratics on the moraines, along with radiocarbon ages around the margins of a pond in the adjacent Forlidas Valley suggest only moderate ice sheet thickening and advance of less than 2.5 km along-valley during the last glacial advance, assumed to be the LGM (Hodgson et al. 2012). The timing of this advance is not well constrained but radiocarbon dates on lacustrine algae show that the ice sheet had retreated from Forlidas Valley by 4300 cal yrs BP (Hodgson & Bentley 2013).

Hegland et al. (2012) and Bentley et al. (2012) reported preliminary results of fieldwork undertaken in the Williams, Thomas and Schmidt hills. They observed glacial scours on Mount Hobbs, Williams Hills, and striations on Martin Peak, Thomas Hills, suggesting a maximum ice thickness that was at least 562 to 675 metres greater than today. However, no chronological constraints are currently available for this ice-sheet elevation highstand. The authors also observed moraines consisting of unweathered till at altitudes between 20 and 100 metres above the present ice-sheet surface and assumed that these are likely to post-date the LGM. Using measurements of radar-detected stratigraphy, surface ice-flow velocities and accumulation rates Campbell at al. (2013) investigated the relationships between local valley-glacier and regional ice-sheet dynamics in and around the Schmidt Hills. The authors found evidence that ice-margin elevations in the Schmidt Hills have lowered by about 3 metres over the last ca. 1200 years without a concurrent change in the surface elevation of the neighbouring Foundation Ice Stream.

4.2.4. Shackleton Range

In the Shackleton Range the summits have been over-ridden by the ice sheet but cosmogenic isotope data suggest this happened over 1 Ma ago (Fogwill et al. 2004). Lateral moraines that lie ~250 metres above present day ice at the grounding line and ~ 200 metres above present ice further upstream on Slessor Glacier were originally suggested to most likely mark the upper limit of the LGM ice sheet but were not dated directly (Höfle & Buggisch 1993, Kerr & Hermichen 1999, Fogwill et al. 2004, Bentley et al. 2006). More recently, a comprehensive geomorphological and cosmogenic dating study of the lower flanks of the Shackleton Range showed that there was no direct evidence of any significant thickening during the LGM (Hein et al. 2011, 2013), and indeed the data are best explained by stability of the Slessor-Recovery ice stream system during the LGM. Dating of erratic boulders yielded a pattern of 'young' (<50 ka) ages that were confined, without exception, to the moraines forming at the present-day ice sheet margin. Above these moraines all exposure ages were >109 ka, and many of these showed a complex exposure history.

The simplest explanation of this pattern is that the LGM ice sheet did not thicken in the Shackleton Range - and may even have been thinner than present - and that the higher, older erratics all date to previous (pre-LGM) ice sheet expansions (Hein et al. 2011, 2013). As with the Ellsworth Mountains it is not possible to rule out the possibility of short-lived thickening events that spanned only several hundred to a few thousand years and left no erratics or other geological imprint, but after discussing such alternative explanations (cold-based ice leaving no erratics, or change in ice dynamics such that erratics were not brought to the margin along the ice streams), Hein et al. (2011) concluded that these would require conditions for which there was neither data nor observations, and hence they favoured the minimal LGM thickening model.

We note also that two dates on sub-samples of mumiyo from a site on Mt. Provender were reported by Hiller et al. (1988, 1995) but the precise sample location was not reported, and so we cannot assess its relationship to present-day ice. The uncorrected ages were 8970±250 and 9770±200 ^{14}C yrs BP (no laboratory codes given).

4.2.5. Western and central Dronning Maud Land

Constraints for ice thickness changes in western Dronning Maud Land since the LGM are restricted to the Heimefrontfjella region (the westernmost part of Maudheimvidda, see Fig. 1), where Hättestrand & Johansen (2005) carried out geomorphological mapping and Thor & Low (2011) collected mumiyo samples for radiocarbon dating. Hättestrand and Johansen (2005) mapped moraines in the vicinity of the Scharffenbergbotnen valley (centred at ca. 74°35'S, 11°08'W and 1200-1600 metres above sea level), which extend up to 200-250 metres above the present ice surface on the surrounding valley slopes, and generally to less than 100 metres above the present ice surface on slopes outside the valley. Although the authors did not obtain dates from the moraines, they tentatively inferred an LGM age for them. The radiocarbon dates from the basal layers in two mumiyo samples collected on the Haldorsentoppen nunatak in Sivorgfjella directly to the SW of the Scharffenbergbotnen valley (at ca. 74°34'36"S, 11°13' 24"W and 1245 metres above sea level) yielded ages of 37,400±1500 and 3120±70 uncorrected ^{14}C yrs BP, respectively (Thor & Low 2011). These dates indicate that Sivorgfjella may not have been over-ridden by ice since at least ~37 ^{14}C ka BP.

Huybrechts et al. (2007) carried out modelling of stable hydrogen and oxygen isotopic data from the EDML ice core drilled in central Dronning Maud Land (75°00'S, 0°04'E; Fig. 1). The results suggest there was initial post-LGM thickening followed by thinning over the last 5 ka (Huybrechts et al. 2007). Accumulation rates in central Dronning Maud Land were shown to have been 1.5 to 2 times lower during the last glacial period than after ca. 15 ka (Huybrechts et al. 2009).

Steele & Hiller (1997) reported a large number of mumiyo ages from the near-coastal part of central Dronning Maud Land. These were from a variety of sites including close to present ice (nunatak foot), nunatak summits and intermediate sites. Dates from the nunatak foot locations show that ice was at present-day levels by 5590 corrected ^{14}C yrs BP ('Ice Axe Peak' locality at Robertskollen, 71°28'S, 3°15'W) and 6400 corrected ^{14}C yrs BP (Vesleskarvet, 71°40'S, 2°51'W). Minimum ages for clearance of summits are 7030 corrected ^{14}C yrs BP ('Tumble Ice' locality at Robertskollen, 40 metres above present ice surface) and 6720 corrected ^{14}C yrs BP ('Nunatak V' locality at Johnsbrotet, 71°20'S, 4°10'W, 100 metres above present ice surface). A further study at the same summit locality at Robertskollen yielded mumiyo showing continuous ice absence since 7000 cal yrs BP (Ryan et al. 1992). Based on their GPS data analysis, Argus et al. (2011) reported that the near-coastal part of Dronning Maud Land (Vesleskarvet) is currently rising at a rate of ca. 4±2 mm/yr in response to Holocene unloading of ice.

Although outside our sector it is relevant to note that samples from the Untersee Oasis (71°S, 13°E) show ice absence at nunatak foot locations as far back as ~33 corrected ^{14}C ka BP (Hiller et al. 1988, 1995, Steele & Hiller 1997, Wand & Hermichen 2005): these are at near-coastal locations landward of the narrow East

Antarctic shelf and so may be indicative of ice-sheet history on the shelf immediately east of Filchner Trough.

4.2.6. Berkner Island

At the site of the Berkner Island ice core (79°34′S, 45°39′W; Fig. 1) the stable isotope data are consistent with continuous accumulation on a local ice dome, and appear to exclude the possibility that Berkner Island was over-ridden by interior ice during the LGM. For this reason they can be used to provide a maximum constraint for former ice sheet configurations in the embayment, namely that Berkner Island remained an independent ice dispersal centre throughout the LGM-Holocene (Mulvaney et al. 2007, Bentley et al. 2010).

4.2.7. Summary of terrestrial studies

The terrestrial data show that the WSE preserves a complex glacial history extending over millions of years but with only very minor thickening during the LGM. The available dating evidence suggests that maximum ice sheet expansion (to upper trimline in Ellsworth Mountains, over nunatak summits in Shackleton Range and Dufek Massif) occurred substantially prior to the last glacial cycle, and in some cases millions of years ago. Where dating evidence exists the LGM is represented by modest thickening (>340-540 metres in SE Antarctic Peninsula, 230-480 metres in Ellsworth Mountains, very minor in Dufek Massif, and near to zero in the Shackleton Range). Bentley et al. (2010), Le Brocq et al. (2011) and Whitehouse et al. (2012) have explored the use of the terrestrial constraints on former ice sheet thickness to delimit former ice sheet extent in the WSE, and specifically in Filchner Trough. The model results were consistent with very limited grounding-line advance in the Filchner and Ronne troughs. On the other hand, a recent modelling study on LGM ice-sheet thickness in Antarctica could reproduce successfully constraints on former ice-sheet elevations provided by terrestrial data and ice cores in most Antarctic sectors, but notably not in the eastern WSE, where the predicted ice sheet is thicker than indicated by the terrestrial data (Golledge et al. 2012).

5. Time-slice reconstructions and recent ice-sheet changes

At present the terrestrial and marine data suggest two alternative reconstructions of the LGM ice-sheet extent in the Weddell Sea sector. Importantly both of these scenarios are consistent with low excess ice volumes during the LGM and deglacial period, which would imply only a minor contribution (i.e. just a few metres) to global meltwater pulses during the last deglaciation (Bentley et al. 2010, Hillenbrand et al. 2012).

Scenario A assumes that the LGM extent of ice in the Weddell Sea sector was largely as modelled using terrestrial data to constrain ice-sheet thickness by Bentley et al. (2010), Le Brocq et al. (2011) and Whitehouse et al. (2012). In this scenario even the oldest dates obtained from the marine sediment cores (Fig. 6) are minimum ages for grounded ice retreat from the continental shelf, and the grounding event recorded in subglacial bedforms and sediments was substantially pre-LGM. Scenario A implies that significant grounded ice-sheet advance during the LGM was restricted to the shelf offshore from the eastern and central Ronne Ice Shelf, whereas the grounding line remained in the vicinity of its modern position or showed only minor advance in most of the Weddell Sea sector and especially in the deep Filchner and Ronne troughs. This scenario was also the preferred explanation for the old marine radiocarbon ages obtained from the East Antarctic continental shelf of the Weddell Sea sector (Anderson & Andrews 1999, Stolldorf et al. 2012). For the various time-slices of grounding line position in Scenario A we give those derived from modelling studies of Whitehouse et al. (2012). We use linear interpolation between the modelled position of the grounding line at 20 ka, which is based initially on Bentley et al. (2010) and Le Brocq et al. (2011), and the present-day position of the grounding line to infer its location at 15 ka, 10 ka and 5 ka. It is important to note that the reconstructed grounding-line positions are not therefore based on marine geological evidence but instead are *inferred*, based on glaciological modelling to remain consistent with terrestrial geological data. Full details of this approach are given in Whitehouse et al. (2012).

Scenario B assumes that the dates from the marine sediment cores are a mix of minimum and maximum ages for the last ice-sheet retreat (i.e. that the old dates were obtained from reworked microfossils that lived before the last ice-sheet advance) and that the most extended of the apparent hiatuses observed in the different parts of the Weddell Sea sector (see Fig. 5b) were caused by grounded ice sheet advance across the core sites. In Scenario B the dates constraining the termination of the hiatus between ~31.0 and ~21.5 cal ka BP observed north of the Filchner-Ronne and Riiser-Larsen ice shelves are ages close to the last grounding-line retreat. The corresponding dates (taken from shelf cores only) are displayed in Figure 7. According to Scenario B, grounded ice did extend to the shelf break north of the Filchner-Ronne Ice Shelf during the LGM. To ensure consistency with the terrestrial data this scenario requires very thin, low profile ice on the continental shelf. This ice may have been just thick enough for grounding and may have remained grounded for only several hundred to a few thousand years (Bentley et al. 2010, Le Brocq et al. 2011, Hillenbrand et al. 2012, Larter et al. 2012). For the various time-slices displaying the ice-sheet extent according to Scenario B from 25 cal ka BP to 5 cal ka BP (Figs. 12-16), we give different certainty levels for the grounding-line positions. These levels indicate whether the grounding-line position is (i) constrained by nearby subglacial bedforms of unknown age (Fig. 2), (ii) constrained by nearby sediment cores that recovered subglacial/over-consolidated deposits (Fig. 3), for which no or only limiting ages are available, or (iii) simply inferred.

One crucial limitation for the palaeo-grounding line reconstructions in both scenarios is the lack of marine geophysical and geological information for the middle and outer shelf offshore from the Ronne Ice Shelf (Figs. 2, 3). Here, no data on subglacial bedforms exist and no dates have been obtained from the only two cores (IWSOE68-2 and IWSOE68-11), which recovered less than 40 cm of glaciomarine sediments (Supplementary Table 1). The maximum grounding-line position in this part of the WSE predicted by Scenario A is inferred from the relationship between ice-sheet thickness constrained by the terrestrial data from the hinterland and shelf bathymetry, thereby using a modelled ice-sheet surface profile (for details see Whitehouse et al. 2012). The reconstruction shown in Scenario B is based on the assumption that ice draining the WAIS and APIS at the LGM advanced onto the outer shelf as it did in their other drainage sectors along the Pacific margin (e.g. Anderson et al. 2002, Livingstone et al. 2012).

5.1. Scenario A

20 ka: The ice sheet was at or close to its maximum thickness in the Ellsworth Mountains, was at a maximum thickness in the SE Antarctic Peninsula and was at its present level or thinner in the Shackleton Range. Berkner Island was an independent ice dispersal centre and thus not over-ridden by inland ice (Fig. 8). Glaciological modelling of the ice-sheet grounding line to remain consistent with onshore glacial geological data suggests that the 20 ka grounding line had reached close to the continental shelf break at the mouth of Hughes Trough and in the region immediately north of Berkner Island. In the Filchner Trough and Ronne Trough grounded ice was much less extensive and was confined to the inner- or mid-shelf parts of these troughs (Fig. 8). On the shelf east of Filchner Trough the grounding line was located on the mid-shelf and did not reach the continental shelf break. Although the grounding line is shown with a deep embayment within two of the Weddell Sea troughs, in reality we expect there to have existed either extensive ice shelves or lightly-grounded ice across these regions, both of which could have supported the rapid streaming ice flow which typically occurs along major ice-sheet outlets (Whitehouse et al. 2012). Modelling of EDML ice core isotopic data suggest accumulation-driven *thickening* began at this time in the Dronning Maud Land region and continued through to ~5 ka. Mumiyo ages from the easternmost part of the sector and adjacent region suggest that ice may have been close to its present-day thickness since ~33 corrected ^{14}C ka BP at this location.

15 ka: The lower trimline in the Ellsworth Mountains was abandoned by the thinning ice sheet at or around 15 ka, which continued through the Holocene. In the Shackleton Range the ice was at its present level or thinner. According to the model of Whitehouse et al. (2012), the grounding line had retreated landward along troughs and away from the continental shelf break north of Berkner Island (Fig. 9). On the shelf east of Filchner Trough the grounding line had retreated back onto the inner shelf such that it was close to or at the present-day grounding line.

10 ka: The grounding line had continued its retreat and was located on the inner shelf everywhere, except immediately north of Berkner Island (Fig. 10). Ice elevations in the Shackleton Range were at present-day levels or thinner.

5 ka: The grounding line was at or close to the present-day grounding line, and so for example in the southernmost Weddell Sea was only a few tens of kilometres from the modern grounding lines of Foundation Ice Stream, Support Force Glacier and Institute Ice Stream (Fig. 11). In the Ellsworth Mountains ice elevations were <160 metres above present, and most LGM ice had been lost by ca. 4 ka. In the SE Antarctic Peninsula ice was <300 metres thicker than present, while ice elevations in the Shackleton Range were at present-day levels or thinner. The precise timing at which the ice elevations in the Ellsworth Mountains and SE Antarctic Peninsula reached present are not tightly-constrained but the data from the Ellsworth Mountains are consistent with this occurring sometime between 2 ka and present. In the Pensacola Mountains ice had largely retreated from Forlidas Valley in the Dufek Massif by 4.3 ka, and ice-margin elevations in the Schmidt Hills lowered by ca. 3 metres over the last 1200 years. Modelling of isotopic data from EDML suggests that ice-sheet *thinning* in central Dronning Maud Land began around 5 ka. Many sites there and further east showed continuous accumulation of mumiyo (and thus ice close to present levels) prior to ~5 cal ka BP.

5.2. Scenario B

25 cal ka BP: Dates from sites 3-7-1 and 3-17-1 (Fig. 4) indicate that grounded ice had retreated from the shelf offshore from the Brunt Ice Shelf and the Quar Ice Shelf (Fig. 12). In the rest of the Weddell Sea sector, the grounding line may have been located at the shelf break or at an outer shelf position. The outer moraine belt observed north of the Riiser-Larsen Ice Shelf (Fig. 2) may mark the grounding-line position in this area at 25 cal ka BP.

20 cal ka BP: The grounding line had retreated from site A85-10, which lies landward of the outer moraine belt north of the Riiser-Larsen Ice Shelf (Fig. 4). The inner moraine belt (Fig. 2) may have been deposited at this time. The chronology of core 2-19-1 indicates that the outermost shelf between Filchner Trough and Hughes Tough had become free of grounded ice at some time before 18.2 cal ka BP (Figs. 4, 6). Therefore, we assume that the grounding line had started to retreat from the shelf break in most parts of the Weddell Sea sector at around 20 cal ka BP (Fig. 13).

15 cal ka BP: The WAIS and EAIS had retreated from outer shelf locations north of the Filchner-Ronne Ice Shelf (Fig. 14). A grounding-zone wedge and linear iceberg furrows on the outermost shelf within Filchner Trough (Fig. 2) suggest that a pause in ice-sheet retreat and a minor re-advance occurred after initial grounding-line retreat (Larter et al. 2012). Offshore from the Riiser-Larsen Ice Shelf, the grounding line may have started to retreat from the inner moraine belt.

10 cal ka BP: The outer shelf on the eastern flank of Filchner Trough (site G2, Fig. 4) and the inner shelf north of the Riiser-Larsen Ice Shelf (site KK9601, Fig. 4) were free of grounded ice (Fig. 15). Ice retreat in the rest of the study area continued.

5 cal ka BP: The grounding line was located landward of most of the core sites, for which chronological information is available (Fig. 16). Only individual small embayments along the Coats Land coast may have remained covered by grounded ice at 5 cal ka BP (e.g. site G17, Fig. 4). In the western part of the Weddell Sea sector, the grounding line may have been located close to the modern calving lines of the Filchner-Ronne Ice Shelf.

5.3. Recent changes

Satellite radar altimetry measurements indicated that those parts of the EAIS which drain into the Weddell Sea sector to the east of Filchner Trough had thickened by a few centimetres per year from 1992 to 2003 (Davis et al. 2005). Also the catchments of ice streams feeding into the Filchner and Ronne ice shelves thickened during that time period, while their fast moving sections remained unchanged (Joughin & Bamber 2005). Radar interferometry data collected between 1992 and 2006 suggested a positive mass balance for the Filchner Ice Shelf but the measurements for the Ronne Ice Shelf and the drainage basins east of Filchner Trough were inconclusive (Rignot et al. 2008). More accurate laser altimeter measurements carried out between 2003 and 2008 revealed a thickening of 2 to 4 cm/yr for most ice shelves in the Weddell Sea sector, a thinning of 1 to 2 cm/yr for the Quar and Ekstrøm ice shelves and no change for the Fimbul Ice Shelf (Pritchard et al. 2012). Recently, a study using the same data set came to similar conclusions regarding the ice-shelf melting in the eastern part of the Weddell Sea sector but concluded a thinning of 13±10 cm/yr for the Filchner Ice Shelf and 14±10 cm/yr for the Ronne Ice Shelf (Rignot et al. 2013).

No significant advances or retreats of the grounding line have been reported for the Weddell Sea sector over the last few decades. However, major iceberg calving events affected the Filchner and Ronne ice shelves between 1986 and 2000 (e.g. Lambrecht et al. 2007). These recurrent calving events had a complex impact on sea-ice concentration and water mass circulation, and thus on melting and freezing processes in the sub-ice shelf cavity (e.g. Grosfeld et al. 2001, Nicholls et al. 2009). Therefore, minor shifts of the grounding line in response to these calving events cannot be ruled out.

6. Discussion

6.1. Discrepancies between the reconstructions from marine and terrestrial datasets and possible explanations

The main discrepancies between Scenarios A and B in reconstructing the ice-sheet configuration in the Weddell Sea sector during the last glacial period are (i) the maximum extent of grounded ice on the continental shelf (except for the shelf between the Filchner and Ronne troughs), and (ii) the grounding-line positions in the deep inner shelf parts of the Filchner and Ronne troughs (Figs. 8, 12). The differences in grounding-line positions during the last deglaciation (Figs. 9-11 and 13-16) are direct consequences of these mismatches in maximum ice-sheet size. The discrepancies in the reconstructed maximum ice-sheet configurations are probably larger than for any other Antarctic sector. We discuss possible reasons for this below but it has to be kept in mind that in only a few sectors of Antarctica are both cosmogenic exposure ages and marine deglaciation dates available from the same drainage basin. Examples of such areas are the Mac.Robertson Land coast in East Antarctica and the Marguerite Trough palaeo-ice stream basin on the SW Antarctic Peninsula, where both datasets allowed consistent palaeo-reconstructions (Mackintosh et al. 2011, Bentley et al. 2011b). Nevertheless, more drainage basins should be targeted by both terrestrial and marine dating in order to evaluate whether the apparently inconsistent marine and terrestrial reconstructions in the Weddell Sea sector are exceptional.

If Scenario A were correct, the pristine preservation of subglacial bedforms of pre-LGM age on the WSE shelf would imply that glaciomarine deposition over the last 25 kyr was insufficient to bury these features. Elsewhere, it has been recognised during the last few years that even some pristine glacial landforms mapped on the Antarctic continental shelf provide a composite picture resulting from different phases during either the same glacial period or different glacial periods (e.g. Heroy & Anderson 2005, Graham et al. 2009, Reinardy et al. 2011). Furthermore, sedimentation rates under Antarctic ice shelves are as low as ca. 2-3 cm/kyr (e.g. Hemer et al. 2007). Therefore, formation of the subglacial geomorphology on the WSE shelf during the penultimate glacial period (Marine Isotope Stage 6 from ca. 191-130 ka) combined with long-term ice shelf coverage throughout the last glacial period could explain its pristine appearance (Larter et al. 2012). Notably, the mismatch between Scenarios A and B in the Weddell Sea sector is not only based on different conclusions from the available terrestrial and marine datasets, but also on different interpretations of the available radiocarbon ages obtained from the marine sediment cores. These interpretations crucially depend on the facies assignment of the sediments the dated samples were taken from (cf. Elverhøi 1981 with Anderson & Andrews 1999, and cf. Anderson et al. 1980 with Stolldorf et al. 2012). If a date was obtained from microfossils deposited *in-situ* within a glaciomarine setting, it would give a minimum age for grounded ice-sheet retreat, but if reworked microfossils from a subglacial till were dated, the corresponding age would provide a maximum date for the last advance of grounded ice across the core site. An additional complication in the Weddell Sea sector is that here, in apparent contrast to other Antarctic sectors, glaciomarine sediments may have been over-consolidated after their deposition by overriding grounded ice (e.g. Elverhøi 1984, Hillenbrand et al. 2012). This problem implies that even if conclusive evidence for the glaciomarine origin of a sample of pre-LGM age is provided, the date does not necessarily rule out grounded ice advance across the core site during the LGM.

Notably the evidence for grounding on the shelf provided by the presence of subglacial bedforms and the occurrence of subglacially over-consolidated as well as subglacially deposited sediments is consistent with a short-lived ice sheet advance that lasted only several hundred to a few thousand years. This raises the possibility that if Scenario B were correct, then the boundary between unweathered and weathered rocks observed in the Shackleton Range (Fogwill et al. 2004) and the Ellsworth Mountains (Bentley et al. 2010) might not indicate the maximum elevation of the LGM ice-sheet surface, but an intermediate elevation following short-lived LGM ice-sheet thickening (Clark 2011). Thicker, non-erosive, cold-based ice may have preserved ‘weathered’ rocks above these limits at the LGM. If the maximum thickening occurred for a short term only, it may not be resolved in the available exposure ages. These explanations were not completely ruled out by Bentley et al. (2011a) and Hein et al. (2011), but considered to be very unlikely, and that there was no terrestrial evidence for such an ice sheet thickening. Both Hillenbrand et al. (2012) and Larter et al. (2012) point out that short-term LGM grounding were consistent with their observations and interpretation of the marine datasets. Evidence is growing that subglacial features formed in a soft substrate on the Antarctic continental shelf may only represent a ‘snapshot’ of the latest phase of maximum ice-sheet extent (Graham et al. 2009, Reinardy et al. 2011), which is consistent with the rapid formation and erosion of bedforms under contemporary ice streams (e.g. Smith et al. 2007, 2012).

Whatever the duration of the LGM thickening, at least three scenarios have been suggested that can reconcile the marine and terrestrial datasets. These were summarised by Larter et al (2012): (i) The LGM ice sheet had an extremely low surface gradient and resembled an ‘ice plain’ (cf. Le Brocq et al. 2011, Hillenbrand et al. 2012). ‘Ice plains‘ are observed just upstream of the grounding line of some contemporary ice streams and are characterised by very low basal shear stresses, resulting in surface slope angles with tangents $<10^{-3}$ (e.g. Alley et al. 1989, Bindschadler et al. 2005). (ii) The Filchner-Ronne ice shelf advanced across the shelf, and a minor thickening combined with the LGM sea-level drop of ca. 130 metres resulted in a ‘touchdown’ of the ice shelf/sheet on the seabed. Support for this hypothesis comes from the widespread occurrence of initially glaciomarine sediments that were over-consolidated at some time after their deposition (Fig. 3; Elverhøi 1984, Haase 1986, Melles 1987, Wessels 1989, Hillenbrand et al. 2012). (iii) At the LGM, Slessor and Recovery glaciers had become cold-based and stagnated, while Support Force Glacier and Foundation Ice Stream had remained warm based and both fed into the palaeo-ice stream draining through Filchner Trough (Fig. 1). Such a flow-switch of Foundation Ice Stream is consistent with both some earlier reconstructions of the LGM drainage pattern (Hughes 1977) and subglacial topography (Fretwell et al. 2013) indicating the locus of long-term erosion around Berkner Island. As a consequence of these ice-flow changes, LGM ice-sheet thickening in the Shackleton Range may have remained insignificant, which is consistent with the conclusion by Hein et al. (2011), even though there was grounded ice advance in Filchner Trough. However, advance of a grounded ice stream through Filchner Trough should have provided a buttressing back-stress for Recovery and Slessor glaciers. This would have resulted in their thickening because elsewhere in Antarctica downstream ice ‘damming’ has caused significant glacier thickening (e.g. Anderson et al. 2004).

6.2. Consistencies between the reconstructions from marine and terrestrial datasets

Despite all the discrepancies between Scenarios A and B, there are two remarkable consistencies. First, in both scenarios the contribution of ice-sheet build-up in the Weddell Sea sector during the LGM made only a very minor contribution of a few metres to the global sea-level low stand of ca. 130 metres during this time (cf.

Bentley et al. 2010, Le Brocq et al. 2011, Hillenbrand et al. 2012, Larter et al. 2012, Stolldorf et al. 2012, Whitehouse et al. 2012). Consequently, melting of glacial ice in this sector during the last deglaciation cannot have made a dominant contribution to the meltwater pulses of 10 to 15 metres around ca. 19.1 cal ka BP (Clark et al. 2004) and of 10 to 18 metres at 14.6 cal ka BP, even though an Antarctic source has been repeatedly proposed for meltwater pulse 1A at 14.6 cal ka BP (Clark et al. 2002, Weaver et al. 2003, Deschamps et al. 2012).

Second, even in Scenario B the seabed offshore from the Brunt and the Quar ice shelves was free of grounded ice by at least 25 cal ka BP (Fig.12). Thus, both Scenario A and Scenario B indicate diachronous ice-sheet retreat from the continental shelf of the Weddell Sea sector, with at least parts of the EAIS retreating earlier than the WAIS. This conclusion is consistent with earlier reconstructions of post-LGM ice-sheet retreat from the Antarctic continental shelf on both a regional scale (Elverhøi 1981, Anderson & Andrews 1999, Stolldorf et al. 2012) and a continental scale (Anderson et al. 2002, Livingstone et al. 2012) but is inconsistent with the conclusions of Clark et al. (2009) and Weber et al. (2011) who argued for synchronous advance and retreat around Antarctica. Furthermore, time-transgressive ice-sheet retreat may help to explain the *in-situ* survival of Antarctic shelf benthos during glacial-interglacial cycles (Thatje et al. 2005, Convey et al. 2009). Interestingly, Barnes & Hillenbrand (2010) inferred from the similarity of modern bryozoan assemblages on the Ross Sea shelf and the Weddell Sea shelf (i.e. from samples collected on the seabed offshore from the Brunt, Riiser-Larsen, Quar, Ekstrøm and Jelbart ice shelves) that the seafloor in the two sectors could not have been completely overridden by grounded ice during the last glacial period. This conclusion is in agreement with both geological data from the Ross Sea (Licht et al.

1996, 1999, Domack et al. 1999, Shipp et al. 1999, Bart & Cone 2012) and the different reconstructions for the Weddell Sea sector according to Scenarios A and B presented here.

6.3. Recommendations for future research

Given the very limited amount of the currently available terrestrial and marine geomorphological and chronological data for the Weddell Sea sector, new collection of data and samples and their full exploitation together with that of the already existing material are urgently required. Only such a strategy will allow reconstruction of the ice-sheet history in the Weddell Sea sector during the last glacial cycle with some certainty. Apart from the acquisition of new geomorphological and chronological data from some key areas, such as the Pensacola Mountains and the middle and outer shelf parts of the Hughes, Ronne and Filchner troughs, as well as from terrestrial sites, where pilot studies have been carried out, such as the Heimefrontfjella in western Dronning Maud Land, a more detailed analysis of new and existing samples and data seems to be necessary. For example, any new ^{14}C dates on marine sediment cores from Filchner Trough may help to verify or rule out the existence of the proposed hiatus from ~34.0 to ~18.5 cal ka BP (Fig. 5b) and thus to test the validity of Scenario B, while any new exposure dates on erratics collected from above the trimlines interpreted to indicate the maximum ice-sheet elevations at the LGM may help to test the validity of Scenario A and/or short-lived thickening events. Swath bathymetry maps covering core locations, where over-compacted glaciomarine sediments were recovered, have the potential to show bedforms that will help to clarify, whether the observed over-consolidation was caused by iceberg-scouring or ice-sheet overriding. This important distinction is almost impossible on the basis of sedimentological data and acoustic subbottom profiles alone (e.g. Fütterer & Melles, 1990, Melles & Kuhn 1993).

Novel and refined analytical approaches are required to distinguish subglacial from glaciomarine facies in sediment cores and to evaluate the reliability of the ^{14}C dates obtained from the Weddell Sea shelf. One such method was proposed by Stolldorf et al. (2012) who used subtle grain-size changes to distinguish unsorted and poorly sorted subglacial deposits from better sorted glaciomarine sediments. If available, acoustic subbottom and seismic profiles from core locations should always be considered for the stratigraphic interpretation of sedimentary units and the ^{14}C dates obtained from these units. For example, core 3-3-1 from the eastern flank of the inner shelf part of Filchner Trough (Fig. 4) recovered proximal glaciomarine sediments at its core top, which provided a very old age of 47.7 cal ka BP (Fig. 6; Stolldorf et al. 2012) and may, in fact, be much older (cf. Takada et al. 2003). When the core site is projected onto a nearby seismic profile (Fig. 5 in Anderson et al. 1983 or Fig. 3 in Anderson et al. 1991), it becomes clear that the core probably recovered sediments from the westward dipping reflectors described by Elverhoi & Maisey (1983). This observation alludes to the possibility that the ^{14}C date was obtained from calcareous foraminifera tests that had been reworked from the old dipping strata. Further improvement of the reliability of the ^{14}C ages from the marine sediments may be achieved by dating calcareous benthic foraminifera tests from obviously ‘unmixed’ assemblages typical for modern glaciomarine environments (Stolldorf et al. 2012) and removing possibly reworked foraminifera tests from the samples before AMS dating (Bart & Cone 2012). Furthermore, the suitability of $\delta^{18}O$ records from foraminifera-bearing sediments on the outer WSE shelf for oxygen

isotope stratigraphy (e.g. at sites PS1609 and PS1420; Hillenbrand et al. 2012) should be evaluated by obtaining down-core AMS ^{14}C dates from these cores.
Future research should also focus on testing the hypotheses developed by Hillenbrand et al. (2012) and Larter et al. (2012) for reconciling an LGM ice-sheet advance to the shelf break within Filchner Trough with the limited thickening in the WSE hinterland documented by the terrestrial evidence (Fogwill et al. 2004, Bentley et al. 2010, Hein et al. 2011). For example, ice-sheet model runs could explore the plausibility of bed conditions required for an ice plain to extend all the way from the modern Filchner Ice Shelf front to the shelf break. Provenance studies on Holocene glaciomarine sediments and pre-Holocene subglacial tills from inner shelf cores recovered to the east and west of Berkner Island (Fig. 3) should be carried out to detect possible flow-switches of Foundation Ice Stream in the past. Finally, qualitative insights from the past ice-flow changes in the Weddell Sea sector should be utilised to estimate the risk of possible future deglaciation in this and other sectors of the Antarctic Ice Sheet and the magnitude of associated sea-level rise. For example, the palaeo-record from the WSE can be used for validating the sensitivity of ice-sheet retreat to reverse bed gradients (e.g. Schoof 2007, Katz & Worster 2010, Jamieson et al. 2012), and the outcome can be implemented in numerical ice-sheet models.

7. Conclusions

- Even though the data base of marine and terrestrial geological records from the Weddell Sea sector and its hinterland has significantly increased over the last few years, the LGM to Holocene glacial history of this sector is still poorly known when compared to other sectors of the Antarctic Ice Sheet.

- Subglacial bedforms recorded in high-resolution bathymetric maps and seismic profiles from the Weddell Sea continental shelf document that the grounding lines of the WAIS and EAIS had advanced across the shelf in the past, probably during the Late Pleistocene.
- The glacial geomorphological record in the hinterland of the Weddell Sea sector, surface exposure ages derived from cosmogenic nuclides and changes in ice sheet-thickness archived in the Berkner Island ice core are best explained by no or only minor thickening of the WAIS and EAIS during the last glacial period, suggesting that ice did not ground in the deepest parts of the palaeo-ice stream troughs north of the Filchner-Ronne Ice Shelf.
- Available radiocarbon dates on calcareous microfossils from sediment cores recovered from the continental shelf and uppermost slope can be interpreted to indicate that the last advance of grounded ice occurred either before the last glacial period or at the LGM. This contradicting interpretation originates from (i) the low number of available ages, (ii) a lack of the geomorphological and seismostratigraphic context for most of the dated cores, (iii) the problem of a reliable distinction between subglacial facies and glaciomarine facies, (iv) our inability to clearly identify glaciomarine sediments, which were over-compacted after their deposition by an overriding grounded ice sheet as opposed to an iceberg, (v) a lack of information, whether ^{14}C dates were obtained from autochthonous or reworked allochthonous microfossils, and (vi) the difficulty of evaluating the reliability of ages obtained from sediments recovered on the continental slope in constraining the timing of grounded ice-sheet advance/retreat on the adjacent shelf.

- Grounded ice-sheet advance onto the outer shelf of the Weddell Sea during the last glacial period and no/minor ice-sheet thickening in its hinterland can be reconciled by assuming a short-term advance of ice with a thickness close to floatation and a very low slope gradient and ice-flow changes in the drainage basins of the Filchner and Ronne ice shelves.
- All LGM-Holocene reconstructions for the Weddell Sea sector conclude (i) time-transgressive changes in the various drainage basins of the WAIS and EAIS, (ii) no or only minor ice-sheet build-up at the LGM and (iii) no significant contribution of post-LGM ice-sheet melting to global meltwater pulses during the last deglaciation.

Acknowledgements

We thank the officers, crews and scientific shipboard parties participating in the various marine expeditions to the Weddell Sea sector, the field parties carrying out the terrestrial studies in the hinterland of the Weddell Sea sector, and the logistics organisations making this field work possible. We acknowledge financial support from the Antarctic Climate Evolution (ACE) scientific research programme of the Scientific Committee on Antarctic Research (SCAR) for a workshop held in 2011 in Edinburgh (UK) that kick-started the Antarctic Ice Sheet community reconstruction initiative. CJF is supported by Australian Research Council (FT120100004). Finally, we are grateful to two anonymous reviewers whose constructive and thoughtful comments helped to improve this paper.

8. References

Alley, R.B., Blankenship, D.D., Rooney, S.T. & Bentley, C.R., 1989. Sedimentation beneath ice shelves – the view from ice stream B. – Marine Geology, 85: 101-120.

Anderson, B.M., Hindmarsh, R.C.A. & Lawson, W.J., 2004. A modelling study of the response of Hatherton Glacier to Ross Ice Sheet grounding line retreat. – Global and Planetary Change, 42: 143-153.

Anderson, J.B., 1972a. The marine geology of the Weddell Sea. – Florida State University Sedimentological Research Laboratory, Publication Number 35, Florida State University, Tallahassee, 222 pp.

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

Anderson, J.B., 1999. Antarctic Marine Geology. – Cambridge University Press, Cambridge (UK), 289 pp.

Anderson, J.B. & Andrews, J.T., 1999. Radiocarbon constraints on ice sheet advance and retreat in the Weddell Sea, Antarctica. – Geology, 27: 179-182.

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., Kurtz, D., Weaver, F. & Balshaw, K.M., 1982. Sedimentation on the West Antarctic continental margin – In: Craddock, C. (Ed.), Antarctic Geoscience; University of Wisconsin Press, Madison (U.S.A.), pp. 1003-1012.

Anderson, J.B., Brake, C., Domack, E. Myers, N. & Wright, R., 1983. Development of a polar glacial-marine sedimentation model from Antarctic Quaternary deposits and glaciological information. – In: Molnia, B.F. (Ed.), Glacial-Marine Sedimentation; Plenum Press, New York (U.S.A.), pp. 233-264.

Anderson, J.B., Andrews, B.A., Bartek, L.R. & Truswell, E.M., 1991. Petrology and palynology of glacial sediments: Implications for subglacial geology of the eastern Weddell Sea, Antarctica. – In: Thomson, M.R.A., Crame, J.A. & Thomson, J.W. (Eds.), Geological evolution of Antarctica; Cambridge University Press, Cambridge (UK), pp. 231-235.

Anderson, J.B., Wellner, J.S., Lowe, A.L., Mosola, A.B. & Shipp, S.S., 2001. Footprint of the expanded West Antarctic Ice Sheet: ice stream history and behavior. – GSA Today, 11: 4-9.

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.

Andrews, J.T., Domack, E.W., Cunningham, W.L., Leventer, A., Licht, K.J., Jull, A.J.T., DeMaster, D.J. & Jennings, A.E., 1999. Problems and possible solutions concerning radiocarbon dating of surface marine sediments, Ross Sea, Antarctica. – Quaternary Research, 52: 206-216.

Argus, D.F., Blewitt, G., Peltier, R.W. & Kreemer, C., 2011. Rise of the Ellsworth mountains and parts of the East Antarctic coast observed with GPS. – Geophysical Research Letters, 38: L16303, doi:10.1029/2011GL048025.

Barnes, D.K.A. & Hillenbrand, C.-D., 2010. Faunal evidence for a late quaternary trans-Antarctic seaway. – Global Change Biology, 16: 3297-3303.

Bart, P.J. & Cone, A.N., 2012. Early stall of West Antarctic Ice Sheet advance on the eastern Ross Sea middle shelf followed by retreat at 27,500 ^{14}C yr BP. – Palaeogeography, Palaeoclimatology, Palaeoecology, 335-336: 52-60.

Bart, P.J., De Batist, M. & Jokat, W. 1999. Interglacial collapse of Crary Trough-Mouth Fan, Weddell Sea, Antarctica: Implications for Antarctic glacial history. – Journal of Sedimentary Research, 69 (6): 1276-1289.

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.

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.

Bentley, M.J., Fogwill, C.J., Kubik, P.W., & Sugden, D.E., 2006. Geomorphological evidence and cosmogenic $^{10}Be/^{26}Al$ exposure ages for the Last Glacial Maximum and deglaciation of the Antarctic Peninsula Ice Sheet. – Geological Society of America Bulletin, 118: 1149-1159.

Bentley, M.J., Fogwill, C.J., Le Brocq, A.M., Hubbard, A.L., Sugden, D.E., Dunai, T.J. & Freeman, S.P.H.T., 2010. Deglacial history of the West Antarctic Ice Sheet in the Weddell Sea Embayment: Constraints on past ice volume change. – Geology, 38: 411-414.

Bentley, M.J., Fogwill, C.J., Le Brocq, A.M., Hubbard, A.L., Sugden, D.E., Dunai, T.J. & Freeman, S.P.H.T., 2011a. Deglacial history of the West Antarctic Ice Sheet in the Weddell Sea Embayment: constraints on past ice volume change: reply. – Geology, 39: e240. doi:10.1130/G32140Y.1.

Bentley, M.J., Johnson, J.S., Hodgson, D.A., Dunai, T.J., Freeman, S. & Ó Cofaigh, C., 2011b. Rapid deglaciation of Marguerite Bay, western Antarctic Peninsula in the Early Holocene. – Quaternary Science Reviews, 30: 3338-3349.

Bentley, M.J., Hein, A., Sugden, D.E., Whitehouse, P., Vieli, A. & Hindmarsh, R.C.A., 2012. Post-glacial thinning history of the Foundation Ice Stream, Weddell Sea embayment, Antarctica. – Abstract C51C-0787 presented at 2012 Fall Meeting, AGU, San Francisco, California, 3-7 December 2012.

Berkman, P.A. & Forman, S.L., 1996. Pre-bomb radiocarbon and the reservoir correction for calcareous marine species in the Southern Ocean. – Geophysical Research Letters, 23: 363-366.

Bindschadler, R., Vornberger, P. & Gray, L., 2005. Changes in the ice plain of Whillans Ice Stream, West Antarctica. – Journal of Glaciology, 51: 620-636.

Boyer, S.J. 1979. Glacial geological observations in the Dufek Massif and Forrestal Range, 1978-79. – Antarctic Journal of the United States, 14 (5): 46-48.

Campbell, S., Balco, G., Todd, C., Conway, H., Huybers, K., Simmons, C. & Vermeulen, M., 2013. Radar-detected englacial stratigraphy in the Pensacola Mountains, Antarctica: implications for recent changes in ice flow and accumulation. – Annals of Glaciology, 54 (63): 91-100.

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

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

Clark, P.U., 2011. Deglacial history of the West Antarctic Ice Sheet in the Weddell Sea Embayment: constraints on past ice volume change: comment. – Geology, 39: e239. doi:10.1130/G31533C.1.

Clark, P.U., Mitrovica, J.X., Milne, G.A. & Tamisiea, M.E., 2002. Sea-level finger printing as a direct test for the source of global Meltwater Pulse 1A. – Science, 295: 2438-2441.

Clark, P.U., McCabe, A.M., Mix, A.C. & Weaver, A.J., 2004. Rapid rise of sea level 19,000 years ago and its global implications. – Science, 304: 1141-1144.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W. & McCabe, A.M., 2009. The Last Glacial Maximum. – Science, 325: 710-714.

Convey, P., Stevens, M.I., Hodgson D.A., Smellie, J.L., Hillenbrand, C.-D., Barnes, D.K.A., Clarke, A., Pugh, P.J.A., Linse, K. & Craig Cary, S., 2009. Exploring biological constraints on the glacial history of Antarctica. – Quaternary Science Reviews, 28: 3035-3048.

Crawford, K., Kuhn, G. & Hambrey, M.J., 1996. Changes in the character of glaciomarine sedimentation in the southwestern Weddell Sea, Antarctica: evidence from the core PS1423-2. – Annals of Glaciology, 22: 200-204.

Davis, C.H., Li, Y., McConnell, J.R., Frey, M.M. & Hanna, E., 2005. Snowfall-driven growth in East Antarctic ice sheet mitigates recent sea-level rise. – Science, 308: 1898-1901.

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., et al. (Eds.), Geology and paleontology of the Ellsworth Mountains, West Antarctica. Geological Society of America Memoir, 170: 403-432.

Deschamps, P., Durand, N., Bard, E., Hamelin, B., Camoin, G., Thomas, A.L., Henderson, G.M., Okuno, J. & Yokoyama, Y., 2012. Ice-sheet collapse and sea-level rise at the Bølling warming 14,600 years ago. – Nature, 483: 559-564.

Domack, E.W., Jacobson, E.A., Shipp, 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.

Dowdeswell, J.A. & Bamber, J.L., 2007. Keel depths of modern Antarctic icebergs and implications for sea-floor scouring in the geological record. – Marine Geology, 243: 120-131.

Ehrmann, W.U., Melles, M., Kuhn, G., & Grobe, H., 1992. Significance of clay mineral assemblages in the Antarctic Ocean. – Marine Geology, 107: 249-273.

Elverhøi, A., 1981. Evidence for a late Wisconsin glaciation of the Weddell Sea. – Nature, 293: 641-642.

Elverhøi, A., 1984. Glacigenic and associated marine sediments in the Weddell Sea, fjords of Spitsbergen and the Barents Sea: A review. – Marine Geology, 57: 53-88.

Elverhøi, A. & Maisey, G., 1983. Glacial erosion and morphology of the eastern and southeastern Weddell Sea shelf. – In: Oliver, R.L., James, P.R. & Jago, J.B. (Eds.), Antarctic Earth Science, Proceedings of the Fourth International Symposium on Antarctic Earth Science, Adelaide (Australia) 1982; Australian Academy of Science, Canberra (Australia), pp. 483-487.

Elverhøi, A. & Roaldset, E., 1983. Glaciomanne sediments and suspended particulate matter, Weddell Sea shelf, Antarctica. – Polar Research, 1: 1-21.

EPICA community members, 2006. One-to-one coupling of glacial climate variability in Greenland and Antarctica. – Nature, 444: 195-198.

Evans, J. & Pudsey, C.J., 2002. Sedimentation associated with Antarctic Peninsula ice shelves: implications for paleoenvironmental reconstructions of glacimarine sediments. – Journal of the Geological Society 159: 233-237.

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.

Fogwill, C.J., Hein, A.S., Bentley, M.J. & Sugden, D.E., 2012. Do blue-ice moraines in the Heritage Range show the West Antarctic ice sheet survived the last interglacial? – Palaeogeography, Palaeoclimatology, Palaeoecology, 335-336: 61-70.

Fretwell, P., Pritchard, H.D. & 58 others, 2013. Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. – The Cryosphere, 7: 375-393; doi:10.5194/tc-7-375-2013.

Fukamachi, Y., Rintoul, S.R., Church, J.A., Aoki, S., Sokolov, S., Rosenberg, M.A. & Wakatsuchi, M., 2010. Strong export of Antarctic Bottom Water east of the Kerguelen Plateau. – Nature Geoscience, 3: 327-331.

Fütterer, D.K. & Melles, M. 1990. Sediment patterns in the southern Weddell Sea: Filchner Shelf and Filchner Depression. – In: Bleil, U. & Thiede, J. (Eds.), Geological History of the Polar Oceans; Arctic vs. Antarctic, NATO/ASI Series C, Kluwer Academic Press, Dordrecht (Netherlands), pp. 381-401.

Gales, J.A., Larter, R.D., Mitchell, N.C., Hillenbrand, C.-D., Østerhus, S. & Shoosmith, D.R., 2012. Southern Weddell Sea shelf edge geomorphology: Implications for cold, high salinity water overflow as an Antarctic gully-forming mechanism. – Journal of Geophysical Research, 117: doi:10.1029/2012JF002357.

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 d a circum-Antarctic view based on siliceous microfossil records. – Quaternary Science Reviews, 24: 869-896.

Golledge, N.R., Fogwill, C.J., Mackintosh, A.N. & Buckley, K.M., 2012. Dynamics of the Last Glacial Maximum Antarctic Ice Sheet and its response to ocean forcing. – Proceedings of the National Academy of Sciences, 109: 16052-16056.

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.

Grobe, H. & Mackensen, A. 1992. Late Quaternary climatic cycles as recorded in sediments from the Antarctic continental margin. – In: Kennett, J.P. & Warnke, D. A. (Eds.), The Antarctic Paleoenvironment: A Perspective on Global Change, Antarctic Research Series, vol. 56; American Geophysical Union, Washington D.C., pp. 349-376.

Grosfeld, K., Schröder, M., Fahrbach, E., Gerdes, R. & Mackensen, A., 2001. How iceberg calving and grounding change the circulation and hydrography in the Filchner Ice Shelf-Ocean System. – Journal of Geophysical Research, 106: 9039-9055.

Haase. G.M., 1986. Glaciomarine sediments along the Filchner/Ronne Ice Shelf. southern Weddell Sea - First results of the 1983/84 ANTARKTIS-II/4 expedition. – Marine Geology, 72: 241-258.

Hättestrand, C. & Johansen, N., 2005. Supraglacial moraines in Scharffenbergbotnen, Heimefrontfjella, Dronning Maud Land, Antarctica – significance for reconstructing former blue ice areas. – Antarctic Science, 17: 225-236.

Haugland, K., 1982. Sesimic reconnaissance Survey in the Weddell Sea. – In: Craddock, C. (Ed.), Antarctic Geoscience, University of Wisconsin Press, Madison (U.S.A.), pp. 405-413.

Haugland, K., Kristoffersen, Y. & Velde, A., 1985: Seismic investigations in the Weddell Sea Embayment. – In: Husebuy, E.S., Johnson, G.L. & Kristoffersen, Y. (Eds.), Geophysics of the Polar Regions. Tectonophysics, 114: 1-21.

Hedges. R.E.M., Housley, R.A., Ramsey, C.B. & van Klinken, G.J., 1995. Radiocarbon dates from the Oxford AMS system: achaeometry datelist 19. – Archaeometry, 37 (1): 195-214.

Hegland, M., Vermeulen, M., Todd, C., Balco, G., Huybers, K., Campbell, S., Conway, H. & Simmons, C., 2012. Glacial Geomorphology of the Pensacola Mountains, Weddell Sea Sector, Antarctica. – Abstracts of the WAIS Workshop 2012 (http://www.waisworkshop.org/abstracts/2012/WAISWorkshop2012abstracts.pdf), p. 21.

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.

Hein, A.S., Fogwill, C.J., Sugden, D.E. & Xu, S., 2013. Geological scatter of cosmogenic-nuclide exposure ages in the Shackleton Range, Antarctica: Implications for glacial history. – Quaternary Geochronology, http://dx.doi.org/10.1016/j.quageo.2013.03.008.

Hellmer, H., Kauker, F., Timmermann, R., Determann, J. & Rae, J., 2012. Twenty-first-century warming of a large Antarctic ice-shelf cavity by a redirected coastal current. – Nature, 485: 225-228.

Hemer, M.A., Post, A.L., O'Brien, P.E., Craven, M., Truswell, E.M., Roberts, D. & Harris, P.T., 2007. Sedimentological signatures of the sub-Amery Ice Shelf circulation. – Antarctic Science, 19: 497-506.

Heroy, D.C. & Anderson, J.B., 2005. Ice-sheet extent of the Antarctica Peninsula region during the Last Glacial Maximum (LGM) – insights from glacial geomorphology. – Geological Society of America Bulletin, 117: 1497-1512.

Hillenbrand, C.-D., Baesler, A. & Grobe, H., 2005. The sedimentary record of the last glaciation in the western Bellingshausen Sea (West Antarctica): implications for the interpretation of diamictons in a polar-marine setting. – Marine Geology, 216: 191-204.

Hillenbrand, C.-D., Larter, R.D., Dowdeswell, J.A., Ehrmann W., Ó Cofaigh, C., Benetti, S., Graham, A.G.C. & Grobe, H., 2010. 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: 2741-2763.

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.

Hiller, A., Wand, U., Kämpf, H. & Stackebrandt, W., 1988. Occupation of the Antarctic continent by petrels during the past 35,000 years: inferences from a ^{14}C study of stomach oil deposits. – Polar Biology, 9: 69-77.

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.

Hodgson, D.A. & Bentley, M.J., 2013. Lake highstands in the Pensacola Mountains and Shackleton Range 4300-2250 cal. yr BP: Evidence of a warm climate anomaly in the interior of Antarctica. – The Holocene, 23: 388-397.

Hodgson, D.A., Bentley, M.J., Schnabel, C., Cziferszky, A., Fretwell, P., Convey, P. & Xu, S., 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.

Höfle, H.C. & Buggisch, W., 1993. Glacial geology and petrography of erratics in the Shackleton Range, Antarctica. – Polarforschung, 63: 183-201.

Hughen, K.A., 2007. Radiocarbon dating of deep-sea sediments. – In: Hillaire-Marcel, C. & De Vernal, A. (eds.), Proxies in Late Cenozoic Paleoceanography, Deveolopments in Marine Geology, 1: 185-209; Elsevier (Amsterdam).

Hughes, T., 1977. West Antarctic Ice Streams. – Reviews of Geophysics and Space Physics, 15: 1-46.

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.

Huybrechts, P., Rybak, O., Pattyn, F., Ruth, U. & Steinhage, D., 2007. Ice thinning, upstream advection, and non-climatic biases for the upper 89% of the EDML ice core from a nested model of the Antarctic ice sheet. – Climate of the Past, 3: 577-589.

Huybrechts, P., Rybak, O., Steinhage, D. & Pattyn, F., 2009. Past and present accumulation rate reconstruction along the Dome Fuji–Kohnen radio-echo sounding profile, Dronning Maud Land, East Antarctica. – Annals of Glaciology, 50 (51): 112-120.

IPCC, 2007. Summary for policymakers. – In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. & Miller, H.L. (Eds.), Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press, Cambridge, 1-18.

Jakobsson, M., Anderson, J.B., Nitsche, F.O., Gyllencreutz, R., Kirshner, A., Kirchner, N., O'Regan, M.A., Mohammad, R. & Eriksson, B., 2012. Ice sheet retreat dynamics inferred from glacial morphology of the central Pine Island Bay Trough, West Antarctica. – Quaternary Science Reviews, 38: 1-10.

Jamieson, S.S.R., Vieli, A., Livingstone, S.J., Ó Cofaigh, C., Stokes, C.R., Hillenbrand, C.-D. & Dowdeswell, J.A. (2012): Ice stream grounding-line stability on a reverse bed slope. – Nature Geoscience: doi:10.1038/ngeo1600.

Jokat, W., Fechner, N. & Studinger, M., 1997. Geodynamic models of the Weddell Sea Embayment in view of new geophysical data. – In: Ricchi, C.A. (Ed.), The Antarctic Region: Geological Evolution and Processes, Terra Antartica Publication, Siena (Italy), pp. 453-459.

Joughin, I. & Alley, R.B., 2011. Stability of the West Antarctic Ice Sheet in a warming world. – Nature Geoscience, 4: 506-513.

Joughin, I. & Bamber, J.L., 2005. Thickening of the ice stream catchments feeding the Filchner-Ronne Ice Shelf, Antarctica. – Geophysical Research Letters, 32, L17503, doi:10.1029/2005GL023844.

Joughin, I., Bamber, J.L., Scambos, T., Tulaczyk, S., Fahnestock, M. & MacAyeal, D.R., 2006. Integrating satellite observations with modelling: basal shear stress of the Filcher–Ronne ice streams, Antarctica. – Philosophical Transactions of the Royal Society of London (Series A), 364: 1795-1814.

Katz, R.F. & Worster, M.G., 2010. Stability of ice-sheet grounding lines. – Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science, 466: 1597-1620.

Kerr, A. & Hermichen, W.D., 1999. Glacial modification of the Shackleton Range, Antarctica. – Terra Antartica, 6: 353–360.

Kilfeather, A.A., Ó Cofaigh, C., Lloyd, J.M., Dowdeswell, J.D., 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.

King, M.A., Bingham, R.J., Moore, P., Whitehouse, P.L., Bentley, M.J. & Milne, G.A., 2012. Lower satellite-gravimetry estimates of Antarctic sea-level contribution. – Nature, 491: 586-590.

Kirshner, A.E., Anderson, J.B., Jakobsson, M., O'Regan, M., Majewski, W. & Nitsche, F.O., 2012. Post-LGM deglaciation in Pine Island Bay, West Antarctica. – Quaternary Science Reviews, 38: 11-26.

Kristoffersen, Y., Strand, K., Vorren, T., Harwood, D. & Webb, P., 2000a. Pilot shallow drilling on the continental shelf, Dronning Maud Land, Antarctica. – Antarctic Science, 12 (4): 463-470.

Kristoffersen, Y., Winterhalter, B. & Solheim, A., 2000b. Shelf progradation on a glaciated continental margin, Queen Maud Land, Antarctica. – Marine Geology 165: 109-122.

Kuhn, G. & Weber, M., 1993. Acoustical characterization of sediments by *Parasound* and 3.5 kHz systems: Related sedimentary processes on the southeastern Weddell Sea continental slope, Antarctica. – Marine Geology, 113: 201-217.

Kuvaas, B. & Kristoffersen, Y., 1991. The Crary Fan: a trough-mouth fan on the Weddell Sea continental margin, Antarctica. – Marine Geology, 97: 345-362.

Lambrecht, A., Sandhäger, H., Vaughan, D.G. & Mayer, C., 2007. New ice thickness maps of Filchner–Ronne Ice Shelf, Antarctica, with specific focus on grounding lines and marine ice. – Antarctic Science, 19: 521-532.

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.

Le Brocq, A.M., Bentley, M.J., Hubbard, A., Fogwill, C.J., Sugden, D.E. & Whiteghouse, P.L., 2011. Reconstructing the Last Glacial Maximum ice sheet in the Weddell Sea Embayment, Antarctica, using numerical modelling constrained by field evidence. – Quaternary Science Reviews, 30: 2422-2432.

Licht, K.J. & Andrews, J.T., 2002. The 14C record of Late Pleistocene ice advance and retreat in the central Ross Sea, Antarctica. – Arctic, Antarctic and Alpine Research, 34: 324-333.

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: 223-226.

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: 91-103.

Lien, R., Solheim, A., Elverhøi, A. & Rokoengen, K., 1989. Iceberg scouring and sea bed morphology on the eastern Weddell Sea shelf, Antarctica. – Polar Research, 7: 43-57.

Livingstone, S.J., Ó Cofaigh, C., Stokes, C.R., Hillenbrand , C.-D., Vieli, A. & Jamieson, S.S.R., 2012. Antarctic palaeo-ice streams. – Earth Science Reviews, 111: 90-128.

Mackensen A., 2001. Oxygen and carbon stable isotope tracers of Weddell Sea water masses: new data and some paleoceanographic implications. – Deep-Sea Research I, 48: 1401-1422.

Mackintosh, A., Golledge, N., Domack, E., Dunbar, R., Leventer, A., White, D., Pollard, D., DeConto, R., Fink, D., Zwartz, D., Gore, D. & Lavoie, C., 2011. Retreat of the East Antarctic ice sheet during the last glacial termination. – Nature Geoscience, 4: 195-202.

Melles, M., 1987. Sedimentation in der Filchner-Depression, südöstlicher Weddellmeer-Schelf, Antarktis. – Unpublished diploma thesis; Institute and Museum of Geology and Palaeontology, Georg August University, Göttingen (Germany), 180 pp.

Melles, M., 1991. Paläoglaziologie und Paläozeanographie im Spätquartär am südlichen Kontinentalrand des Weddellmeeres. – Reports on Polar Research, 81; Alfred Wegener Institute for Polar and Marine Research, Bremerhaven (Germany), 190 pp.

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.

Meredith, M.P., 2013. Replenishing the abyss. – Nature Geoscience, 6: 166-167.

Michels, K.H., Kuhn, G., Hillenbrand, C.-D., Diekmann, B., Fütterer, D.K., Grobe, H. & Uenzelmann-Neben, G., 2002. The southern Weddell Sea: Combined contourite - turbidite sedimentation at the southeastern margin of the Weddell Gyre. – In: Stow, D.A.V., Pudsey, C.J., Howe, J.A., Faugeres, J.-C. & Viana, A.R. (Eds.), Deep-Water Contourites: Modern drifts and ancient series, seismic and sedimentary characteristics; Geological Society of London Memoirs, 22; London (UK), pp. 305-323.

Miller, H., Henriet, J.R., Kaul, N. & Moons, A., 1990. A fine-scale seismic stratigraphy of the eastern margin of the Weddell Sea. – In: Bleil, U. & Thiede, J. (Eds.), Geological History of the Polar Oceans; Arctic vs. Antarctic, NATO/ASI Series C, Kluwer Academic Press, Dordrecht (Netherlands), pp. 131-161.

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.

Mulvaney, R., Arrowsmith, C., Barnola, J., McCormack, T., Loulergue, L., Raynaud, D., Lipenkov, V. & Hindmarsh, R., 2007. A deglaciation climate and ice sheet history of the Weddell Sea region from the Berkner Island ice core. – Quaternary International, 167-168; Supplement: 294-295.

Naveira Garabato, A.C., McDonagh, E.L., Stevens, D.P., Heywood, K.J. & Sanders, R.J., 2002. On the export of Antarctic BottomWater from the Weddell Sea. – Deep-Sea Res. II, 49: 4715-4742.

Nicholls, K.W., Padman, L., Schröder, M., Woodgate, R. A., Jenkins, A. & Østerhus, S., 2003. Water mass modification over the continental shelf north of Ronne Ice Shelf, Antarctica. – Journal of Geophysical Research, 108 (C8): 3260, doi:10.1029/2002JC001713.

Nicholls, K.W., Østerhus, S., Makinson, K., Gammelsrød, T. & Fahrbach, E., 2009. Ice-ocean processes over the continental shelf of the southern Weddell Sea, Antarctica: A review. – Reviews of Geophysics, 47: RG3003, doi:10.1029/2007RG000250.

Ó Cofaigh, C., Dowdeswell, J.A., Allen, C.S., Hiemstra, J., Pudsey, C.J., Evans, J. & Evans, D.J.A., 2005a. Flow dynamics and till genesis associated with a marine-based Antarctic palaeo-ice stream. – Quaternary Science Reviews, 24: 709-740.

Ó Cofaigh, C., Larter, R.D., Dowdeswell, J.A., Hillenbrand, C.-D., Pudsey, C.J., Evans, J. & Morris, P., 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, doi:10.1029/2005JB003619.

Orheim, O. (Ed.), 1985. Report of the Norwegian Antarctic Research Expediton (NARE) 1984/85. – Norsk Polarinstitutt Rapportserie 22, Oslo, 138 pp.

Orsi, A.H., Nowlin, W.D. & Whitworth III, T., 1993. On the circulation and stratification of the Weddell Gyre. – Deep Sea Research I, 40: 169-203.

Pollard, D. & DeConto, R.M., 2009. Modelling West Antarctic ice sheet growth and collapse through the past five million years. – Nature, 458: 329-333.

Pritchard, H.D., Ligtenberg, S.R.M., Fricker, H.A., Vaughan, D.G., van den Broeke, M.R. & Padman, L., 2012. Antarctic ice-sheet loss driven by basal melting of ice shelves. – Nature, 484: 502-505.

Pudsey, C.J., Evans, J., Domack, E.W., Morris, P. & Del Valle, R., 2001. Bathymetry and acoustic facies beneath the former Larsen-A and Prince Gustav Ice Shelves, NW Weddell Sea. – Antarctic Science, 13: 312-322.

Rahmstorf, S., 2002. Ocean circulation and climate during the past 120,000 years. – Nature, 419: 206-214.

Reinardy, B.T.I., Larter, R.D., Hillenbrand, C.-D., Murray, T., Hiemstra, J.F. & Booth, A., 2011. Streaming flow of an Antarctic Peninsula palaeo-ice stream, both by basal sliding and deformation of substrate. – Journal of Glaciology, 57: 1-13.

Reimer, P.J. and 27 others, 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0-50,000 years cal BP. – Radiocarbon, 51: 1111-1150.

Rignot, E., Bamber, J.L., van den Broeke, M.R., Davis, C., Li, Y., van de Berg, W.J. & van Meijgaard, E., 2008. Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. – Nature Geoscience, 1: 106-110.

Rignot, E. Jacobs, S., Mouginot, J. & Scheuchl B., 2013. Ice shelf melting around Antarctica. – Science Express, doi:10.1126/science.1235798.

Robinson, L.F. & van de Flierdt, T., 2009. Southern Ocean evidence for reduced export of North Atlantic Deep Water during Heinrich Event 1. – Geology, 37: 195-198.

Rosenheim, B.E., Day, M.B., Domack, E., Schrum, H., Benthien, A. & Hays, J.M., 2008. Antarctic sediment chronology by programmed-temperature pyrolysis: Methodology and data treatment. – Geochemistry, Geophysics, Geosystems, 9, Q04005: doi:10.1029/2007GC001816.

Ross, N., Siegert, M.J., Woodward, J., Smith, A.M., Corr, H.F.J., Bentley, M.J., Hindmarsh, R.C.A., King, E.C. & Rivera, A., 2011. Holocene stability of the Amundsen-Weddell ice divide, West Antarctica. – Geology, 39: 935-938.

Ross, N., Bingham, R.G., Corr, H.F.J., Ferracioli, F., Jordan, T.A., Le Brocq, A., Rippin, D.M., Young, D., Blankenship, D.D. & Siegert, M.J., 2012. Steep reverse bed slope at the grounding line of the Weddell Sea sector in West Antarctica. – Nature Geoscience, 5: 393-396.

Ryan, P.G., Steele, W.K., Siegfried, W.R. & Vogel, J.C., 1992. Radiocarbon dates of snow petrel regurgitations can reveal exposure periods for nunataks in Antarctica. – South African Journal of Science, 88: 578-580.

Schenke, H.-W., Hinze, H., Dijkstra, S., Hoppmann, B., Niederjasper, F. & Schöne, T., 1998. The New Bathymetric Charts of the Weddell Sea: AWI BCWS. – In: Jacobs, S. & Weiss, R. (Eds.), Antarctic Research Series, 75; American Geophysical Union, Washington D.C., pp. 371-380.

Schoof, C., 2007. Ice sheet grounding line dynamics: Steady states, stability, and hysteresis. – Journal of Geophysical Research, 112: F03S28, doi:10.1029/2006JF000664.

Shepherd, A. & 46 others, 2012. A reconciled estimate of ice sheet mass balance. – Science, 338: 1183-1189.

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.

Sikes, E.L., Samson, C.R., Guilderson, T.P. & Howard, W.R., 2000. Old radiocarbon ages in the southwest Pacific Ocean during the last glacial period and deglaciation. – Nature, 405: 555-559.

Skinner, L.C., Fallon, S., Waelbroeck, C., Michel, E., Barker, S., 2010. Ventilation of the deep Southern Ocean and deglacial CO_2 rise. – Science, 328: 1147-1151.

Smith, A.M., Murray, T., Nicholls, K.W., Makinson, K., Ađalgeirsdottir, G., Behar, A.E., & Vaughan, D.G., 2007. Rapid erosion, drumlin formation, and changing hydrology beneath an Antarctic ice stream. – Geology, 35: 127-130.

Smith, A.M., Bentley, C.R., Bingham, R.G. & Jordan, T.A., 2012. Rapid subglacial erosion beneath Pine Island Glacier, West Antarctica. – Geophysical Research Letters, 39: L12501, doi:10.1029/2012GL051651.

Smith, J.A., Hillenbrand, C.-D., Kuhn, G., Larter, R.D., Graham, A.G.C., Ehrmann, W., Moreton, S.G. & Forwick, M., 2011. Deglacial history of the West Antarctic Ice Sheet in the western Amundsen Sea Embayment. – Quaternary Science Reviews, 30: 488-505.

Smith, L.M. & Licht, K.J., 2000. Radiocarbon date list IX: Antarctica, Arctic Ocean, and the northern North Atlantic region. – Institute of Arctic and Alpine Research, University of Colorado, Boulder (U.S.A.), Occasional Paper 54, 139 pp.

Steele, W.K. & Hiller, A., 1997. Radiocarbon dates of snow petrel (*Pagodroma nivea*) nest sites in central Dronning Maud Land, Antarctica. – Polar Record, 33: 29-38.

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.

Sugden, D.E., Bentley, M.J. & Ó Cofaigh, C., 2006. Geological and geomorphological insights into Antarctic ice sheet evolution. – Philosophical Transactions of the Royal Society of London (Series A), 364: 1607-1625.

Swithinbank, C., Brunk, K. & Sievers, J., 1988. A glaciological map of Filchner-Ronne Ice Shelf, Antarctica. – Annals of Glacio!ogy, 11: 150-155.

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: 1323-1328.

Thatje, S., Hillenbrand, C.-D. & Larter, R., 2005. On the origin of Antarctic marine benthic community structure. – Trends in Ecology and Evolution, 20: 534-540.

Thor, G. & Low, M., 2011. The persistence of the snow petrel (*Pagodroma nivea*) in Dronning Maud Land (Antarctica) for over 37,000 years. – Polar Biology, 34: 609-613.

Todd, C. & Stone, J., 2004. Deglaciation of the southern Ellsworth Mountains, Weddell Sea sector of the West Antarctic Ice Sheet [abs.]. – In Proceedings, 11th Annual WAIS Workshop; Sterling, Virginia, West Antarctic Ice Sheet Initiative.

Van Beek, P., Reyss, J.-L., Paterne, M., Gersonde, R., Rutgers van der Loeff, M. & Kuhn, G., 2002. ^{226}Ra in barite: absolute dating of Holocene Southern Ocean sediments and reconstruction of sea-surface reservoir ages. – Geology, 30: 731-734.

Vaughan, D.G. & Arthern, R., 2007. Why is it hard to predict the future of ice sheets? – Science, 315: 1503-1504.

Vaughan, D.G., Sievers, J., Doake, C.S.M., Hinze, H., Mantripp, D.R., Pozdeev, V.S., Sandhäger, H., Schenke, H.W., Solheim, A. & Thyssen, F., 1995. Subglacial and seabed topography, ice thickness and water column thickness in the vicinity of Filchner-Ronne-Schelfeis, Antarctica. – Polarforschung, 64 (2): 75-88.

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

Wand, U. & Hermichen, W.-D., 2005. Late Quaternary ice level changes in central Dronning Maud Land, East Antarctica, as inferred from ^{14}C ages of mumiyo deposits in snow petrel colonies. – Geologisches Jahrbuch B, 97: 237-254.

Weaver, A.J., Saenko, O.A., Clark, P.U. & Mitrovica, J.X., 2003. Meltwater Pulse 1A from Antarctica as a trigger of the Bølling-Allerød Warm Interval. – Science, 299: 1709-1713.

Weber, M.E., Clark, P.U., Ricken, W., Mitrovica, J.X., Hostetler, S.W. & Kuhn, G., 2011. Interhemispheric ice-sheet synchronicity during the Last Glacial Maximum. – Science, 334: 1265-1269.

Weertman, J., 1974. Stability of the junction of an ice sheet and an ice shelf. – Journal of Glaciololgy, 13: 3-11.

Wellner, J.S., Heroy, D.C. & Anderson, J.B., 2006. The death mask of the Antarctic Ice Sheet: Comparison of glacial geomorphic features across the continental shelf. – Geomorphology, 75: 157-171.

Wessels, M., 1989. Sedimentationsprozesse an der Filchner Schelfeiskante, Antarktis. – Unpublished diploma thesis; Institute and Museum of Geology and Palaeontology, Georg August University, Göttingen (Germany), 132 pp.

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.

Wright, A.P., White, D.A., Gore, D.B. & Siegert, M.J., 2008. Antarctica at the Last Glacial Maximum, Deglaciation and the Holocene. – In: Florindo, F. & Siegert, M. (Eds.), Antarctic Climate Evolution, Advances in Antarctic Earth Sciences; Developments in Earth & Environmental Sciences, 8; Elsevier, Amsterdam, pp. 531-570.

Captions for figures and supplementary tables

Figure 1: Overview map over the Weddell Sea sector with shelf bathymetry and ice-sheet surface elevation (in metres above sea level) according to Bedmap2 (Fretwell et al. 2013) and the main physiographic and glaciological features. Inset map shows the Weddell Sea sector outlined by the red line within the context of Antarctica, with ice shelves being displayed in light blue shading (APIS: Antarctic Peninsula Ice Sheet, EAIS: East Antarctic Ice Sheet, WAIS: West Antarctic Ice Sheet).

Figure 2: Locations of subglacial bedforms in the Weddell Sea sector mapped by high-resolution bathymetry. The circles highlight the areas for which data have been published by Kristoffersen et al. (2000b), Larter et al. (2012) and Stolldorf et al. (2012).

Figure 3: Sites of marine sediment cores retrieved from the continental shelf and upper continental slope (above 1000 metres water depth) in the Weddell Sea sector and distribution of normally consolidated glaciomarine sediments, over-compacted glaciomarine sediments and subglacial tills recovered in these cores (for details, see Supplementary Table 1).

Figure 4: Sites of marine sediment cores retrieved from the continental shelf and upper continental slope (above 1000 metres water depth) in the Weddell Sea sector, for which radiometric and AMS radiocarbon dates have been published (for details, see Supplementary Table 2). Note that core PS1418 provided a core-top age only.

Figure 5: Conventional radiocarbon dates versus calibrated (or corrected) radiocarbon ages from the cores displayed in Figure 4 (for details see Supplementary Table 2).

5a: All ages grouped for different regions (note: Brunt Ice Shelf dates are exclusively from core 3-7-1, Quar Ice Shelf dates are exclusively from core 3-17-1 and the Fimbul Ice Shelf date is from core 206). Minimum ages are marked with arrows, and dates from cores recovered on the continental slope are underscored. Light grey shading indicates the time span of a potential hiatus from ~46.5 to ~41.5 corrected ^{14}C ka BP that may have affected the entire Weddell Sea sector. However, ^{14}C dates obtained from calcareous (micro-)fossils exceeding ca. 35 ^{14}C ka BP may be unreliable, and the true ages may be older (e.g. Takada et al. 2003, Hughen 2007).

5b: Conventional radiocarbon dates versus calibrated (or corrected) radiocarbon ages (i) offshore from the Ronne Ice Shelf and from within Filchner Trough, (ii) from the eastern flank of Filchner Trough, and (iii) offshore from the Riiser-Laren Ice Shelf. Only dates from cores recovered on the continental shelf are shown. Grey shading indicates the time spans of potential hiatuses. Note that the radiocarbon dates exceeding ca. 35 ^{14}C ka BP and the corresponding hiatuses may be unreliable. The dark grey shading highlights the most extended hiatuses in the three areas. These apparent hiatuses overlap during the time interval from ~31.0 to ~21.5 cal ka BP.

Figure 6: Oldest calibrated (or corrected) radiocarbon ages from the cores displayed in Figure 4 (except from core PS1418).

Figure 7: Oldest calibrated radiocarbon ages obtained from cores offshore from the Brunt, Quar and Fimbul ice shelves (Fig. 5a) and calibrated radiocarbon ages constraining the termination of the most extended hiatuses observed north of the Filchner-Ronne and Riiser-Larsen ice shelves (see Fig. 5b). Only dates from cores collected from the continental shelf are displayed. These ages form the basis for the time-slice reconstructions according to Scenario B (see Figs. 12-16).

Figure 8: Grounded ice-sheet extent in the Weddell Sea sector at 20 ka according to Scenario A.

Figure 9: Grounded ice-sheet extent in the Weddell Sea sector at 15 ka according to Scenario A.

Figure 10: Grounded ice-sheet extent in the Weddell Sea sector at 10 ka according to Scenario A.

Figure 11: Grounded ice-sheet extent in the Weddell Sea sector at 5 ka according to Scenario A.

Figure 12: Grounded ice-sheet extent in the Weddell Sea sector at 25 cal ka BP according to Scenario B. The position of the grounding line (GL) was reconstructed using the ages displayed in Figure 7. The different certainty levels given for the GL indicate whether its position is (i) constrained by nearby subglacial bedforms of unknown age (Fig. 2), (ii) constrained by nearby sediment cores that recovered subglacial/over-consolidated deposits of unknown age (Fig. 3), or (iii) simply inferred.

Figure 13: Grounded ice-sheet extent in the Weddell Sea sector at 20 cal ka BP according to Scenario B.

Figure 14: Grounded ice-sheet extent in the Weddell Sea sector at 15 cal ka BP according to Scenario B.

Figure 15: Grounded ice-sheet extent in the Weddell Sea sector at 10 cal ka BP according to Scenario B.

Figure 16: Grounded ice-sheet extent in the Weddell Sea sector at 5 cal ka BP according to Scenario B.

Supplementary Table 1: Metadata for marine sediment cores retrieved from the continental shelf and upper continental slope in the Weddell Sea sector. Recovery of subglacial tills and over-consolidated sediments, respectively, is also indicated.

Supplementary Table 2: Radiocarbon dates of marine sediment cores retrieved from the continental shelf and upper continental slope in the Weddell Sea sector.

Supplementary Table 3: Geographical location, physiographic context, physical properties, cosmogenic nuclide data and exposure ages for terrestrial samples collected from the hinterland of the Weddell Sea sector.

Supplementary Table 4: Radiocarbon dates of terrestrial samples from the hinterland of the Weddell Sea sector.

Fig. 1

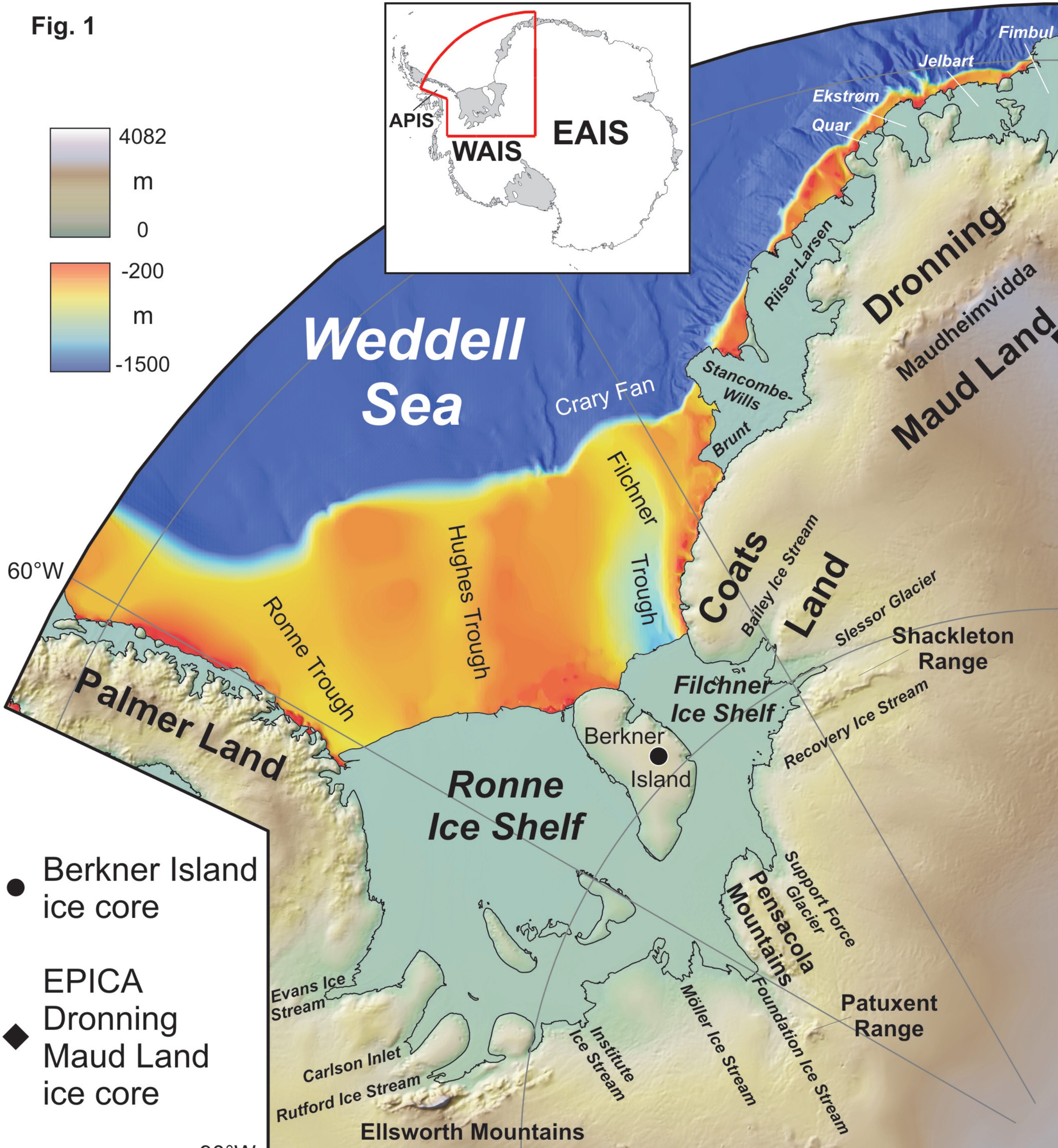
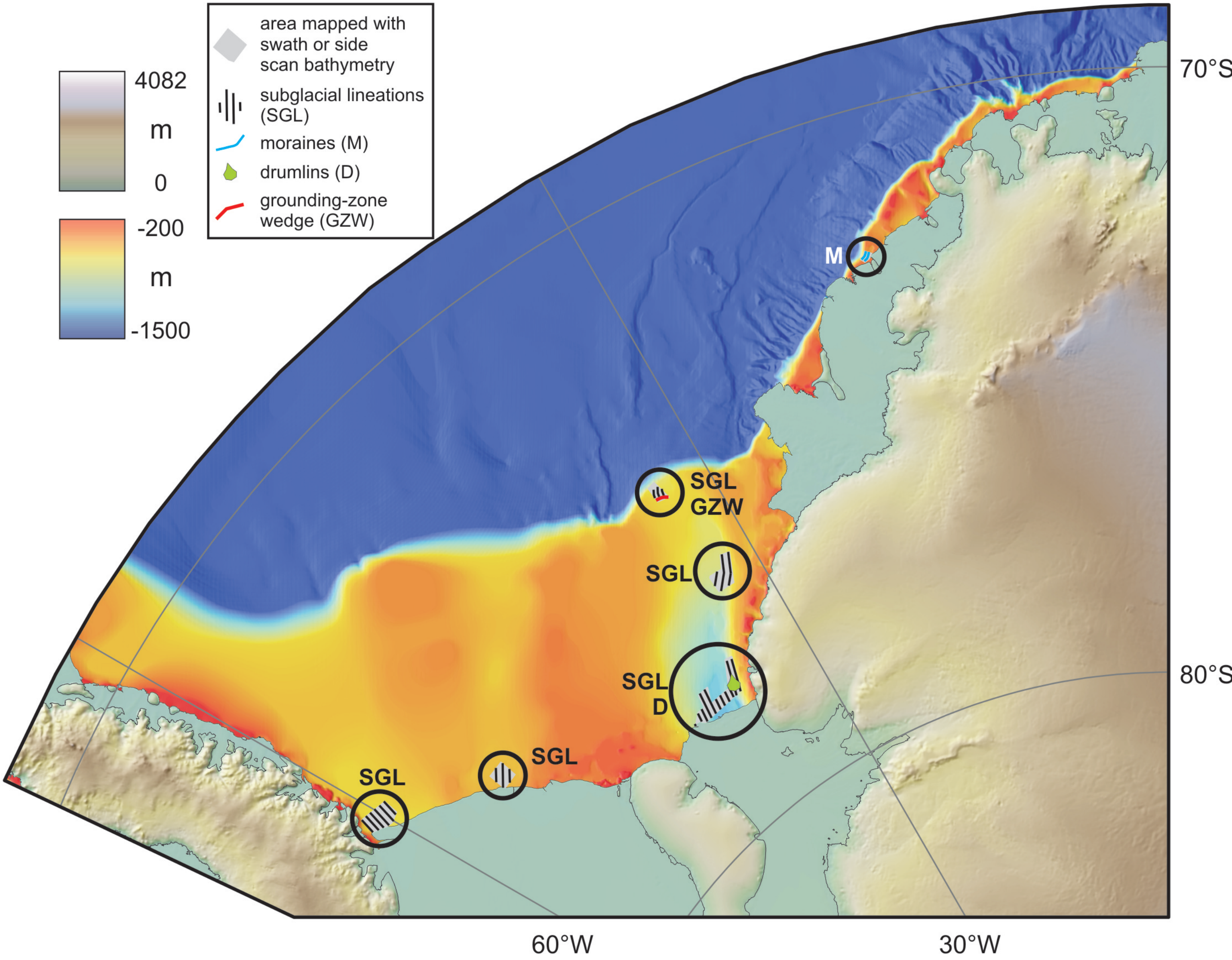

4082
m
0
-200
m
-1500
APIS
WAIS
EAIS
Weddell Sea
Crary Fan
Filchner Trough
Hughes Trough
Ronne Trough
Palmer Land
Fimbul
Jelbart
Ekstrøm
Quar
70°S
Riiser-Larsen
Dronning Maud Land
Maudheimvidda
Stancombe-Wills
Brunt
Coats Land
Bailey Ice Stream
Slessor Glacier
80°S
Shackleton Range
Filchner Ice Shelf
Recovery Ice Stream
Berkner Island
Ronne Ice Shelf
60°W
Support Force Glacier
Pensacola Mountains
Foundation Ice Stream
Patuxent Range
Möller Ice Stream
Institute Ice Stream
Evans Ice Stream
Carlson Inlet
Rutford Ice Stream
Ellsworth Mountains
90°W
Berkner Island ice core
EPICA Dronning Maud Land ice core

Fig. 2



4082
m
0
-200
m
-1500
area mapped with swath or side scan bathymetry
subglacial lineations (SGL)
moraines (M)
drumlins (D)
grounding-zone wedge (GZW)
M
SGL
GZW
SGL
SGL
D
SGL
SGL
70°S
80°S
60°W
30°W

Fig. 3

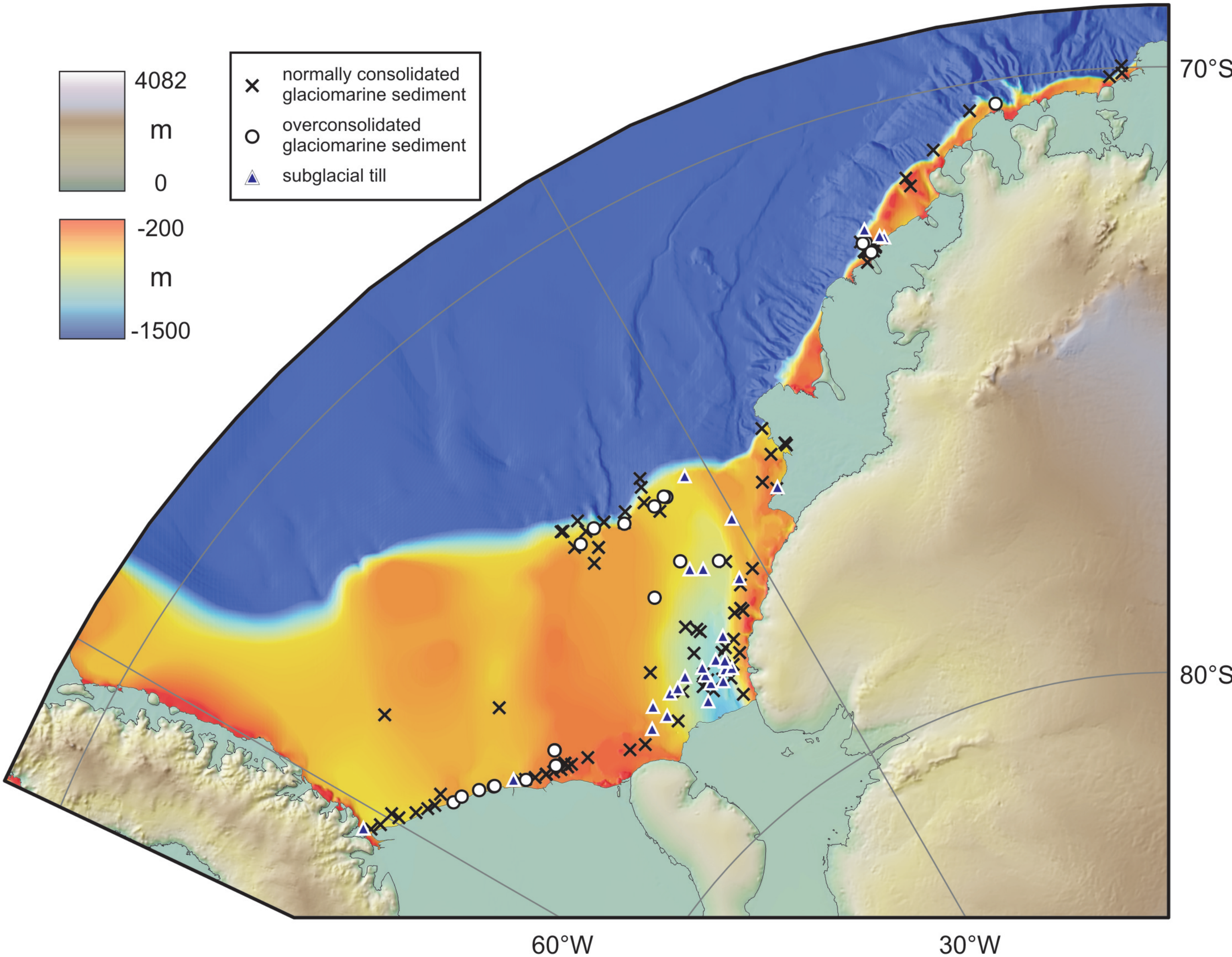
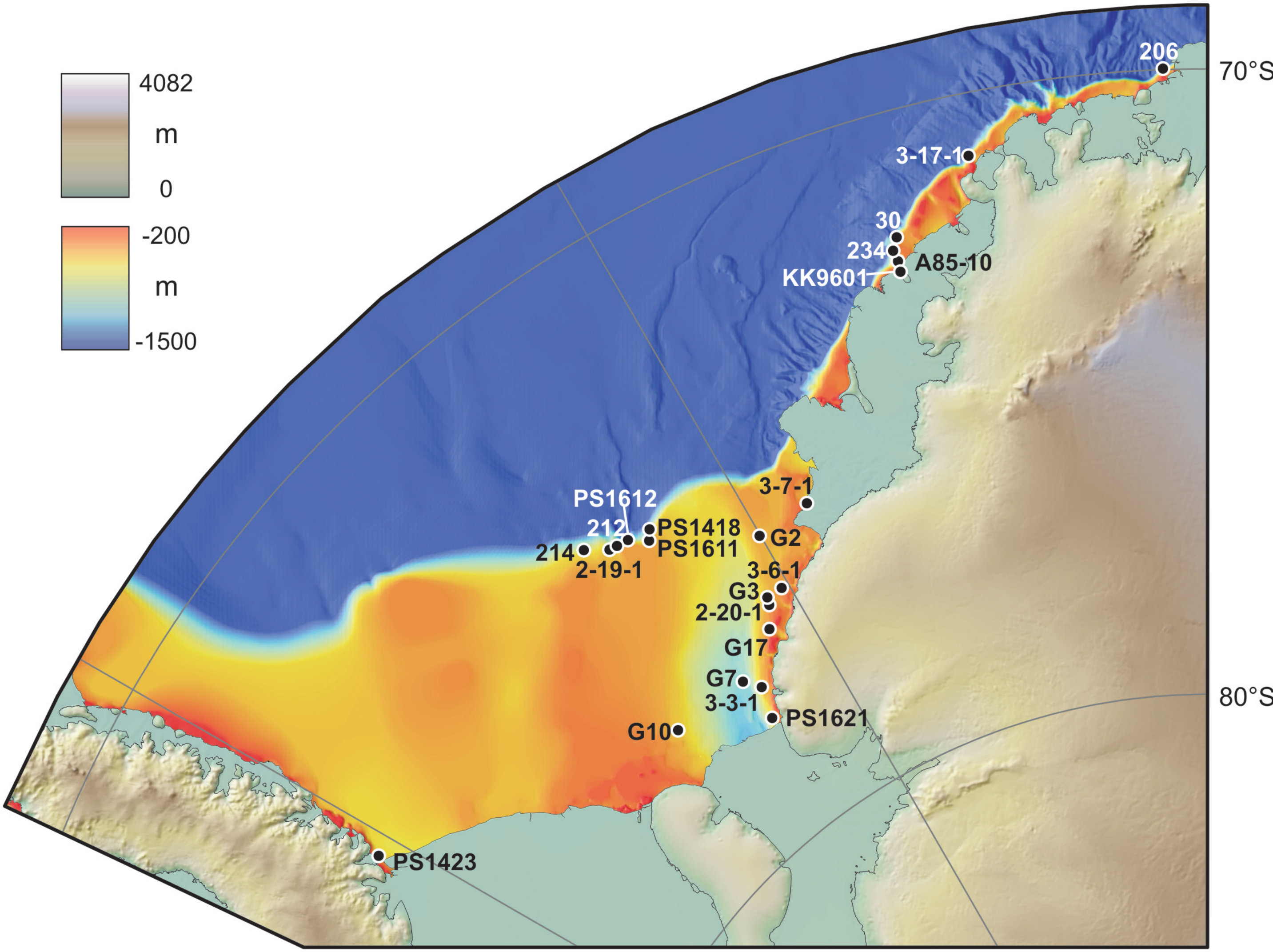

4082
m
0
-200
m
-1500
normally consolidated glaciomarine sediment
overconsolidated glaciomarine sediment
subglacial till
70°S
80°S
60°W
30°W

Fig. 4



4082
m
0
-200
m
-1500
206
70°S
3-17-1
30
234
A85-10
KK9601
3-7-1
PS1612
212
PS1418
G2
214
PS1611
2-19-1
3-6-1
G3
2-20-1
G17
G7
3-3-1
PS1621
80°S
G10
PS1423
60°W
30°W

Fig. 5a)

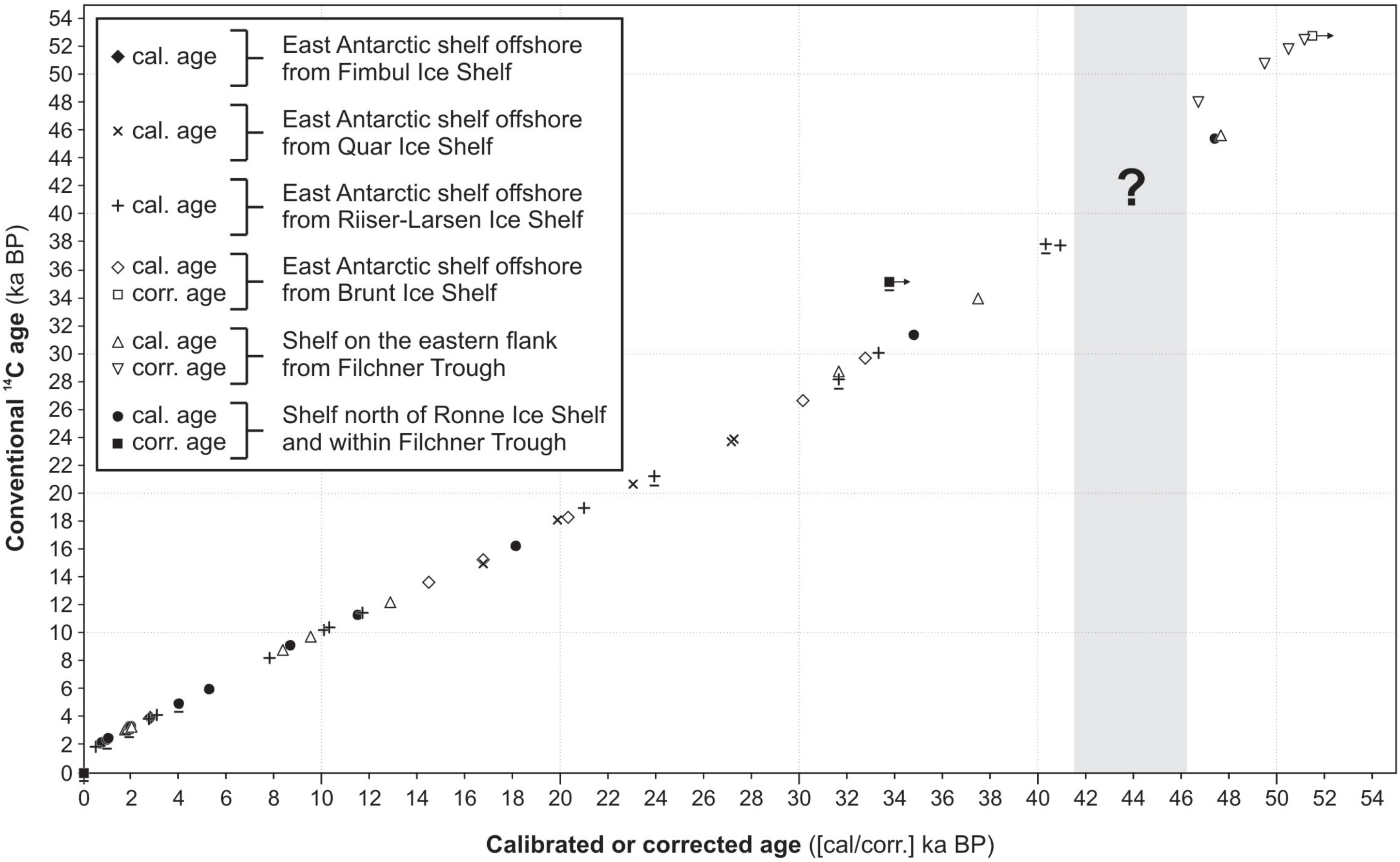

Conventional ^{14}C age (ka BP)
Calibrated or corrected age ([cal/corr.] ka BP)
cal. age
East Antarctic shelf offshore from Fimbul Ice Shelf
cal. age
East Antarctic shelf offshore from Quar Ice Shelf
cal. age
East Antarctic shelf offshore from Riiser-Larsen Ice Shelf
cal. age
corr. age
East Antarctic shelf offshore from Brunt Ice Shelf
cal. age
corr. age
Shelf on the eastern flank from Filchner Trough
cal. age
corr. age
Shelf north of Ronne Ice Shelf and within Filchner Trough
?

Fig. 5b)

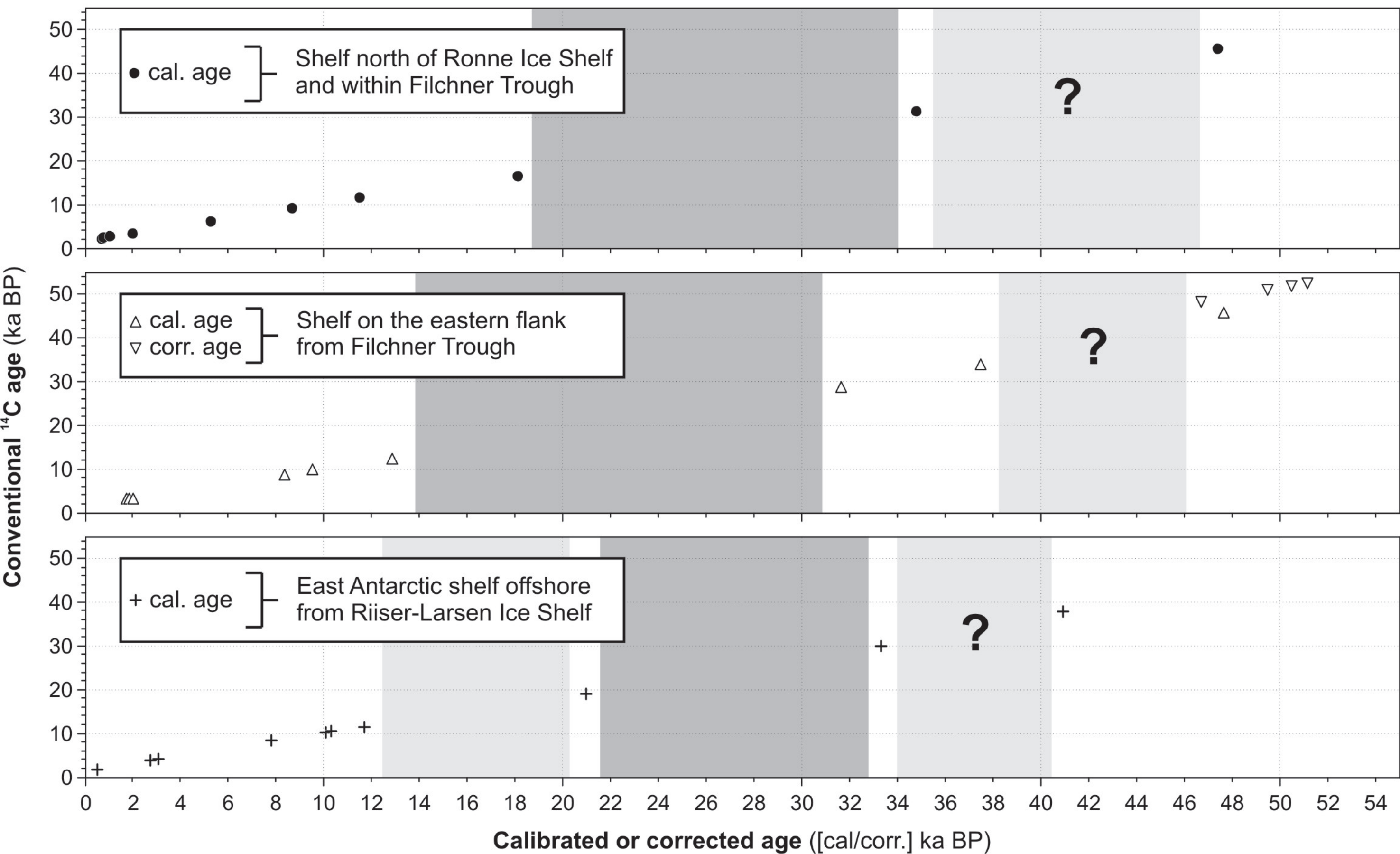
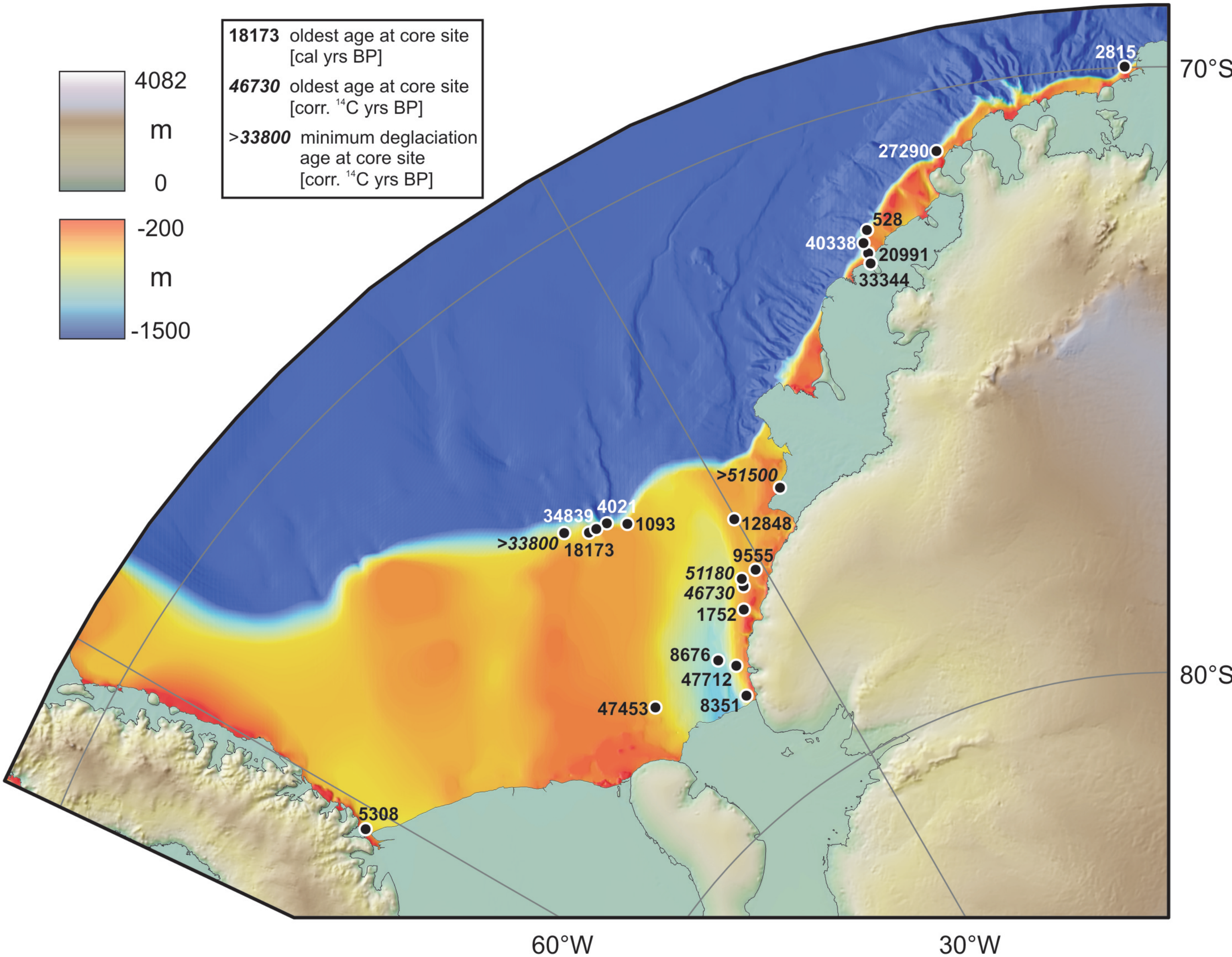

Conventional ^{14}C age (ka BP)
Calibrated or corrected age ([cal/corr.] ka BP)
cal. age
Shelf north of Ronne Ice Shelf and within Filchner Trough
cal. age
corr. age
Shelf on the eastern flank from Filchner Trough
cal. age
East Antarctic shelf offshore from Riiser-Larsen Ice Shelf
?

Fig. 6



4082
m
0
-200
m
-1500
18173 oldest age at core site [cal yrs BP]
46730 oldest age at core site [corr. 14C yrs BP]
>33800 minimum deglaciation age at core site [corr. 14C yrs BP]
70°S
80°S
60°W
30°W
2815
27290
528
40338
20991
33344
>51500
12848
34839
4021
1093
>33800
18173
9555
51180
46730
1752
8676
47712
8351
47453
5308

Fig. 7

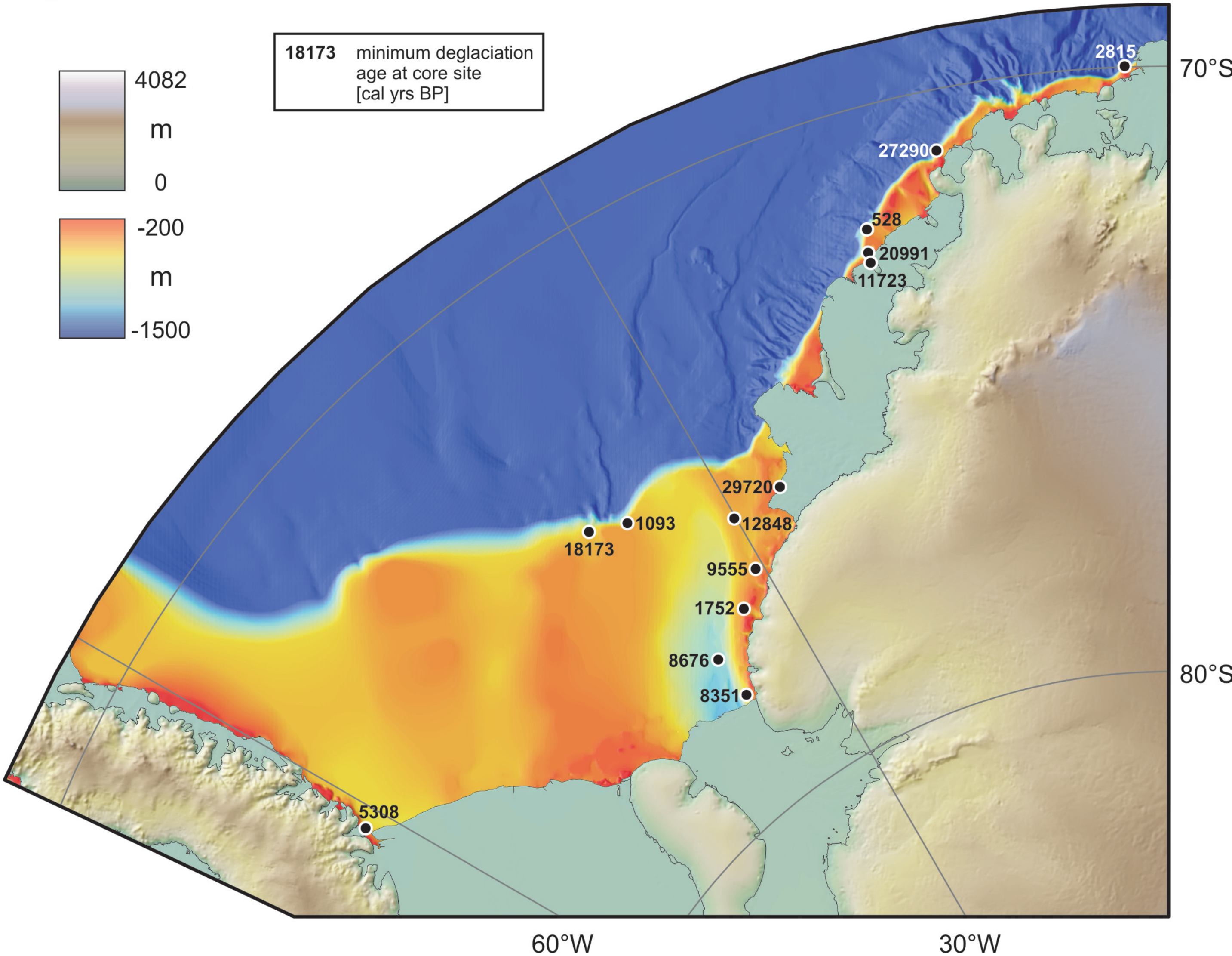

4082
m
0
-200
m
-1500
18173 minimum deglaciation age at core site [cal yrs BP]
2815
27290
528
20991
11723
29720
1093
12848
18173
9555
1752
8676
8351
5308
70°S
80°S
60°W
30°W

Fig 8

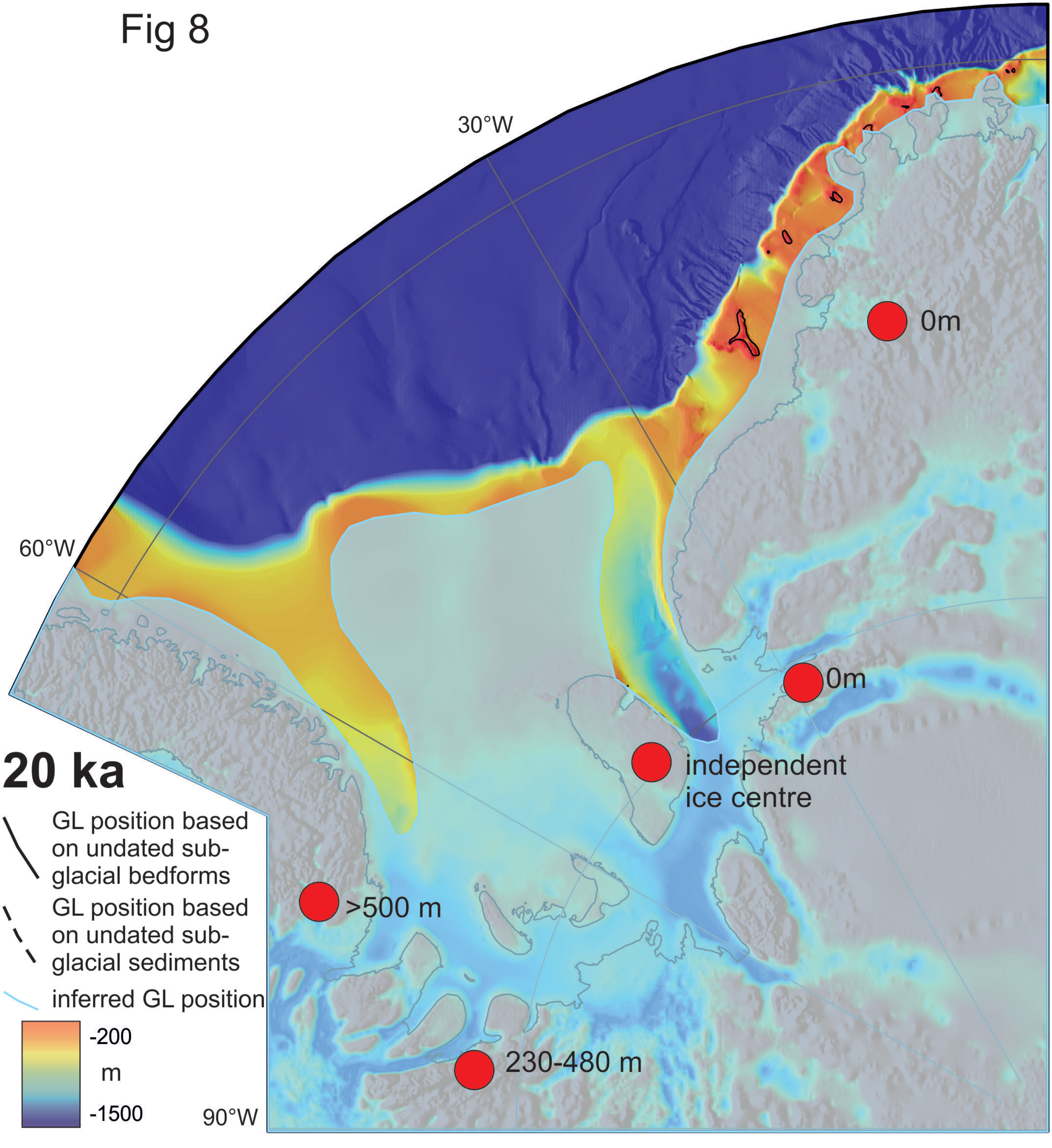
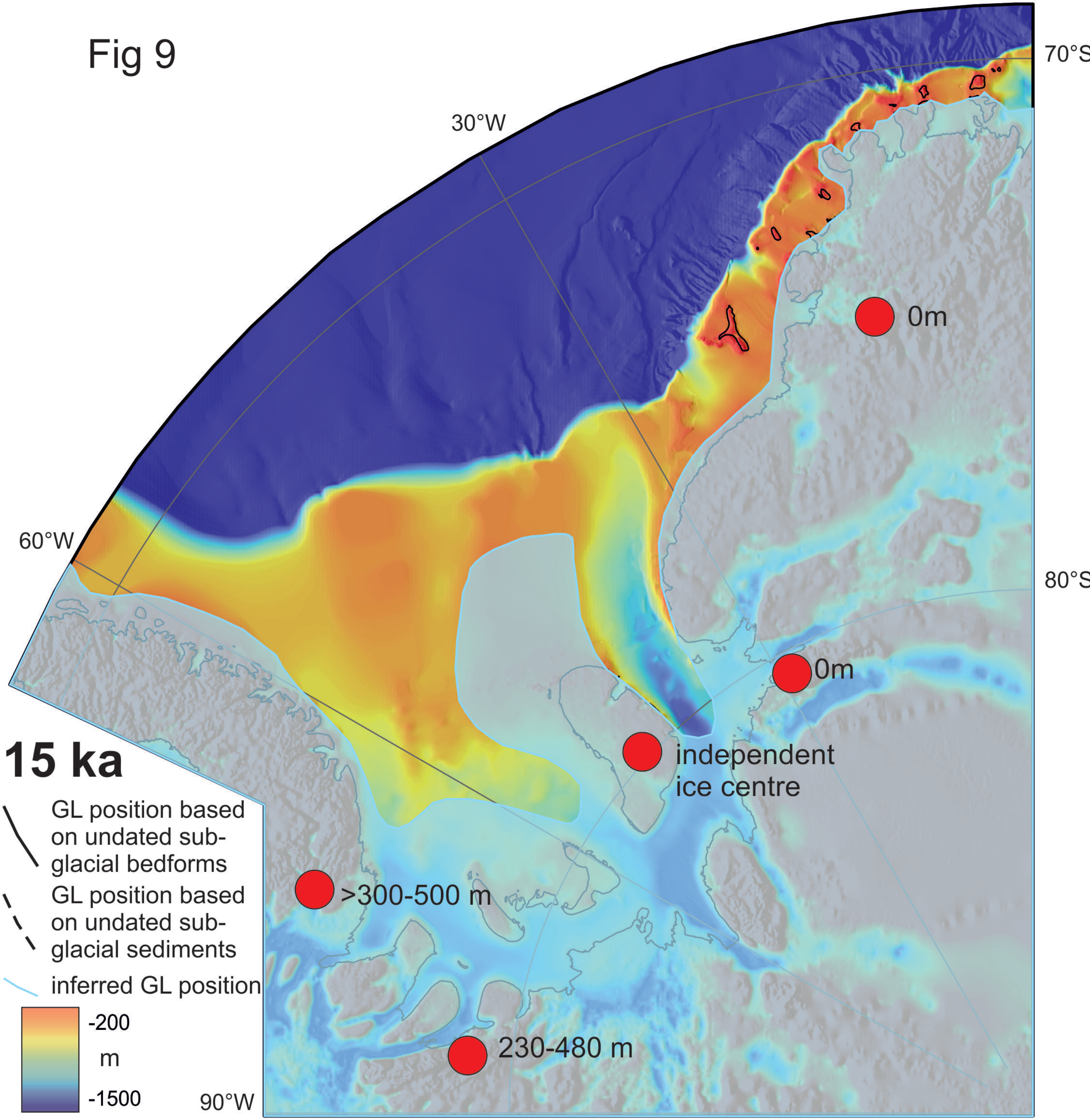
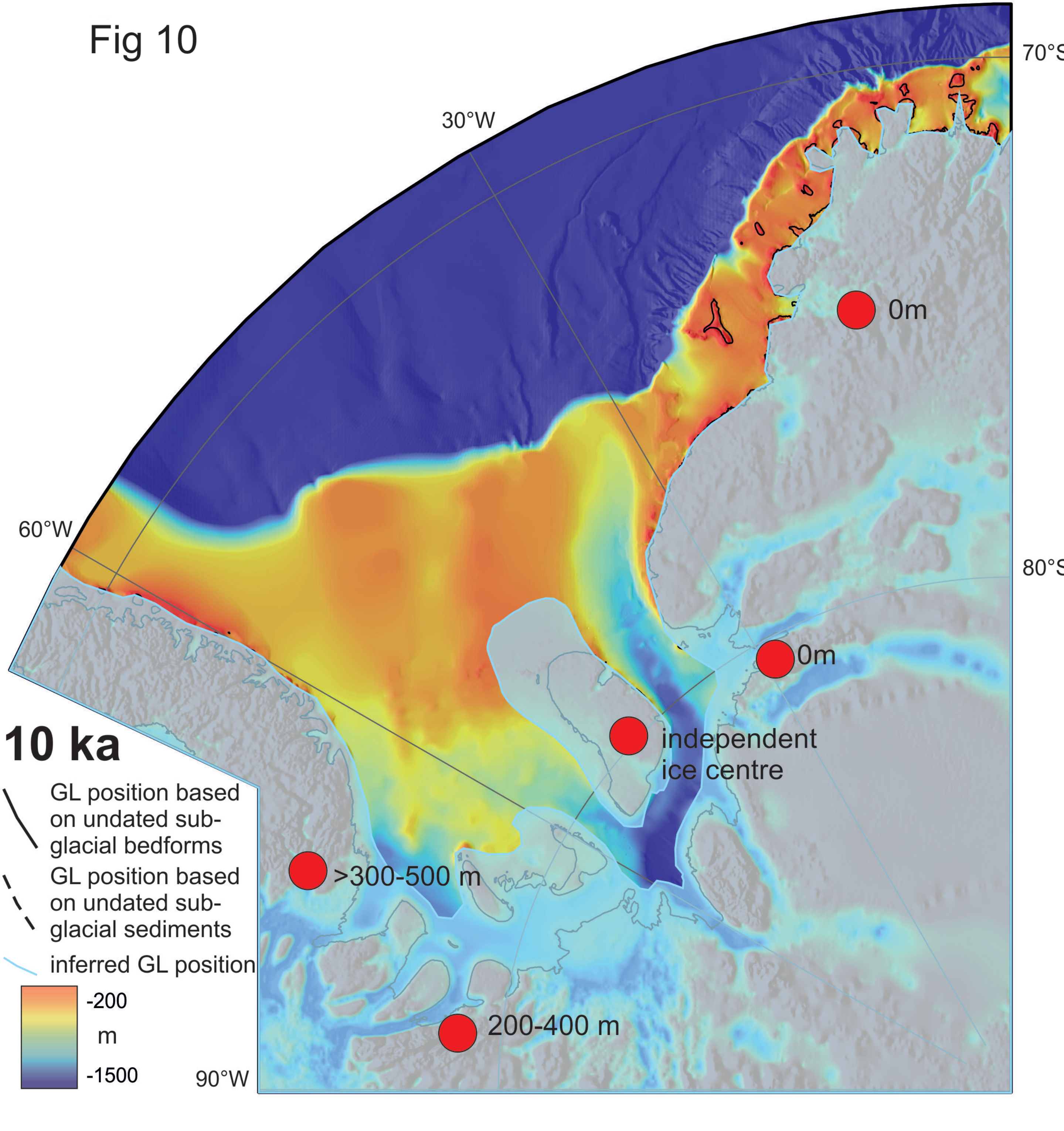

70°S
30°W
60°W
80°S
90°W
0m
0m
independent ice centre
>500 m
230-480 m
20 ka
GL position based on undated sub-glacial bedforms
GL position based on undated sub-glacial sediments
inferred GL position
-200
m
-1500

Fig 9



70°S
30°W
60°W
80°S
90°W
0m
0m
independent ice centre
>300-500 m
230-480 m
15 ka
GL position based on undated sub-glacial bedforms
GL position based on undated sub-glacial sediments
inferred GL position
-200
m
-1500

Fig 10



70°S
30°W
0m
60°W
80°S
0m
independent
ice centre
10 ka
GL position based
on undated sub-
glacial bedforms
>300-500 m
GL position based
on undated sub-
glacial sediments
inferred GL position
-200
m
200-400 m
-1500
90°W

Fig 11

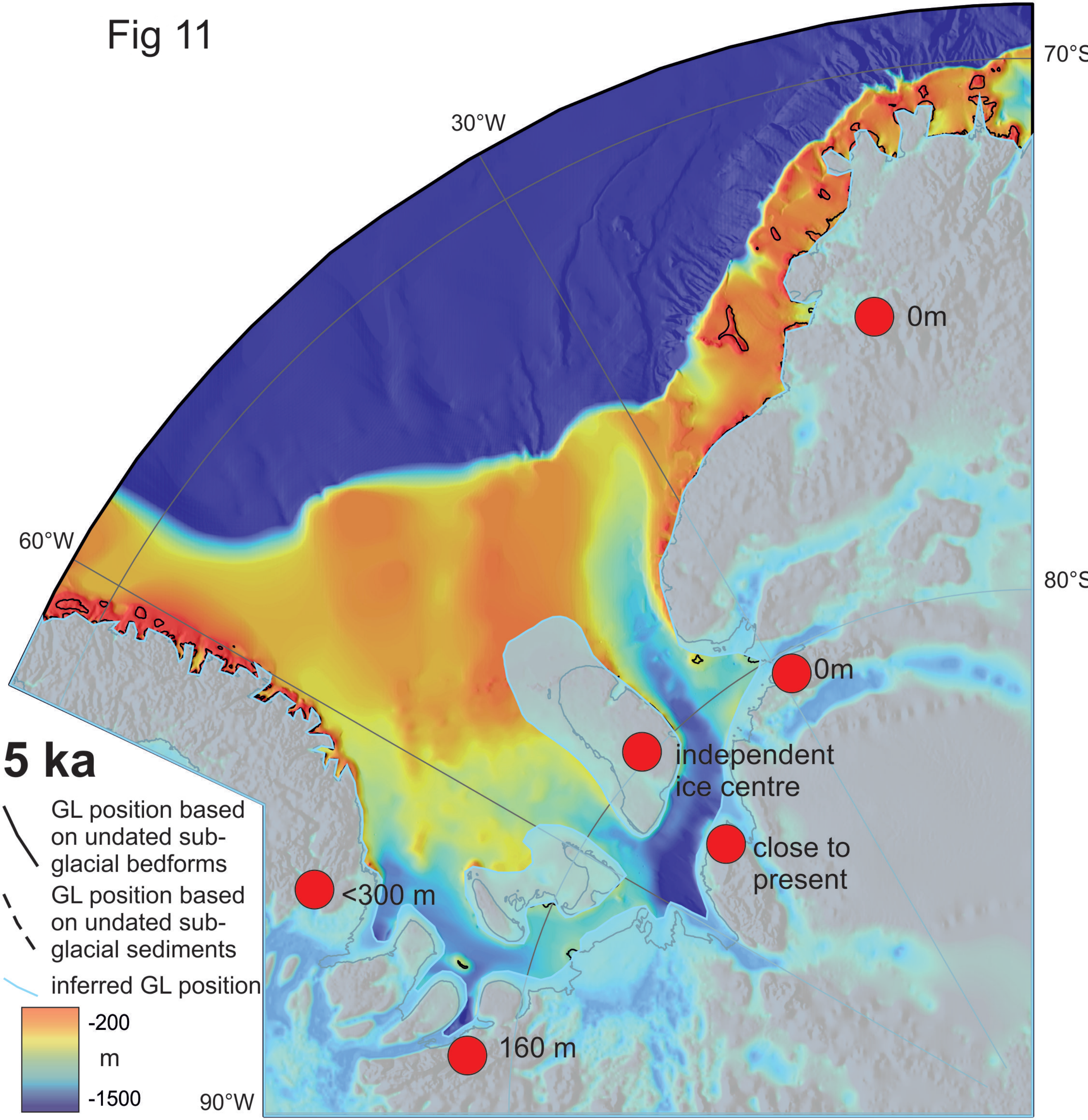

70°S
30°W
0m
60°W
80°S
0m
independent ice centre
5 ka
GL position based on undated sub-glacial bedforms
close to present
<300 m
GL position based on undated sub-glacial sediments
inferred GL position
-200
m
-1500
160 m
90°W

Fig. 12

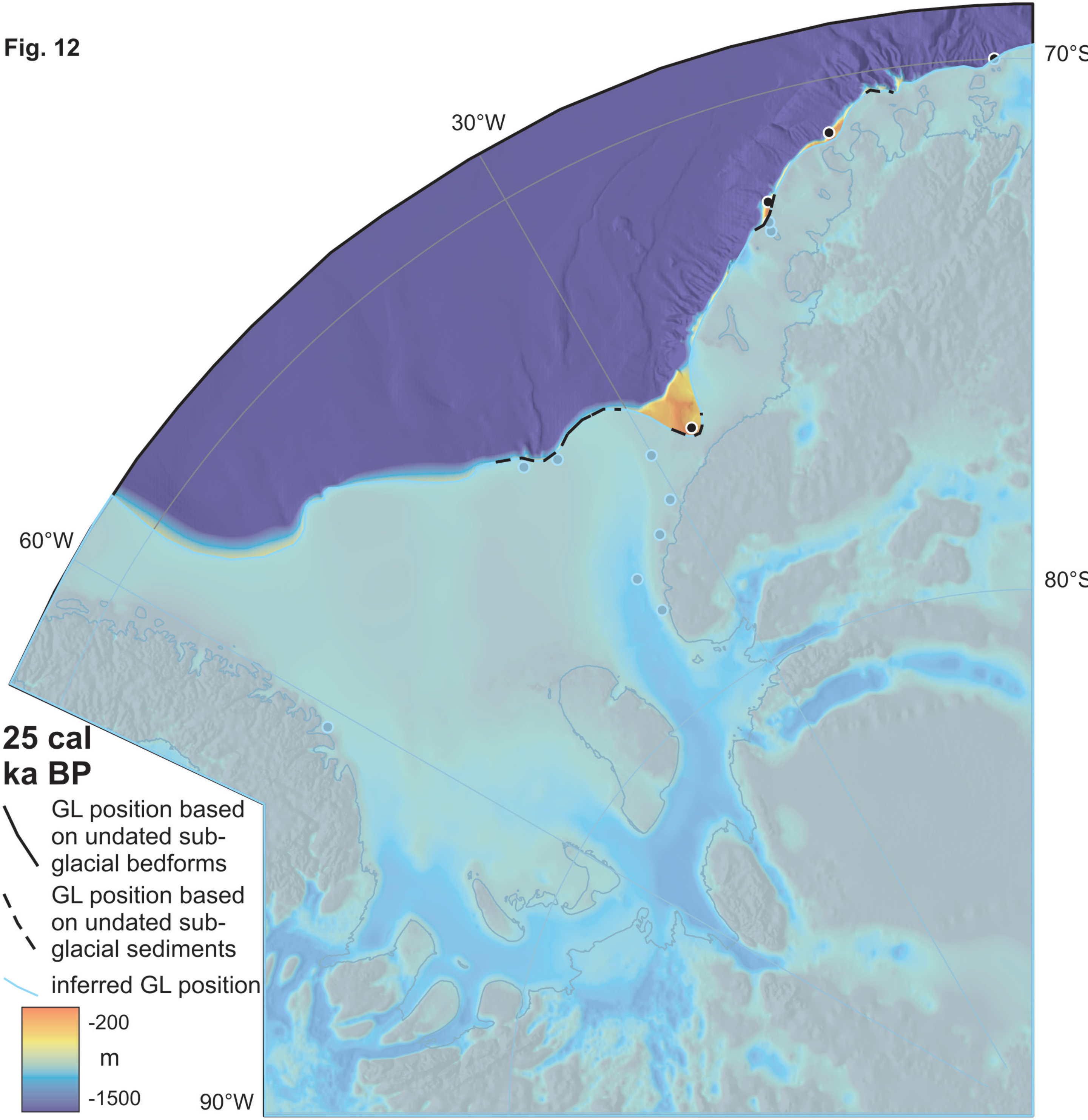
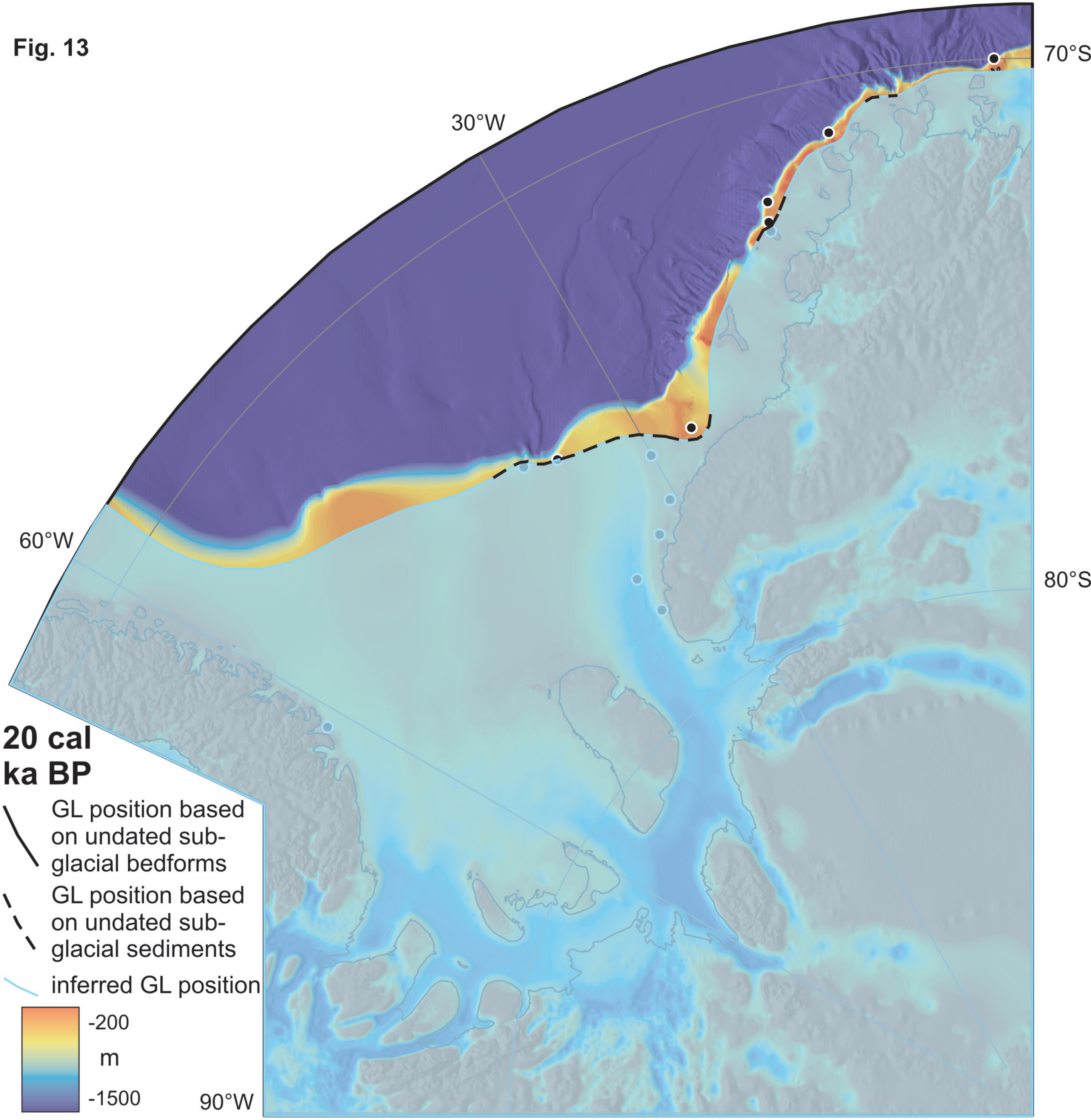

30°W
70°S
60°W
80°S
90°W
25 cal ka BP
GL position based on undated sub-glacial bedforms
GL position based on undated sub-glacial sediments
inferred GL position
-200
m
-1500

Fig. 13



70°S
30°W
60°W
80°S
90°W
20 cal ka BP
GL position based on undated sub-glacial bedforms
GL position based on undated sub-glacial sediments
inferred GL position
-200
m
-1500

Fig. 14

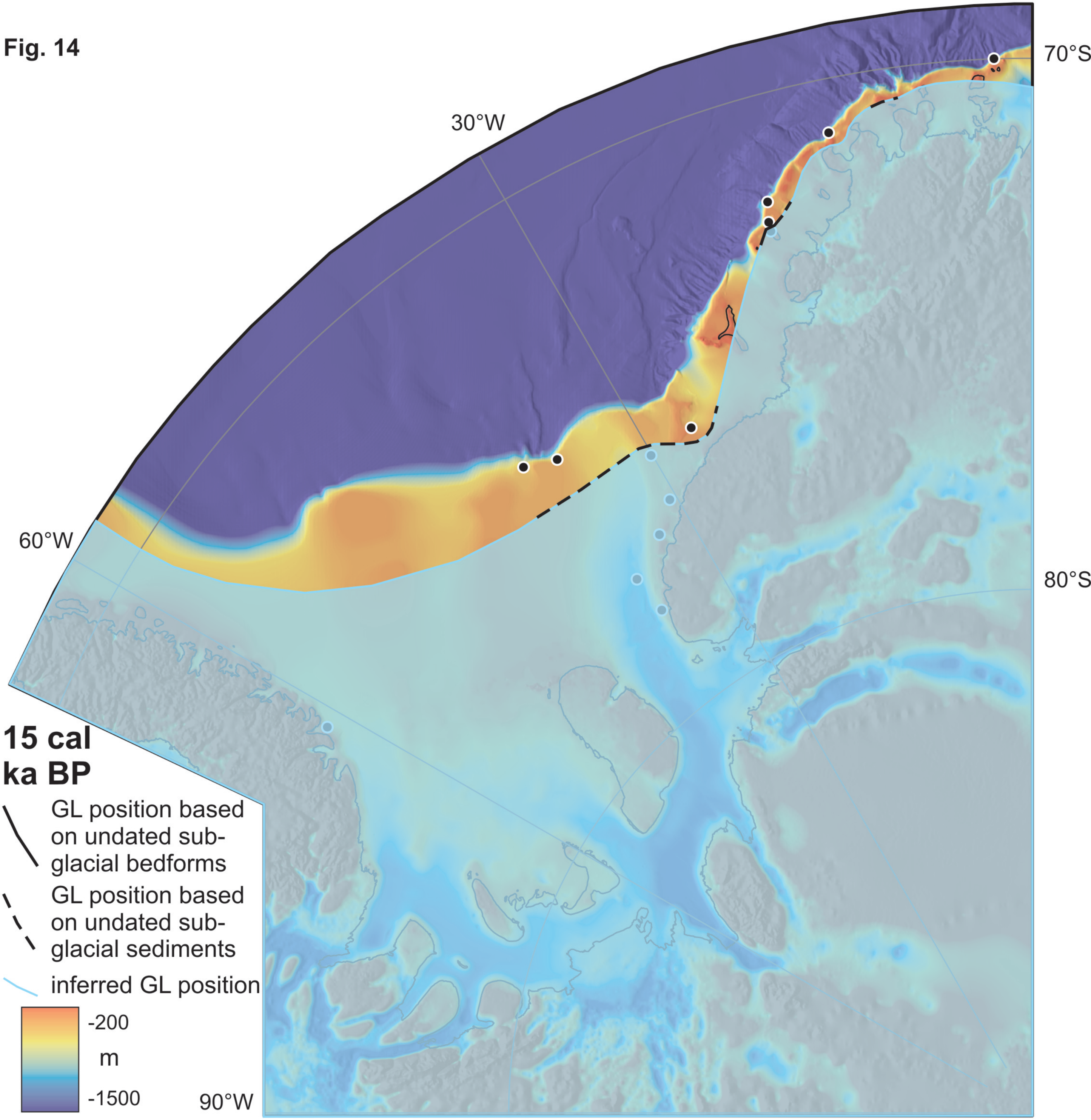
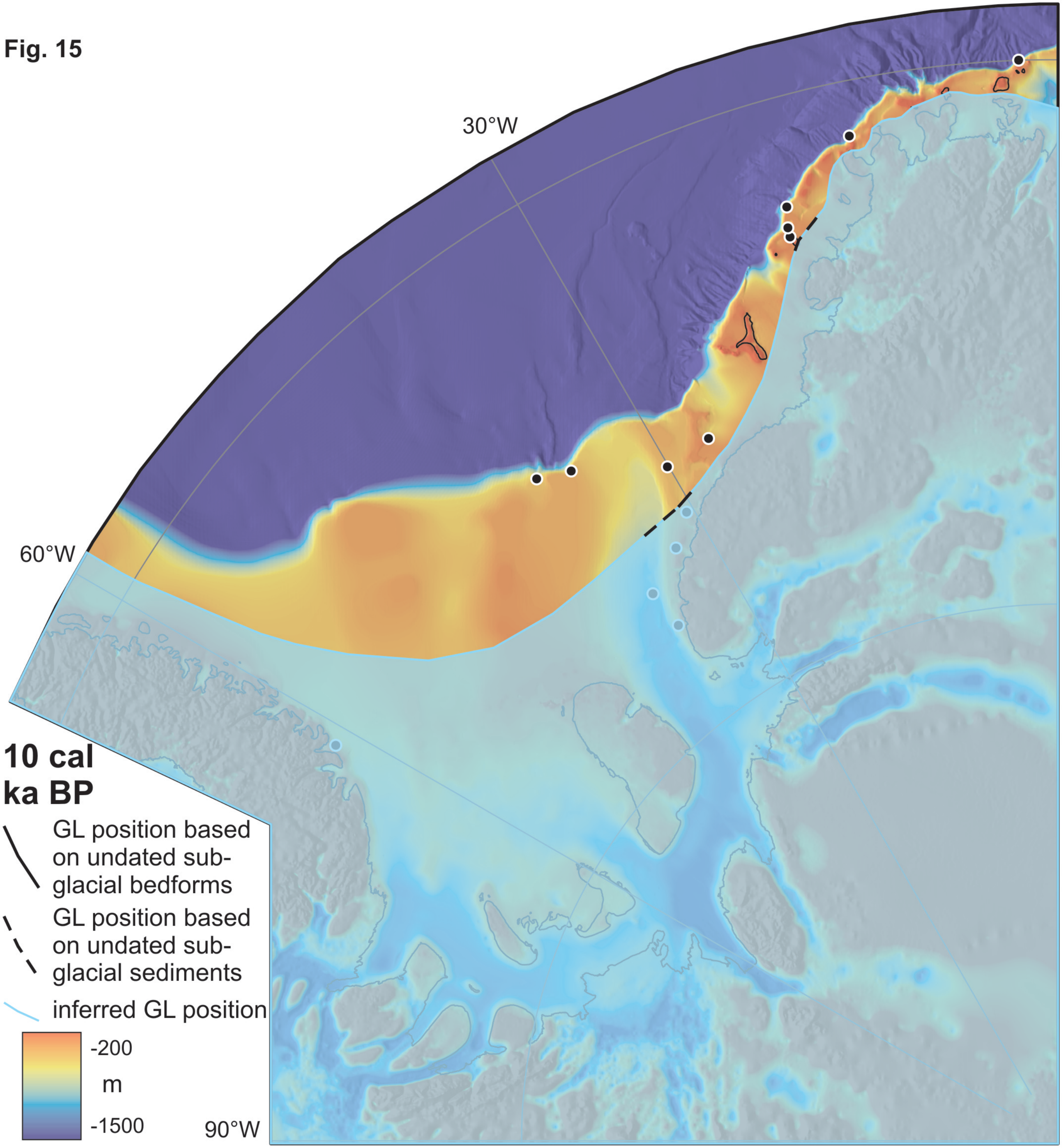
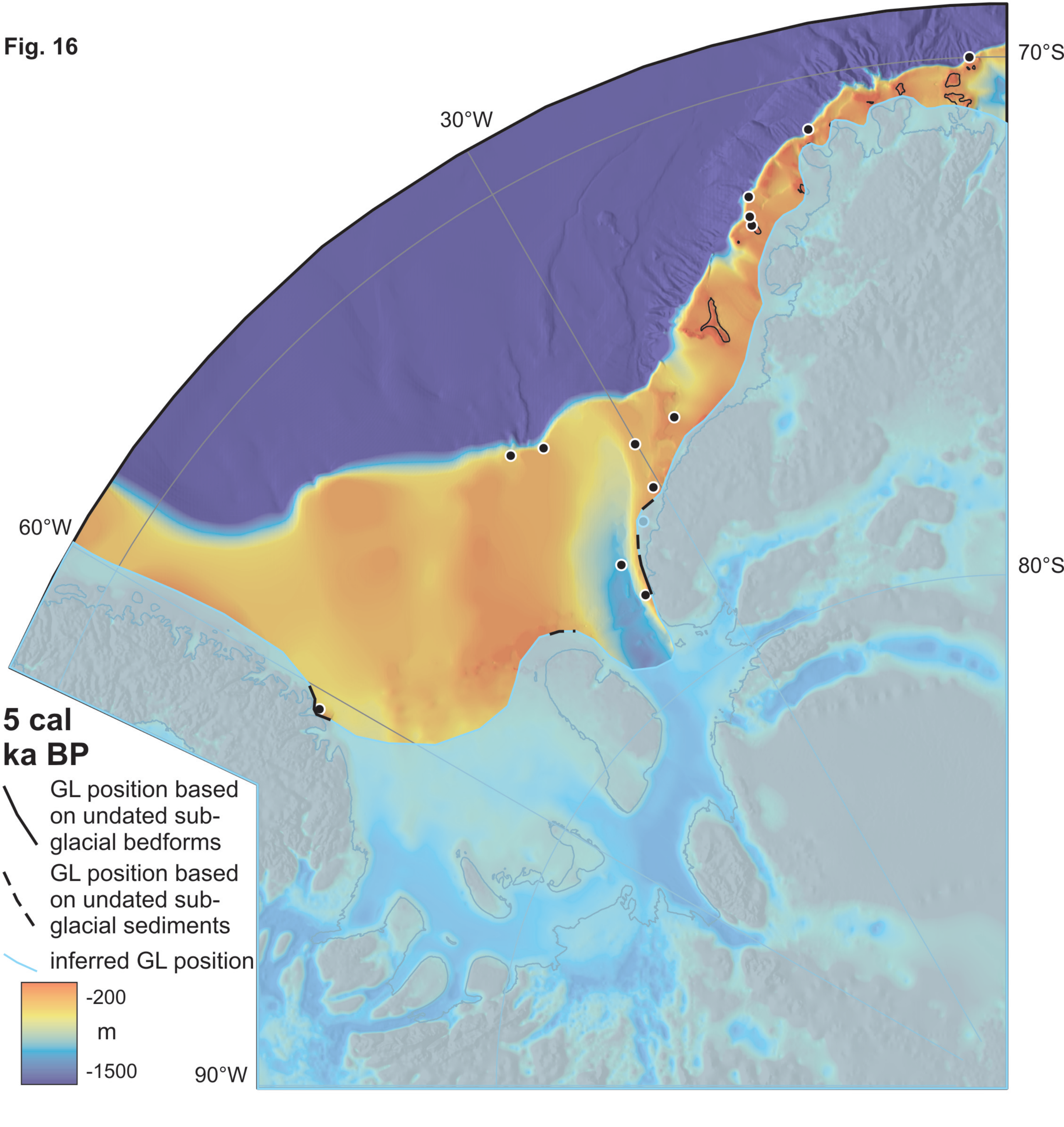

30°W
70°S
60°W
80°S
90°W
15 cal ka BP
GL position based on undated sub-glacial bedforms
GL position based on undated sub-glacial sediments
inferred GL position
-200
m
-1500

Fig. 15



30°W
70°S
60°W
80°S
90°W
10 cal ka BP
GL position based on undated sub-glacial bedforms
GL position based on undated sub-glacial sediments
inferred GL position
-200
m
-1500

Fig. 16



70°S
30°W
60°W
80°S
90°W
5 cal ka BP
GL position based on undated sub-glacial bedforms
GL position based on undated sub-glacial sediments
inferred GL position
-200
m
-1500