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A community-based geological reconstruction of Antarctic Ice Sheet deglaciation since the Last Glacial Maximum

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[1] RAISED = Reconstruction of Antarctic Ice Sheet Deglaciation.

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ABSTRACT

A robust understanding of Antarctic Ice Sheet deglacial history since the Last Glacial Maximum is important in order to constrain ice sheet and glacial-isostatic adjustment models, and to explore the forcing mechanisms responsible for ice sheet retreat. Such understanding can be derived from a broad range of geological and glaciological datasets and recent decades have seen an upsurge in such data gathering around the continent and Sub-Antarctic islands. Here, we report a new synthesis of those datasets, based on an accompanying series of reviews of the geological data, organised by sector. We present a series of timeslice maps for 20 ka, 15 ka, 10 ka and 5 ka, including grounding line position and ice sheet thickness changes, along with a clear assessment of levels of confidence. The reconstruction shows that the Antarctic Ice sheet did not everywhere reach the continental shelf edge at its maximum, that initial retreat was asynchronous, and that the spatial pattern of deglaciation was highly variable, particularly on the inner shelf. The deglacial reconstruction is consistent with a moderate overall excess ice volume and with a relatively small Antarctic contribution to meltwater pulse 1a. We discuss key areas of uncertainty both around the continent and by time interval, and we highlight potential priorities for future work. The synthesis is intended to be a resource for the modelling and glacial geological community.

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1. Aim and rationale

This paper provides an overview of, and introduction to, a community-based reconstruction of the deglaciation of the Antarctic Ice Sheet. Reconstructing the Antarctic Ice Sheet through its most recent (post-Last Glacial Maximum; LGM) deglacial history is important for a number of reasons (Bentley, 2010). Firstly, ice sheet modellers require field data against which to constrain and test their models of ice sheet change. The development of a practical approach to modelling grounding line dynamics (Schoof, 2007) has led to a new generation of models (e.g. Pollard and DeConto, 2009; Pattyn et al., 2012) that require such field constraints. Secondly, the most recent millennia of Antarctic Ice Sheet history are important for evaluating the response of the ice sheet to various forcing agents (e.g. sea-level rise, atmospheric and oceanographic temperature influences) and constraining past rates of grounding-line retreat. Thirdly, the use of recent satellite gravity measurements (e.g. GRACE), and other geodetic data such as GPS, for estimating ice-sheet mass balance requires an understanding of Glacial-Isostatic Adjustment (GIA). In the case of GRACE, the satellite-pair cannot distinguish between changes in mass from ice, and those from transfer of mass in the mantle. This means that robust ice-sheet reconstructions are required to generate GIA corrections and it is these corrections that are regarded as the greatest limiting factors for gravimetric estimates of ice-sheet mass balance (Chen et al., 2006; Velicogna and Wahr, 2013). There have been notable attempts to develop models of ice-sheet extent and thickness as a basis of GIA corrections (Ivins and James, 2005; Whitehouse et al., 2012a; Ivins et al., 2013) but it is not clear if these are comprehensive in their inclusion of all available marine and terrestrial glacial geological data. In addition, ice-sheet reconstructions are also important for constraining the location of biological refugia during glaciation (Convey et al., 2008) and understanding climatic and oceanographic change during the glacial–interglacial transition.

Several decades of work have produced a large body of geological data constraining Antarctic Ice Sheet history. There have been a number of attempts to synthesise the data but many of these reconstructions have focussed only on LGM ice-sheet extent (Denton and Hughes, 1981; Anderson, 1999; Bentley, 1999; Anderson et al., 2002; Denton and Hughes, 2002; Wright et al., 2008; Livingstone et al., 2012) and in some places they have been superseded by new datasets. Importantly, the period between the LGM and present has not seen similar attention. Moreover, significant progress has been made in developing and refining the methods used to acquire and analyse data needed for terrestrial and marine records of past ice-sheet thickness and extent (e.g. mapping of subglacial bedforms on the continental shelf using multibeam-swath bathymetry). Many of these new datasets that have been acquired have yet to be incorporated into continent-wide reconstructions of the ice sheet.

The glacial geological literature is widely dispersed across journals and reports ('grey' literature), covers a broad range of techniques, is presented in many different formats, and is subject to various uncertainties (especially dating) that may be subtle, and have changed over time as techniques and understanding have developed. Understandably, therefore, it can be difficult for modellers to penetrate and use this literature to constrain and test their models.

This volume contains results from a co-ordinated effort by the Antarctic glacial geology community to develop a synthesis of Antarctic ice-sheet history and to create a series of ice-sheet reconstructions that can be used by ice sheet and GIA modellers. It should also foster further research and debate within the geological community on the progress made in understanding Antarctic Ice Sheet history. Other ice sheet communities have already completed such syntheses, including the Laurentide (Dyke et al., 2002), the Fennoscandian (Gyllencreutz et al., 2007), and the British-Irish (Clark et al., 2012) ice sheets.

The RAISED consortium comprises a wide community of glacial and marine geologists and others working on ice sheet history. Collectively we have assembled a group of experts able to develop and document a series of reconstructions for each of the sectors around Antarctica, and drawn these together into a synthesis that we believe is comprehensive, provides realistic assessment of uncertainty and is broadly representative of the views of the whole community, and which can be used by modellers.

The detailed reviews are divided into six sectors: East Antarctica (Mackintosh et al., 2014), Ross Sea (Anderson et al., 2014), Amundsen-Bellingshausen Sea (Larter et al., 2014), Antarctic Peninsula (Ó Cofaigh et al., 2014), Weddell Sea (Hillenbrand et al., 2014) and sub-Antarctic Islands (Hodgson et al., 2014). The approximate sector boundaries are shown in Fig. 1. The divisions are based broadly on glaciological and topographic grounds. Most sectors are named by coastal sector because much of the data comes from the continental shelf or coastal nunataks, but sectors also extend inland to encompass relevant ice-core data, where available. The sector division we have used is also fairly compatible with earlier divisions of the continent by modellers, glaciologists, and field studies and so should facilitate broad comparison.

This overview paper summarises these sector-by-sector reviews and presents an Antarctic-wide reconstruction of deglaciation since the LGM. We also discuss the common themes that emerge, and identify key areas for further work. We emphasise that anyone wishing to utilise any part of the reconstruction is strongly advised to read the relevant sector papers, which include much more detail including extended discussions of where and why there are key uncertainties.

2. Approach and Methods

For all sectors we have attempted, where possible, to provide reconstructions of the ice sheet (with clear identification of the range of uncertainty) for a series of timeslices, namely 20 ka, 15 ka, 10 ka, and 5 ka. In some sectors the available data are not sufficient to allow this classification: these are discussed further below. In a few sectors data availability was sufficient to allow a further timeslice of 25 ka: these are discussed in the relevant papers. The timeslices were chosen to strike a balance between the reality of available data, and providing sufficient closely-spaced reconstructions for them to be useful to modellers, as well as to provide reconstructions of time periods other than the maximum. A spacing of 5 ka was chosen to provide a reasonable compromise between data availability and the needs of modellers. The use of *dated* timeslices also has the advantage of avoiding terms like 'the LGM', which has been used rather variably both to refer to local ice-sheet maxima, and as a global chronostratigraphic term to refer to the period c. 26.5–19 ka BP (see Clark et al., 2009 for discussion). This has led to some confusion in ice-sheet syntheses. Whilst the 20 ka timeslice can be a useful rough proxy for the global LGM, it is clear from Anderson et al. (2002) and this volume that the Antarctic Ice Sheets did not reach a synchronous maximum extent, and that Local Last Glacial Maximum (LLGM; (Clark et al., 2009)) positions differ widely in timing.

Each paper in this volume synthesises the available marine and terrestrial glacial geological datasets to determine the position of the ice-sheet grounding-line, the ice-sheet upper surface, and in some cases flow-directional features for that particular sector and timeslice. We have made considerable efforts to be clear about uncertainty in the position and timing of retreat of the grounding-line and, as such, it is intended to demonstrate where there are robust constraints for models as opposed to geographic areas or time intervals where the position of the grounding-line or ice-sheet surface is less certain. There are a number of challenges associated with dating the geological evidence of deglaciation around Antarctica: offshore this includes the marine-reservoir effect, and reworking of old carbon, and onshore the reworking of previously exposed erratics presents problems for cosmogenic dating. These uncertainties are assessed in full in each of the sector papers. The use of timeslices also allows future development of more closely-spaced reconstructions, as available datasets expand to address specific debates. In cases where there are time intervals that are unusually data-rich it will be possible to develop new timeslice reconstructions. This may be particularly appropriate for intervals during the immediate post-maximum deglaciation where there is often much more marine geological data available.

2.1. Availability of data

Each of the sector reviews provides substantial datasets identifying critical chronological data that have been used to constrain the reconstructions – these are available online as supplementary datasets. We also include here, as a supplementary dataset, the Antarctic-wide timeslice reconstructions of grounding-line and ice-sheet surface (Supplementary Information). We emphasise that any use of the data should rest on careful reading, and citation, of the appropriate individual sector paper(s): these are where critical issues of dating uncertainties and calibration, alternative models and other issues are discussed in detail.

3. Reconstructions

We show the combined reconstructions for each timeslice in Fig. 2. Around the West Antarctic margin and those parts of the East Antarctic Ice Sheet (EAIS) that flow into the Ross Sea and Weddell Sea the available data allow timeslice reconstructions of 20 ka, 15 ka, 10 ka, and 5 ka (Fig. 2a–d). Note that, due to a lack of constraining data around much of the East Antarctic margin and in particular a lack of dating control, we are unable yet to attempt a full time-slice reconstruction of the deglaciation of the largest part of the EAIS (Mackintosh et al., 2014). However, this does not mean

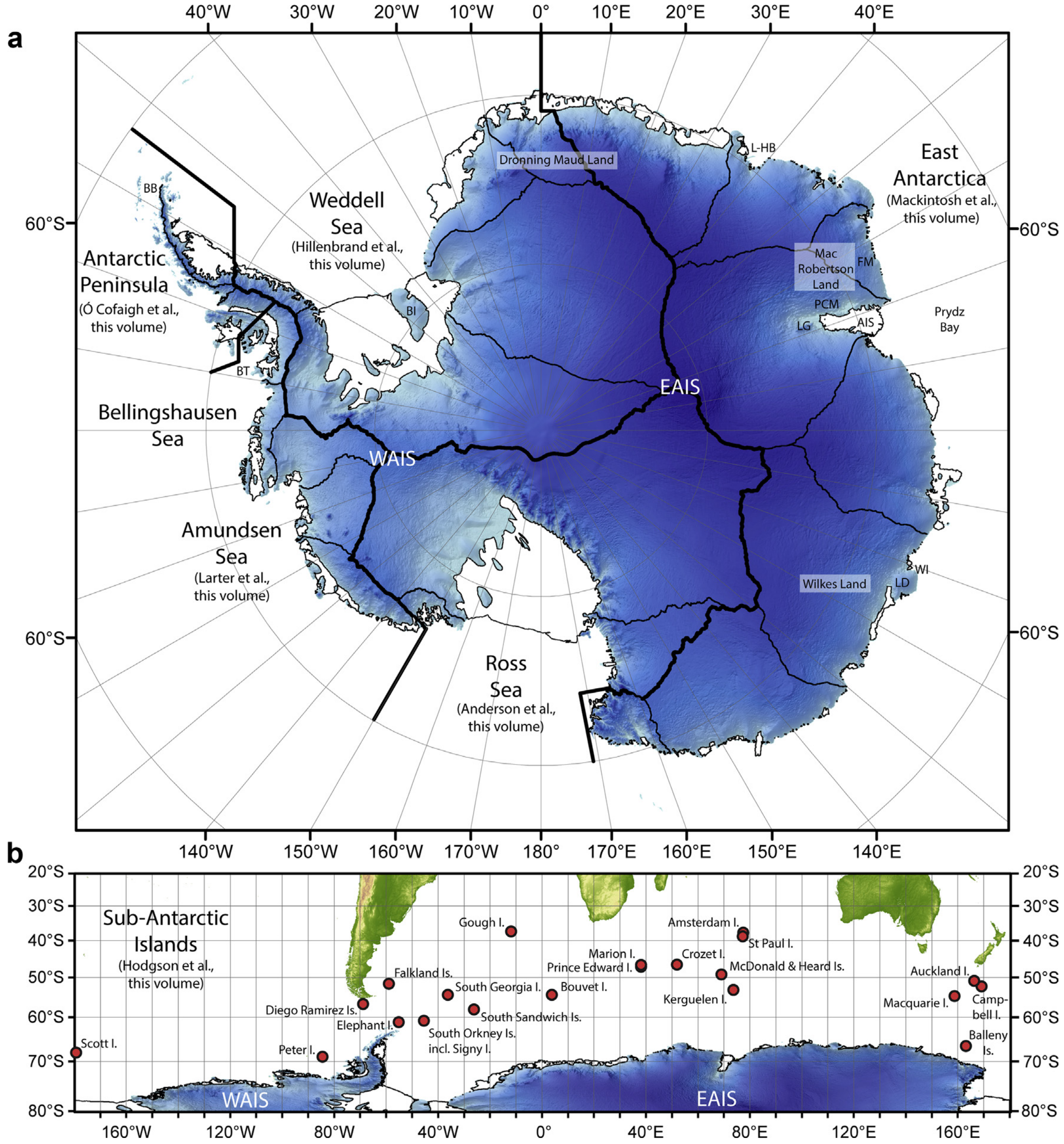

Fig. 1. Map of sector boundaries for the reconstructions presented in this volume. (a) Map of Antarctica. Blue shading indicates ice sheet elevation, ice shelves in white. Ice divides based on Zwally et al. (2012). EAIS = East Antarctic Ice Sheet; WAIS = West Antarctic Ice Sheet; L-HB = Lützow-Holm Bay; FM = Framnes Mountains; PCM = Prince Charles Mountains; LG = Lambert Glacier; AIS = Amery Ice Shelf; WI = Windmill Islands; LD = Law Dome; BT = Belgica Trough; BB = Bransfield Basin; BI = Berkner Island. (b) Map of sites (red dots) included in the review of sub-Antarctic islands (Hodgson et al., 2014).

that no constraints are possible. Accordingly, we include the EAIS in the 20 ka timeslice (Fig. 2a) with ice sheet thickness changes in this sector from Mackintosh et al. (2014), and a grounding line position based on Livingstone et al. (2012), but modified to be fully consistent with grounding-line features described by Mackintosh et al. (2014) in Prydz Bay and George V Shelf. Moreover, Mackintosh et al. (2014) discuss the data in great detail region-by-region around the East Antarctic margin, including areas such as Mac. Robertson Land and adjacent to the Lambert/Amery system where robust constraints do exist. For the sub-Antarctic islands there are data available for maximum configurations of the ice masses over some islands, but there are few data for subsequent periods and so we are not yet in a position to provide timeslice reconstructions for deglacial configurations (see Hodgson et al. (2014) for full discussion).

3.1. 20 ka timeslice

Around much of Antarctica the grounding line was close to the continental shelf break at 20 ka. However, there are important exceptions in the Ross Sea, Prydz Bay, and Weddell Sea regions. Moreover, in some areas the maximum extent was reached prior to 20 ka and retreat had begun by this time (e.g. Hillenbrand et al., 2014).

There is an ongoing debate about the extent of ice in the Weddell Sea at the LGM, and the post-LGM retreat history (Hillenbrand et al., 2014). In broad terms, the available marine geological data in the Weddell Sea have been interpreted as showing extensive ice on the continental shelf at 20 ka. However, data are sparse in the southern Weddell Sea where the confluence of ice flowing from the East Antarctic and West Antarctic Ice Sheets occurred. In this

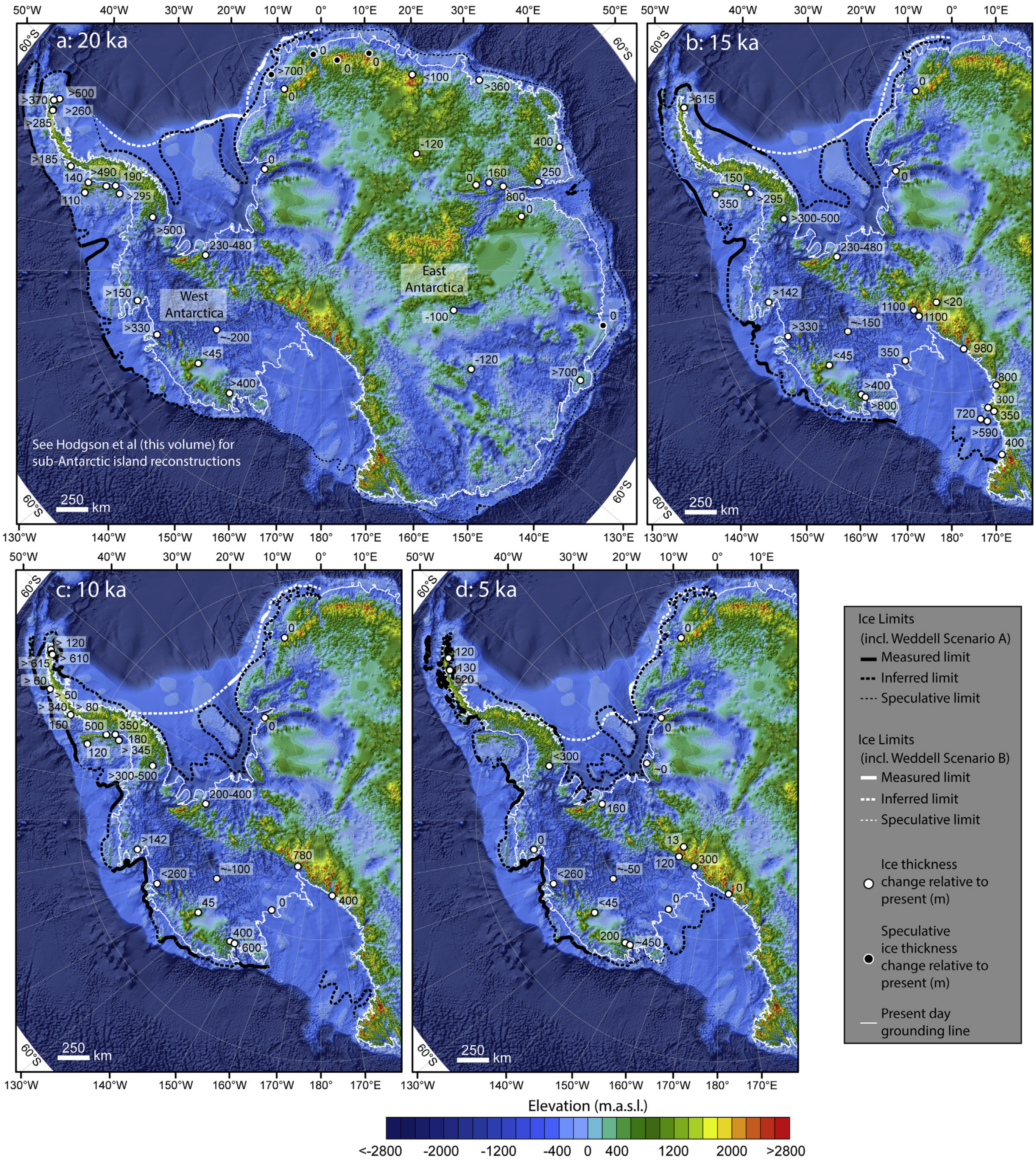

Fig. 2. Timeslice reconstructions for the Antarctic Ice Sheet. Bed topography from BEDMAP2 (Fretwell et al., 2013). (a) 20 ka; (b) 15 ka; (c) 10 ka; (d) 5 ka. In all cases we show grounding line position and ice sheet thickness change (in metres relative to present elevation) or reconstructed ice sheet elevation (Ross Sea only). For grounding line positions the level of uncertainty is indicated by line style. For most of the sub-Antarctic islands, only information on maximum extent is known, and so we do not show the full timeslice reconstruction (see Hodgson et al. (2014)). For the 20 ka timeslice there are portions of the East Antarctic sector and Ross Sea sector where we are unable to place a firm grounding line limit; in these areas we adopt the grounding line in Livingstone et al. (2012) but emphasise that the nature of the uncertainty in grounding line position in these areas are discussed in full in Mackintosh et al. (2014) and Anderson et al. (2014)

region, the retreat history of the EAIS is still open to debate and the retreat history of the West Antarctic Ice Sheet (WAIS) is virtually unconstrained by reliable radiocarbon dates (Hillenbrand et al., 2012; Stolldorf et al., 2012). Terrestrial glacial-geological data show very little change in elevation of the EAIS (e.g. Hein et al., 2011) and by use of ice sheet models the terrestrial data have been used to infer much less extensive grounded ice on the shelf than in the Hillenbrand et al. (2012) reconstruction (e.g. Bentley et al., 2010). The two scenarios imply very different spatial extent of the ice sheet in the Weddell Sea embayment and this is reflected in Fig. 2 by the use of an alternative, more extensive grounding line (Scenario B) in the Weddell Sea. So in this region the selection of a particular limit depends on the interpretation of the available data. Hillenbrand et al. (2014) discuss both scenarios in detail and following Hillenbrand et al. (2012) and Larter et al. (2012), suggest that one potential way to reconcile these conflicting reconstructions would be for thin, low-gradient, lightly-grounded ice sheets to have extended across the outer shelf.

In the Antarctic Peninsula sector the ice sheet was grounded to the outer shelf/shelf edge at the LGM until ~20 ka BP (O'Cofaigh et al., 2014). Based on the distribution of glacial landforms and subglacial sediments, palaeo-drainage of the ice sheet across the inner and middle shelf was partitioned into a series of ice streams flowing in cross-shelf bathymetric troughs.

In the Belgica Trough, Bellingshausen Sea the grounding line was deeply embayed and ice-sheet retreat had begun already (Larter et al., 2014). In the Amundsen Sea Embayment, geomorphological features and a small number of radiocarbon dates from the outer shelf indicate that the grounding line extended to, or close to, the shelf edge. However, data constraining the earliest stages of grounding-line retreat are sparse. Foraminifera-bearing layers of LGM age in one core near the shelf edge suggest that either retreat started before 20 ka or the grounding line position fluctuated across the outer shelf at around this time.

Anderson et al. (2014) demonstrate that over half of the ice that was grounded in the Ross Sea came from East Antarctica. In eastern Ross Sea, subglacial geomorphological features extend to the shelf margin, indicating that the WAIS extended across the continental shelf during the last ice-sheet expansion. However, the precise timing of this expansion remains unresolved and we are unable to constrain the limit at 20 ka. Marine radiocarbon ages, mainly acid insoluble organic (AIO) ages, indicate that the ice sheet probably retreated from the shelf prior to the LGM. Terrestrial and glaciological data from the margins of the Ross Sea embayment indicate that the ice sheet retreated during the Holocene. Ongoing research is focused on obtaining compound specific radiocarbon ages aimed at resolving this controversy.

Although large tracts of East Antarctica have not been studied in detail, Mackintosh et al. (2014) show that the ice sheet in Mac. Robertson Land reached close to the continental-shelf margin at this time. In contrast, in Prydz Bay the Lambert/Amery glacier did not extend beyond the inner continental shelf. Onshore, evidence from nunataks in the Prince Charles and Framnes Mountains indicate that the ice sheet thickened by hundreds of metres near the current coast or grounding lines. On the other hand, preservation of sediments from Marine Isotope Stage 3 or earlier indicates that many low-lying coastal oases remained ice-free during this period. Similarly, in Dronning Maud Land, a limited amount of evidence from nunataks suggests that modest or no thickening of the ice sheet occurred at this time. In the ice-sheet interior, ice-core evidence and ice-sheet models indicate that it is probable that the central domes of the ice sheet were around 100 m lower than present. Note that there are very few direct ages on glacial features from ~20 ka in East Antarctica and inferences of the position and thickness of the former ice sheet are largely based on relatively loose minimum or maximum age constraints.

There is evidence on Sub-Antarctic Heard Island, Bouvet Island, Marion Island, Prince Edward Island and Crozet Island, and maritime Antarctic South Orkney Islands and Elephant Island for glaciations extending well onto their continental shelves. However a lack of age constraints from marine sediment cores means these cannot be unequivocally dated to the LGM or to the 20 ka timeslice.

3.2. 15 ka timeslice

In the Antarctic Peninsula, initial retreat was underway by 18 cal ka BP in the east and by 17.5 cal ka BP in Bransfield Basin. Further south, however, along the western Peninsula margin, the timing of initial pull-back from the outer shelf decreased progressively. Retreat of individual ice streams appears to have been asynchronous with subglacial topography exerting a major control. In the western Weddell Sea, the interpretation underpinning the extensive scenario (B) suggests ice had withdrawn from the shelf edge, whereas in Scenario A the ice had retreated onto the mid-shelf in the western Weddell Sea. The grounding line in the western Ross Sea was little changed from the 20 ka position.

There is only one site in East Antarctica (north of Loewe Massif in the Prince Charles Mountains) where there is clear evidence of ice retreat on the continental shelf prior to 15 ka. At all other sites where direct constraints are available, it appears that the East Antarctic Ice Sheet remained close to its maximum position on the shelf at this time. However, exposure of some terrestrial sites (Mackintosh et al., 2014) suggests a thinned ice sheet in places, particularly along the present-day coast.

In the Belgica Trough, Bellingshausen Sea the retreat of an embayed grounding line continued. Similar embayments into outer-shelf troughs probably developed in the eastern Amundsen Sea area, but the only age constraints available from an inter-stream ridge in the area suggest retreat there must have followed shortly after retreat in the adjacent troughs. In the western part of the Amundsen Sea, the grounding line had already retreated across most of the narrow shelf by 15 ka.

The onset of peat formation and lake sedimentation shows that terrestrial deglaciation was occurring at least at one site on Sub-Antarctic South Georgia, Kerguelen, Auckland and Marion Island (though the latter is extrapolated) and at three sites on Campbell Island.

3.3. 10 ka timeslice

Along the western and eastern margin of the Antarctic Peninsula, the ice sheet underwent significant recession between 15 and 10 cal ka BP and had retreated towards its present configuration by the mid-Holocene. In the east, it may have approached its present configuration by 10 ka.

In the Weddell Sea the grounding line was either at the northern tip of Berkner Island (Scenario B) or close to the inner ice rises of the southwestern Weddell Sea, and close to present in the southeastern Weddell Sea (Scenario A).

In the Ross Sea, retreat of the East Antarctic Ice Sheet from the western continental shelf occurred mainly after 13 cal yr BP and was most rapid during the Holocene. At 10 ka retreat of the West Antarctic Ice Sheet in both the eastern Ross Sea and the western Weddell Sea was well underway.

Marine and onshore evidence indicate substantial ice sheet thinning and lateral retreat of the East Antarctic Ice Sheet had started prior to this timeslice and continued during and after. The marine margin of the East Antarctic Ice Sheet in Wilkes Land had retreated to within 35 km of its present grounding position. Ice retreat had also begun by this time in the Windmill Islands adjacent to Law Dome, in Prydz Bay, and on the continental shelf in Mac.-Robertson Land and Lützow-Holm Bay. Terrestrial evidence from the Prince Charles and Framnes Mountains indicates that substantial thinning had already occurred by this time.

In those Sub-Antarctic Islands that were glaciated the majority show extensive accumulation of terrestrial deposits by 10 ka including South Georgia, Marion Island, Crozet, Kerguelen, and Auckland Island. One moraine has also been dated onshore by ^{10}Be at South Georgia delineating a still stand in ice retreat (or a minor advance), and at Signy Island marine sediment cores from the adjacent shelf show the onset of post-glacial marine sediments in this time slice.

In the Amundsen Sea Embayment, there was rapid grounding-line retreat from the middle and inner shelf after about 13 ka, so that the ice margin right across the Amundsen Sea was close to its modern limits by 10 ka.

3.4. *5 ka timeslice*

Around all of Antarctica the ice-sheet grounding-line was on the innermost shelf by 5 ka, and in many regions was at or close to its present position. Notably the Ross Sea, and Weddell Sea (Scenario B) reconstructions still show grounding lines a significant distance outboard of their present locations. In the Framnes Mountains and at Lützow Holm Bay in East Antarctica, dated erratic boulders indicate that the ice-sheet profile had reached very close to its present configuration by this time, and that substantial thinning had occurred between the 10 and 5 ka timeslices. In the maritime and sub-Antarctic most currently ice-free terrestrial areas were exposed by 5 ka with some areas showing evidence of subsequent Holocene ice-front fluctuations.

4. Conclusions from the overview of sector reviews

A number of common themes emerge from the reconstruction and the constituent papers of this volume, and we highlight five of these here. Firstly, the Antarctic Ice sheet did not everywhere reach the continental shelf edge at 20 ka, or the grounding line had already retreated from the shelf edge by this time (Fig. 2a). This includes the western Ross Sea and Prydz Bay, and possibly the Amundsen Sea and eastern Weddell Sea.

Secondly, it is clear that the local LGM (cf. Clark et al., 2009) and retreat from it were not synchronous around the Antarctic margin. Specific examples include ’early’ retreat of the ice sheet margin in the Bellingshausen Sea and parts of the western Amundsen Sea compared to ‘late’ retreat of the western Ross Sea and parts of the Antarctic Peninsula. Moreover, parts of the East Antarctic margin show a very different timing of retreat, with the onset of retreat in some areas occurring by ~18 ka and being near-complete by ~12 ka, but with retreat in other areas only beginning at ~12 ka (Mackintosh et al., 2014). This point has been emphasised before (Anderson et al., 2002; Livingstone et al., 2012) and shows that we should be cautious in interpreting synchronous behaviour of the circum-Antarctic ice margin (Weber et al., 2011). The apparent diachroneity in grounded ice-sheet advance and retreat also opens up the possibility that marine benthic fauna survived the Last Glacial period in-situ on the Antarctic shelf by moving from one continental shelf refuge to another (Thatje et al., 2005).

Thirdly, we do not quantify the volume of the ice sheet here but we note that the extent and thickness data are consistent with those summarised in an increasing number of recent ice-model reconstructions using different ice models (Mackintosh et al., 2011; Golledge et al., 2012; Whitehouse et al., 2012a; Golledge et al., 2013). These models all concluded that the total Antarctic contribution to post-glacial sea level rise was probably <10 m of equivalent eustatic sea level; smaller than previous model-based estimates. These more modest estimates of Antarctic Ice Sheet volume have implications for balancing the global LGM sea-level budget (see Andrews, 1992; Bentley, 1999 for discussion), and for GIA correction of contemporary mass balance (King et al., 2012; Shepherd et al., 2012; Ivins et al., 2013).

Fourthly, the contribution of the Antarctic Ice Sheet to Meltwater Pulse-1A (MWP-1A), an abrupt ~20 m rise in global sea level 14.65–14.31 ka (Deschamps et al., 2012), has been debated. Interpretation and modelling of far-field sea level records suggests a significant or dominant Antarctic contribution (Clark et al., 2002; Weaver et al., 2003), whereas, in contrast, interpretation of Antarctic glacial geology from around the continent suggests only a very minor contribution (Licht, 2004; Bentley et al., 2010; Mackintosh et al., 2011). MWP-1A occurred between our timeslices for 15 ka and 10 ka. Inspection of the difference between those timeslices and close inspection of the limiting ages for deglaciation around the continent do not show a major change at the time of MWP-1A. Even after taking dating uncertainties into account this is consistent with only a minor contribution of Antarctica to this melwater pulse. Fifthly, in some areas the spatial pattern of deglaciation of the shelf is highly variable. This is particularly the case during the Holocene when the ice sheet was grounded on the inner shelf. A number of factors might explain this diachronous retreat behaviour between individual troughs on the shelf including, perhaps most importantly, the effect of local topography/bathymetry on ice sheet dynamics and channelling of any inflow of relatively warm ocean water to the grounding line (Anderson et al., 2002; Heroy and Anderson, 2007; Ó Cofaigh et al., 2008; Livingstone et al., 2012; Jamieson et al., 2012). Other factors include variability in the area, elevation and climate conditions of glacial drainage basins that contributed to the expanded ice sheets around the continent; spatial differences in isostatic depression and rebound; and potential for intrusion of warm deep water onto the continental shelf (Anderson et al., 2013).

5. Recommendations for future work

It is clear from the reconstructions that the level of knowledge of Antarctic Ice Sheet history is extremely variable in time and space. Each of the sector reviews identifies suggestions for future work and we highlight some of those here. With the exception of Mac.-Robertson Land and the Lambert/Amery system where most work has been focussed, East Antarctica contains substantial regions where we still do not know the broad deglacial history, and these have prevented a full circum-Antarctic timeslice-based reconstruction. The acquisition of further terrestrial and marine data around the East Antarctic margin has to be a priority, and in particular we identify the need for robust geochronological information from onshore localities to constrain former East Antarctic Ice Sheet thickness (Mackintosh et al., 2014). In the Weddell Sea, obtaining targeted data to distinguish between the two alternative scenarios A and B would go a long way to helping resolve a significant debate about ice sheet extent in this region (Hillenbrand et al., 2014).

The glacial history of the sub-Antarctic islands is exceptionally poorly known – in many cases we do not even have a broad understanding of the maximum ice-sheet configuration at the LGM, let alone the subsequent deglacial history. Yet such islands can provide important information on sub-Antarctic environmental change and can be a useful test bed for understanding the mechanisms of ice-sheet retreat in the later phases of deglaciation (Hodgson et al., 2014).

In contrast to the Bellingshausen Sea, whose deglaciation history is poorly constrained because it is entirely based on AIO dates from marine cores, the amount of geological and geophysical data in the Amundsen Sea has multiplied rapidly in recent years. However, we still require further chronological control on the steps in retreat that are increasingly being identified in the geomorphological record of the region. This would aid efforts to better understand if the recent ice sheet change in this important area is exceptional (Larter et al., 2014). Although the ice-sheet retreat history of the Antarctic Peninsula sector, particularly along its western margin, is one of the best constrained in Antarctica, there remain major data gaps, most notably along the Weddell Sea margin. In line with several other sectors the constraints on the timing of ice-sheet retreat are poor, and even in comparatively well-studied areas of the Peninsula we still require further chronological control so as to assess the variability between different ice-stream catchments and retreat rate.

Whilst the 20 ka timeslice is relatively well known, at least around West Antarctica, the constraints on ice-sheet configuration reduce rapidly through the deglacial period, and in several areas we know surprisingly little about the Holocene configuration of the ice sheet. Whilst deglacial reconstructions have been published for the Ross Sea (Conway et al., 1999), the eastern Ross Sea is still poorly constrained. We lack radiocarbon age constraints for ice-sheet retreat from the continental shelf and must rely heavily on terrestrial glacial-geological and glaciological data from the inner shelf. Understanding the Holocene is particularly important both for providing the context for recent ice-sheet change (understanding if it is unusual or a part of Holocene variability), and because ongoing GIA is particularly sensitive to the most recent changes in ice loading (Ivins et al., 2000; Nield et al., 2012; Whitehouse et al., 2012b).

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Appendix A. Supplementary data

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References

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

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. Quat. Sci. Rev. 21, 49–70.

Anderson, J.B., Kirshner, A.E., Simms, A.R., 2013. Geological Constraints on Antarctica's Contribution to Post-LGM Sea-Level Rise. In: Hambrey, M.J., Barker, P.F., Barrett, P.J., Bowman, V., Davies, B., Smellie, J.L., Tranter, M. (Eds.), Antarctic Palaeoenvironments and Earth-Surface Processes, Geological Society, London, Special Publications, 381. http://dx.doi.org/10.1144/SP381.13.

Anderson, J.B., Conway, H., Bart, P.J., Witus, A.E., Greenwood, S.L., McKay, R.M., Hall, B.L., Ackert, R.P., Licht, K., Jakobsson, M., Stone, J.O., 2014. Ross Sea paleo-ice sheet drainage and deglacial history during and since the LGM. Quat. Sci. Rev. 100, 31–54. http://dx.doi.org/10.1016/j.quascirev.2013.08.020.

Andrews, J.T., 1992. Glaciation - a case of missing water. Nature 358, 281–291.

Bentley, M.J., 1999. Volume of Antarctic Ice at the Last Glacial Maximum, and its impact on global sea level change. Quat. Sci. Rev. 18, 1569–1595.

Bentley, M.J., 2010. The Antarctic palaeo record and its role in improving predictions of future Antarctic Ice Sheet change. J. Quat. Sci. 25, 5–18.

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

Chen, J.L., Wilson, C.R., Blankenship, D.D., Tapley, B.D., 2006. Antarctic mass rates from GRACE. Geophys. Res. Lett. 33, L11502.

Clark, C.D., Hughes, A.L.C., Greenwood, S.L., Jordan, C., Sejrup, H.P., 2012. Pattern and timing of retreat of the last British-Irish Ice Sheet. Quat. Sci. Rev. 44, 112–146.

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.

Clark, P.U., Mitrovica, J.X., Milne, G.A., Tamisiea, M.E., 2002. Sea-level fingerprinting as a direct test for the source of global meltwater pulse IA. Science 295, 2438–2441.

Convey, P., Gibson, J.A.E., Hillenbrand, C.-D., Hodgson, D.A., Pugh, P.J.A., Smellie, J.L., Stevens, M.I., 2008. Antarctic terrestrial life – challenging the history of the frozen continent? Biol. Rev. 83, 103–117.

Conway, H., Hall, B.L., Denton, G.H., Gades, A.M., Waddington, E.D., 1999. Past and future grounding-line retreat of the West Antarctic Ice Sheet. Science 286, 280–283.

Denton, G.H., Hughes, T.J., 1981. The Last Great Ice Sheets. Wiley, New York.

Denton, G.H., Hughes, T.J., 2002. Reconstructing the Antarctic Ice Sheet at the Last Glacial Maximum. Quat. Sci. Rev. 21, 193–202.

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

Dyke, A.S., Andrews, J.T., Clark, P.U., England, J.H., Miller, G.H., Shaw, J., Veillette, J.J., 2002. The Laurentide and Innuitian ice sheets during the Last Glacial Maximum. Quat. Sci. Rev. 21, 9–31.

Fretwell, P., Pritchard, H.D., Vaughan, D.G., Bamber, J.L., Barrand, N.E., Bell, R., Bianchi, C., Bingham, R.G., Blankenship, D.D., Casassa, G., Catania, G., Callens, D., Conway, H., Cook, A.J., Corr, H.F., Damaske, D., Damm, V., Ferraccioli, F., Forsberg, R., Fujita, S., Gim, Y., Gogineni, P., Griggs, J.A., Hindmarsh, R.C.A., Holmlund, P., Holt, J.W., Jacobel, R.W., Jenkins, A., Jokat, W., Jordan, T., King, E.C., Kohler, J., Krabill, W., Riger-Kusk, M., Langley, K.A., Leitchenkov, G., Leuschen, C., Luyendyk, B.P., Matsuoka, K., Mouginot, J., Nitsche, F.O., Nogi, Y., Nost, O.A., Popov, S.V., Rignot, E., Rippin, D.M., Rivera, A., Roberts, J., Ross, N., Siegert, M.J., Smith, A.M., Steinhage, D., Studinger, M., Sun, B., Tinto, B.K., Welch, B.C., Wilson, D., Young, D.A., Xiangbin, C., Zirizzotti, A., 2013. Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. Cryosphere 7, 375–393. http://dx.doi.org/10.5194/tc-7-375-2013.

Golledge, N., 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. Proc. Natl. Acad. Sci. 109, 16052–16056.

Golledge, N.R., Levy, R.H., McKay, R.M., Fogwill, C.J., White, D.A., Graham, A.G.C., Smith, J.A., Hillenbrand, C.-D., Licht, K.J., Denton, G.H., Ackert Jr., R.P., Maas, S.M., Hall, B.L., 2013. Glaciology and geological signature of the Last Glacial Maximum Antarctic Ice Sheet. Quat. Sci. Rev. 78, 225–247.

Gyllencreutz, G., Mangerud, J., Svendsen, J.-I., Lohne, Ø., 2007. DATED - a GIS-based reconstruction and dating database of the Eurasian deglaciation. In: Johansson, P., Sarala, P. (Eds.), Applied Quaternary Research in the Central Part of Glaciated Terrain. Geological Survey of Finland, pp. 113–120.

Hein, A.S., Fogwill, C.J., Sugden, D.E., Xu, S., 2011. Glacial/interglacial ice-stream stability in the Weddell Sea embayment, Antarctica. Earth Planet. Sci. Lett. 307, 211–221.

Heroy, D.C., Anderson, J.B., 2007. Radiocarbon constraints on Antarctic Peninsula ice sheet retreat following the Last Glacial Maximum (LGM). Quat. Sci. Rev. 26, 3286–3297.

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. Quat. Sci. Rev. 32, 25–47.

Hillenbrand, C.-D., Bentley, M.J., Stolldorf, T.D., Hein, A.S., Kuhn, G., Graham, A.G.C., Fogwill, C.J., Kristoffersen, Y., Smith, J.A., Anderson, J.B., Larter, R.D., Melles, M., Hodgson, D.A., Mulvaney, R., Sugden, D.E., 2014. Reconstruction of changes in the Weddell Sea sector of the Antarctic Ice Sheet since the Last Glacial Maximum. Quat. Sci. Rev. 100, 111–136. http://dx.doi.org/10.1016/j.quascirev.2013.07.020.

Hodgson, D.A., Graham, A.G.C., Roberts, S.J., Bentley, M.J., Ó Cofaigh, C., Verleyen, E., Jomelli, V., Favier, V., Brunstein, D., Verfaillie, D., Colhoun, E.A., Saunders, K., Selkirk, P.M., Mackintosh, A., Hedding, D.W., Nel, W., Hall, K., McGlone, M.S., Van der Putten, N., 2014. Terrestrial and submarine evidence for the extent and timing of the Last Glacial Maximum and the onset of deglaciation on the sub-Antarctic islands. Quat. Sci. Rev. 100, 137–158.

Ivins, E.R., James, T.S., 2005. Antarctic glacial isostatic adjustment: a new assessment. Antarct. Sci. 17, 541–553.

Ivins, E.R., James, T.S., Wahr, J., O. Schrama, E.J., Landerer, F.W., Simon, K.M., 2013. Antarctic contribution to sea level rise observed by GRACE with improved GIA correction. J. Geophys. Res. Solid Earth 118, 3126–3141.

Ivins, E.R., Raymond, C.A., James, T.S., 2000. The influence of 5000 year-old and younger glacial mass variability on present-day crustal rebound in the Antarctic Peninsula. Earth Planets Space 52, 1023–1029.

Jamieson, S.S.R., Vieli, A., Livingstone, S.J., Cofaigh, C.O., Stokes, C., Hillenbrand, C.D., Dowdeswell, J.A., 2012. Ice-stream stability on a reverse bed slope. Nat. Geosci. 5, 799–802.

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–+.

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. Quat. Sci. Rev. 53, 111–122.

Larter, R.D., Anderson, J.B., Graham, A.G.C., Gohl, K., Hillenbrand, C.-D., Jakobsson, M., Johnson, J.S., Kuhn, G., Nitsche, F.O., Smith, J.A., Witus, A.E., Bentley, M.J., Dowdeswell, J.A., Ehrmann, W., Klages, J.P., Lindow, J., Ó Cofaigh, C., Spiegel, C., 2014. Reconstruction of changes in the Amundsen Sea and Bellingshausen Sea sector of the West Antarctic Ice Sheet since the Last Glacial Maximum. Quat. Sci. Rev. 100, 55–86. http://dx.doi.org/10.1016/j.quascirev.2013.10.016.

Licht, K.J., 2004. The Ross Sea's contribution to eustatic sea level during meltwater pulse 1A. Sediment. Geol. 165, 343–353.

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

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. Nat. Geosci. 4, 195–202.

Mackintosh, A.N., Verleyen, E., O'Brien, P.E., White, D.A., Jones, R.S., McKay, R., Dunbar, R., Gore, D.B., Fink, D., Post, A.L., Miura, H., Leventer, A., Goodwin, I., Hodgson, D.A., Lilly, K., Crosta, X., Golledge, N.R., Wagner, B., Berg, S., van Ommen, T., Zwartz, D., Roberts, S.J., Vyverman, W., Massé, G., 2014. Retreat history of the East Antarctic Ice Sheet since the Last Glacial Maximum. Quat. Sci. Rev. 100, 10–30. http://dx.doi.org/10.1016/j.quascirev.2013.07.024.

Nield, G.A., Whitehouse, P.L., King, M.A., Clarke, P.J., Bentley, M.J., 2012. Increased ice loading in the Antarctic Peninsula since the 1850s and its effect on glacial isostatic adjustment. Geophys. Res. Lett. 39.

Ó Cofaigh, C., Dowdeswell, J.A., Evans, J., Larter, R.D., 2008. Geological constraints on Antarctic palaeo-ice-stream retreat. Earth Surf. Process. Landf. 33, 513–525.

Ó Cofaigh, C., Davies, B.J., Livingstone, S.J., Smith, J.A., Johnson, J.S., Hocking, E.P., Hodgson, D.A., Anderson, J.B., Bentley, M.J., Canals, M., Domack, E., Dowdeswell, J.A., Evans, J., Glasser, N.F., Hillenbrand, C.-D., Larter, R.D., Roberts, S.J., Simms, A.R., 2014. Reconstruction of Ice-Sheet Changes in the Antarctic Peninsula Since the Last Glacial Maximum. Quat. Sci. Rev. 100, 87–110.

Pattyn, F., Schoof, C., Perichon, L., Hindmarsh, R.C.A., Bueler, E., de Fleurian, B., Durand, G., Gagliardini, O., Gladstone, R., Goldberg, D., Gudmundsson, G.H., Huybrechts, P., Lee, V., Nick, F.M., Payne, A.J., Pollard, D., Rybak, O., Saito, F., Vieli, A., 2012. Results of the Marine Ice Sheet Model Intercomparison Project, MISMIP. Cryosphere 6, 573–588.

Pollard, D., DeConto, R., 2009. Modelling West Antarctic ice sheet growth and collapse through the past five million years. Nature 458, 329–332.

Schoof, C., 2007. Ice sheet grounding line dynamics: Steady states, stability, and hysteresis. J. Geophys. Res.-Earth Surf. 112.

Shepherd, A., Ivins, E.R., Geruo, A., Barletta, V.R., Bentley, M.J., Bettadpur, S., Briggs, K.H., Bromwich, D.H., Forsberg, R., Galin, N., Horwath, M., Jacobs, S., Joughin, I., King, M.A., Lenaerts, J.T.M., Li, J.L., Ligtenberg, S.R.M., Luckman, A., Luthcke, S.B., McMillan, M., Meister, R., Milne, G., Mouginot, J., Muir, A., Nicolas, J.P., Paden, J., Payne, A.J., Pritchard, H., Rignot, E., Rott, H., Sorensen, L.S., Scambos, T.A., Scheuchl, B., Schrama, E.J.O., Smith, B., Sundal, A.V., van Angelen, J.H., van de Berg, W.J., van den Broeke, M.R., Vaughan, D.G., Velicogna, I., Wahr, J., Whitehouse, P.L., Wingham, D.J., Yi, D.H., Young, D., Zwally, H.J., 2012. A Reconciled estimate of ice-sheet mass balance. Science 338, 1183–1189.

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. Quat. Sci. Rev. 48, 20–31.

Thatje, S., Hillenbrand, C.-D., Larter, R., 2005. On the origin of Antarctic marine benthic community structure. Trends Ecol. Evol. 20, 534–540.

Velicogna, I., Wahr, J., 2013. Time-variable gravity observations of ice sheet mass balance: Precision and limitations of the GRACE satellite data. Geophys. Res. Lett. 40, 3055–3063.

Weaver, A.J., Saenko, O.A., Clark, P.U., Mitrovica, J.X., 2003. Meltwater pulse 1A from Antarctica as a trigger of the bolling- allerod 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.

Whitehouse, P.L., Bentley, M.J., Le Brocq, A.M., 2012a. A deglacial model for Antarctica: geological constraints and glaciological modelling as a basis for a new model of Antarctic glacial isostatic adjustment. Quat. Sci. Rev. 32, 1–24.

Whitehouse, P.L., Bentley, M.J., Milne, G.A., King, M.A., Thomas, I.D., 2012b. A new glacial isostatic adjustment model for Antarctica: calibrated and tested using observations of relative sea-level change and present-day uplift rates. Geophys. J. Int. 190, 1464–1482.

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, vol. 8. Elsevier, Amsterdam, pp. 531–570.

Zwally, H. Jay, Giovinetto, Mario B., Beckley, Matthew A., Saba, Jack L., 2012. Antarctic and Greenland Drainage Systems. GSFC Cryospheric Sciences Laboratory. http://icesat4.gsfc.nasa.gov/cryo_data/ant_grn_drainage_systems.php.