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Terrestrial and submarine evidence for the extent and timing of the Last Glacial Maximum and the onset of deglaciation on the maritime-Antarctic and sub-Antarctic islands☆

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A B S T R A C T

This paper is the maritime and sub–Antarctic contribution to the Scientific Committee for Antarctic Research (SCAR) Past Antarctic Ice Sheet Dynamics (PAIS) community Antarctic Ice Sheet reconstruction. The overarching aim for all sectors of Antarctica was to reconstruct the Last Glacial Maximum (LGM) ice sheet extent and thickness, and map the subsequent deglaciation in a series of 5000 year time slices. However, our review of the literature found surprisingly few high quality chronological constraints on changing glacier extents on these timescales in the maritime and sub–Antarctic sector. Therefore, in this paper we focus on an assessment of the terrestrial and offshore evidence for the LGM ice extent, establishing minimum ages for the onset of deglaciation, and separating evidence of deglaciation from LGM limits from those associated with later Holocene glacier fluctuations. Evidence included geomorphological descriptions of glacial landscapes, radiocarbon dated basal peat and lake sediment deposits, cosmogenic isotope ages of glacial features and molecular biological data. We propose a classification of the glacial history of the maritime and sub–Antarctic islands based on this assembled evidence. These include: (Type I) islands which accumulated little or no LGM ice; (Type II) islands with a limited LGM ice extent but evidence of extensive earlier continental shelf glaciations; (Type III) seamounts and volcanoes unlikely to have accumulated significant LGM ice cover; (Type IV) islands

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on shallow shelves with both terrestrial and submarine evidence of LGM (and/or earlier) ice expansion; (Type V) Islands north of the Antarctic Polar Front with terrestrial evidence of LGM ice expansion; and (Type VI) islands with no data. Finally, we review the climatological and geomorphological settings that separate the glaciological history of the islands within this classification scheme.

1. Introduction

Reconstructing the Antarctic Ice Sheet through its Last Glacial Maximum (LGM) and post LGM deglacial history is important for a number of reasons. Firstly, ice sheet modellers require field data against which to constrain and test their models of ice sheet change. The recent 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) that require field constraints. Secondly, the most recent millennia and centuries of ice sheet history provide data on the 'trajectory' of the ice sheet, which are valuable for the initialisation of models. Thirdly, the use of recent satellite gravity measurements (e.g. GRACE), and other geodetic data such as GPS, for ice sheet mass balance estimates requires an understanding of glacial–isostatic adjustment (GIA). In the case of GRACE, the satellite-pair cannot distinguish between recent changes in the mass balance of the ice sheet, and those from the transfer of mass in the mantle resulting from past ice sheet melting. 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 ice mass measurements from satellite gravity (King et al., 2012). It has been suggested that some mass estimates may be in error by as much as 100% (Chen et al., 2006).

Several decades of study have produced an impressive body of work on Antarctic Ice Sheet history. There have been a number of attempts to synthesise the data but many of these have just focussed on the LGM. A notable reconstruction was produced by Ivins and James (2005) which attempted to provide time-slices of the ice sheet from the LGM to the present-day to use as the basis of their GIA modelling. This 'model', termed IJ05, has been widely adopted by the satellite gravity and GPS communities as the ice sheet reconstruction to underpin GIA assessments. The model, although a benchmark at the time, is now becoming a little out-of-date, with the proliferation of data since the early 2000s, and no longer includes all of the glacial geological data available.

As a result, the Antarctic Climate Evolution (ACE) and subsequent Past Antarctic Ice Sheet Dynamics (PAIS) programmes of the Scientific Committee for Antarctic Research (SCAR) proposed a co-ordinated effort by the glacial geology community to develop a synthesis of Antarctic Ice Sheet history. This paper covers the maritime and sub-Antarctic sectors. Other sectors of the Antarctic Ice Sheet, including the maritime Antarctic islands west of the Antarctic Peninsula, are described elsewhere in this Special Issue.

Although the combined volume of the maritime and sub-Antarctic LGM glaciers has had a very limited effect on global sea level, understanding past extent and timing of past glaciations in the sub-Antarctic is important for a number of reasons. First, the maritime and sub-Antarctic glaciers have been amongst the earliest ice masses to respond to recent rapid regional warming (e.g. Gordon et al., 2008; Cook et al., 2010) and, therefore, provide a sensitive indicator of interactions between Southern Hemisphere climate and ice sheet stability. This interaction can, in turn, be used to provide boundary conditions for various physical parameters in glaciological models, including those associated with abrupt climate change and the terminal phases of ice sheet decay. Second, the timing, thickness and extent of glacial maxima and subsequent glacier fluctuations in the maritime and sub-Antarctic region can be used to address questions regarding the relative pacing of climate changes between the hemispheres. For example, it is still not known if many of the maritime and sub-Antarctic islands have synchronous glaciations, follow an Antarctic pattern of glaciation, a South American or New Zealand pattern, or a Northern Hemisphere one. This has clear relevance to research aiming to determine if Southern Hemisphere glaciations precede those in the north (or vice versa), whether polar climates are in or out of phase between the hemispheres (Blunier et al., 1998), and in identifying the significant climate drivers. Third, the extent of glacial maxima on the maritime and sub-Antarctic Islands has determined how much of their terrestrial habitats and surrounding marine shelves have been available and suitable as biological refugia for local and Antarctic continental biota during glaciations (Clarke et al., 2005; Barnes et al., 2006; Convey et al., 2008). This knowledge helps explain evolutionary patterns in biodiversity and regional biogeography.

Whilst for some sectors of the Antarctic Ice Sheet it was possible to follow the original community aim of reconstructing the LGM and deglaciation in a series of 5000 year time slices, our review found surprisingly few high quality age constraints on changing glacier extents on these timescales in the maritime and sub-Antarctic sector. Thus, we limited ourselves to assessing the terrestrial and offshore evidence for the LGM ice extent, and establishing a minimum age for the onset of deglaciation. Specific aims for each of the maritime and sub-Antarctic islands were to:

1. Summarise evidence for LGM ice thickness and extent based on onshore geomorphological evidence, including evidence of glacial isostasy from relative sea level changes.
2. Summarise evidence for LGM ice extent and infer ice thickness using offshore geomorphological evidence from the continental shelf including regional bathymetric compilations.
3. Compile tables of minimum age constraints for glacial features relating to the local LGM (referred to hereon simply as 'LGM') and the onset of deglaciation.
4. Separate evidence of the LGM and onset of deglaciation from deglaciation associated with later Holocene glacier fluctuations

In the discussion we propose a classification of the sub-Antarctic islands based on their glacial history and consider the different climatic and topographic factors controlling glaciation.

1.1. Study area

The sub-Antarctic islands considered in this review are located between 35 and 70°S, but are mainly found within 10–15° of the Antarctic Polar Front (Fig. 1). We also include the South Orkney Islands, and Elephant Island and Clarence Island (the northernmost South Shetland Islands) which are in the maritime Antarctic region (Fig. 1). The remaining South Shetland Islands are covered in the review of Antarctic Peninsula glacial history elsewhere in this Special Issue. Together with the Falkland Islands these sub-Antarctic and maritime Antarctic islands cover an area of approximately c. 26,000 km^2, just under half the area of Tasmania, or 1.3 times the area of Wales. This figure does not take into account the now-submerged offshore portions of the islands, which considerably increase the total area available for accommodating past glaciation.

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