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Reconstruction of ice-sheet changes in the Antarctic Peninsula since the Last Glacial Maximum

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ABSTRACT

This paper compiles and reviews marine and terrestrial data constraining the dimensions and configuration of the Antarctic Peninsula Ice Sheet (APIS) from the Last Glacial Maximum (LGM) through deglaciation to the present day. These data are used to reconstruct grounding-line retreat in 5 ka time-steps from 25 ka BP to present. Glacial landforms and subglacial tills on the eastern and western Antarctic Peninsula (AP) shelf indicate that the APIS was grounded to the outer shelf/shelf edge at the LGM and contained a series of fast-flowing ice streams that drained along cross-shelf bathymetric troughs. The ice sheet was grounded at the shelf edge until ~20 cal ka BP. Chronological control on retreat is provided by radiocarbon dates on glacimarine sediments from the shelf troughs and on lacustrine and terrestrial organic remains, as well as cosmogenic nuclide dates on erratics and ice moulded bedrock. Retreat in the east was underway by about 18 cal ka BP. The earliest dates on recession in the west are from Bransfield Basin where recession was underway by 17.5 cal ka BP. Ice streams were active during deglaciation at least until the ice sheet had pulled back to the mid-shelf. The timing of initial retreat decreased progressively southwards along the western AP shelf; the large ice stream in Marguerite Trough may have remained grounded at the shelf edge until about 14 cal ka BP, although terrestrial cosmogenic nuclide ages indicate that thinning had commenced by 18 ka BP. Between 15 and 10 cal ka BP the APIS underwent significant recession along the western AP margin, although retreat between individual troughs was asynchronous. Ice in Marguerite Trough may have still been grounded on the mid-shelf at 10 cal ka BP. In the Larsen-A region the transition from grounded to floating ice was established by 10.7–10.6 cal ka BP. The APIS had retreated towards its present configuration in the western AP by the mid-Holocene but on the eastern peninsula may have approached its present configuration several thousand years earlier, by the start of the Holocene. Mid to late-Holocene retreat was diachronous with stillstands, re-advances and changes in ice-shelf configuration being recorded in most places. Subglacial

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topography exerted a major control on grounding-line retreat with grounding-zone wedges, and thus by inference slow-downs or stillstands in the retreat of the grounding line, occurring in some cases on reverse bed slopes.

1. Introduction

The Antarctic Peninsula (AP) (Fig. 1) is arguably the most intensively studied region in Antarctica. This reflects its climatic sensitivity and recognition that it is one of the most rapidly warming areas of the globe today (Vaughan et al., 2003; Turner et al., 2005, Bentley et al., 2009). This warming is indicated by a range of observations, but perhaps most dramatically, is manifest in the collapse of ice shelves fringing the Peninsula (e.g., Vaughan and Doake, 1996; Scambos et al., 2003), and in the thinning, retreat and acceleration of marine-terminating outlet glaciers over the last few decades (De Angelis and Skvarca, 2003; Cook et al., 2005).

Understanding of the longer-term Quaternary glacial history of the AP has seen significant advances in the last 20 years, due particularly to technological developments in offshore marine geophysical surveying and terrestrial dating techniques. This has allowed detailed reconstruction of former ice sheet extent and flow on the continental shelf. The Antarctic Peninsula Ice Sheet (APIS) is now recognised to have terminated at the shelf edge at the Last Glacial Maximum (LGM), with ice streams occupying most of the cross-shelf bathymetric troughs (e.g., Pudsey et al., 1994; Larter and Vanneste, 1995; Canals et al., 2000, 2003; Ó Cofaigh et al., 2002; Evans et al., 2004; Heroy and Anderson, 2005, 2007; Anderson and Oakes-Fretwell, 2008). Advances in cosmogenic nuclide surface exposure dating of glacially-transported boulders and bedrock surfaces, optically stimulated luminescence (OSL) of beach cobbles, and radiocarbon dates of lacustrine and terrestrial deposits onshore constrain the timing of terrestrial ice retreat and especially ice-sheet thinning (e.g., Bentley et al., 2006, 2011; Johnson et al., 2011; Hodgson et al., 2013; Simkins et al., 2013; Glasser et al., 2014). Such palaeo-glaciological reconstructions have wider significance because they provide information on the former subglacial processes controlling ice sheet dynamics, for example, through imaging and sampling the former ice-sheet bed using ship-based geophysical methods and coring. Critically, they also provide observational constraints for testing and validating numerical ice-sheet models (e.g., King et al., 2012; Whitehouse et al., 2012a,b; Briggs and Tarasov, 2013). Finally, they provide a long-term palaeo-glaciological perspective on ice sheet change over centennial to millennial timescales.

There have been several syntheses of AP glacial history (Ingólfsson et al., 2003; Heroy and Anderson, 2005; Livingstone et al., 2012; Davies et al., 2012a). The aim of this paper is to summarise the current knowledge of the LGM to present ice sheet history for the AP and provide a series of time-slice reconstructions (isochrones in 5 ka steps) depicting changes in ice-sheet extent and thickness based on terrestrial and marine geomorphological and geological evidence. Tables of marine and terrestrial radiocarbon ages, terrestrial cosmogenic nuclide (TCN), optically stimulated luminescence (OSL), and relative palaeomagnetic intensity (RPI) ages are presented in the Supplementary Information.

2. Study area

Physiographically, the AP consists of a thin spine of mountains that for much of its length forms a plateau 1800–2000 m in elevation, although exceptionally peaks can reach up to 3500 m asl. The peninsula is fringed by a series of islands including, for the purpose of this review, the South Shetland Islands to the northwest (Fig. 1). The continental shelf surrounding the AP is incised by a series of cross-shelf bathymetric troughs with water depths that range from 500 m to more than 1000 m. The mountainous spine of the AP provides an orographic barrier to precipitation and, as a result the eastern AP has a polar continental climate further cooled by the large areas of ice shelves to the east and south and the clockwise flowing Weddell Gyre. By contrast, the western AP is subject to rates of snow accumulation of up to 1400 kg m^{-2} yr^{-1} (Thomas et al., 2008) delivered by the prevailing westerlies (Domack et al., 2003). On the western AP high precipitation results in high accumulation rates and low equilibrium line altitudes. In contrast, the eastern AP is colder with lower precipitation and as a result equilibrium line altitudes are higher and accumulation rates are lower.

Contemporary ice cover on the AP averages 500 m in thickness and covers about 80% of the landmass with a sea-level rise equivalent of about 242 mm (Pritchard and Vaughan, 2007), and an estimated contribution to eustatic sea level since the LGM of about 2.9 m (Heroy and Anderson, 2005). Ice drains eastwards and westwards towards the coast of the peninsula, with the majority of flow occurring as a series of outlet glaciers. The Larsen Ice Shelf occupies a large part of the eastern margin of the peninsula south of about 66° S. There are also smaller ice shelves on the southwestern AP around Alexander Island (Fig. 1). A number of these ice shelves have experienced recent dramatic retreat (e.g., Vaughan and Doake, 1996; Scambos et al., 2003; Holt et al., 2013).

3. Methods

This review includes a large database of marine and terrestrial radiocarbon, cosmogenic nuclide, optically stimulated luminescence and relative palaeomagnetic intensity (RPI) dates which can be used as minimum ages to constrain past ice sheet limits (Fig. 2; Supplementary Data Table 1). The database is an updated version of two recently published reviews (Livingstone et al., 2012; Davies et al., 2012a). Each age has a Map ID number, shown on Fig. 2, which can be cross referenced with the Map ID's given in the Supplementary Information.

3.1. Marine geophysical records of ice-sheet extent

Evidence of former grounded ice on the AP continental shelf has been recorded by echo-sounding, acoustic sub-bottom profiler and seismic reflection data on multiple research cruises spanning many decades. With the advent of multibeam swath bathymetry it has been possible to identify and map glacial landforms, such as mega-scale glacial lineations (MSGLs), drumlins, meltwater channels and grounding-zone wedges (GZWs) in great detail (Fig. 3). This has facilitated comprehensive reconstructions of grounding-line limits during the LGM and subsequent deglaciation, and has permitted the identification of palaeo-ice stream troughs on the shelf (e.g., Livingstone et al., 2012).

Acoustic sub-bottom profiler data, using systems that transmit signals in the 1.5–5 kHz range, provide information about the physical nature of the upper few metres to several tens of metres of