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Testing models of ice cap extent, South Georgia, sub-Antarctic

N.L.M. Barlow [a, b, *], M.J. Bentley [a], G. Spada [c], D.J.A. Evans [a], J.D. Hanson [d], M.D. Brader [a], D.A. White [e], A. Zander [f], S. Berg [g]

[a] Department of Geography, Durham University, South Road, Durham, DH1 3LE, UK
[b] School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK
[c] Dipartimento di Scienze Pure e Applicate (DiSPeA), Urbino University "Carlo Bo", Urbino, Italy
[d] School of Geographical and Earth Sciences, University of Glasgow, Glasgow, G12 8QQ, UK
[e] Institute for Applied Ecology, University of Canberra, Canberra, ACT 2617, Australia
[f] Institute of Geography, University of Cologne, Albertus-Magnus-Platz, 50923, Cologne, Germany
[g] Institute of Geology and Mineralogy, University of Cologne, Zülpicher Str. 49a, 50674, Cologne, Germany

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ABSTRACT

The extent of Last Glacial Maximum ice in South Georgia is contested, with two alternative hypotheses: an extensive (maximum) model of ice reaching the edge of the continental shelf, or a restricted (minimum) model with ice constrained within the inner fjords. We present a new relative sea-level dataset for South Georgia, summarising published and new geomorphological evidence for the marine limit and elevations of former sea levels on the island. Using a glacial isostatic adjustment model (ALMA) specifically suited to regional modelling and working at high spatial resolutions, combined with a series of simulated ice-load histories, we use the relative sea-level data to test between the restricted and extensive ice extent scenarios. The model results suggest that there was most likely an extensive Last Glacial Maximum glaciation of South Georgia, implying that the island was covered by thick (>1000 m) ice, probably to the edge of the continental shelf, with deglaciation occurring relatively early (ca. 15 ka BP, though independent data suggest this may have been as early as 18 ka). The presence of an extensive ice cap extending to the shelf edge would imply that if there were any biological refugia around South Georgia, they must have been relatively localised and restricted to the outermost shelf.

1. Rationale and background

Though limited in size, the extent of glaciations of the sub-Antarctic islands, such as South Georgia, is of considerable interest due to their position in the Southern Ocean, providing a potential link between the climates of South America and West Antarctica (Hall, 2009; Hodgson et al., 2014a, 2014b). Moreover, the extent of ice has important implications as to whether the sub-Antarctic islands acted as glacial refugia for biota (Barnes et al., 2006, 2016; Hodgson et al., 2014b; Hogg et al., 2011; Thatje et al., 2008). Though the contribution of the potential ice mass on South Georgia to global sea level will be modest, recent changes in glacier extent in response to 20th century warming (Cook et al., 2010; Gordon et al., 2008) demonstrates the sensitivity of maritime South Georgia to changes in climate and oceanographic forcing by the Southern Ocean. During the global Last Glacial Maximum (LGM), ice on South Georgia expanded (Bentley et al., 2007; Hodgson et al., 2014b; Sugden and Clapperton, 1977) but there remains significant debate about the maximum ice extent reached during this time. Two widely divergent models have been suggested for the size of the ice cap over South Georgia during the LGM: an extensive (maximum) model of ice reaching the edge of the continental shelf (during at least one glacial phase) (Sugden and Clapperton, 1977), or a restricted (minimum) model with ice being constrained within the inner fjords (Bentley et al., 2007). The aim of this paper is to use glacial-isostatic adjustment (GIA) modelling in association with geomorphological evidence of former marine limits and past sea levels, as a means to test between the alternative models of former ice cap extent on South Georgia.

1.1. The maximum model

The maximum model was suggested by Sugden and Clapperton

* Corresponding author. School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK.
E-mail address: n.l.m.barlow@leeds.ac.uk (N.L.M. Barlow).

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(1977), based on the undulating and glacially scoured morphology of the continental shelf and the deep glacial troughs incised into it. They used precision depth recorder data to suggest that whereas the troughs are offshore extensions of fjords containing many features characteristic of glacier erosion, the areas between the troughs are characterised by irregular topography of the order of 20–80 m of relief. They argued that these features are uncommon on 'normal' continental shelves where sediment deposition tends to obscure irregular relief. Based upon the limited offshore data available, they documented evidence for glacial areal scour almost everywhere on the shelf shallower than 200 m and estimate a maximum ice area of 30,000 km^2. Sugden and Clapperton (1977) suggested that this extensive shelf-extent glaciation must have predated the last island-wide glaciation of South Georgia based upon preserved beach material emplaced on land between two periods of glacial sedimentation.

New bathymetric data, including swath bathymetry of some key areas, led Graham et al. (2008) to suggest an extensive ice cap at the LGM but acknowledged that there was little dating evidence to support this. Their evidence included more detailed mapping of the troughs noted by Sugden and Clapperton (1977), as well as the discovery of submarine landforms interpreted as moraines, located in the troughs close to the shelf edge (Fig. 1).

1.2. The minimum model

A minimum model for ice cap glaciation was suggested by Bentley et al. (2007) based on dated onshore geomorphological evidence mapped across a variety of fjords along the north-east coast of South Georgia. In particular, Bentley et al. (2007) mapped a consistent pattern of moraines that did not extend beyond the fjord mouths, and dated these using cosmogenic nuclide surface exposure dating. They also noted the low elevation (<10 m) of all post-glacial raised beaches, implying a minor amount of glacial isostatic rebound and a relatively small antecedent ice cap. Based on the geomorphology and cosmogenic exposure ages, and a well-dated lake sediment core implying ice-free inner fjords as early as 18,621–19,329 cal yr BP at the Tønsberg Peninsula (Rosqvist et al., 1999), Bentley et al. (2007) suggested that the ice did not extend beyond the fjord mouths at the LGM. Direct observations of recent behaviour of South Georgia glaciers has identified precipitation as the primary controlling factor on tidewater glaciers (Gordon and Timmis, 1992) and using this analogue Bentley et al. (2007) suggested that the restricted extent of LGM glaciation may have been due to low precipitation caused by extensive sea ice presence upwind of South Georgia.

Hodgson et al. (2014a) used multibeam swath bathymetric surveys of nine major fjords around South Georgia to reveal a relatively consistent pattern of submarine geomorphological features. These include a shallow inner basin bounded by an inner basin moraine and a deep basin with a moraine at the outer limits of each of the fjords. Using a relative chronology based primarily on existing terrestrial evidence from Bentley et al. (2007), they suggested that the inner basin moraines date from the last major glacial advance (LGM), and the deep basin moraines from an earlier glaciation, possibly marine isotope stage (MIS) 6. However, they suggested offshore marine work is required to date the deglacial morainic sediments.

1.3. Timing of post-LGM deglaciation

Numerous studies have sought to date the timing of deglaciation on South Georgia using terrestrial proxies for ice retreat, of which Hodgson et al. (2014b) provide a comprehensive review. To date, the offshore evidence is limited to bathymetric surveys with little direct chronological control. The onshore oldest cosmogenic isotope dates mark the oldest mapped ice advance, estimated using an error-weighted mean to have been abandoned at 12.1 ± 1.4 yr BP (Bentley et al., 2007). The oldest evidence for post LGM ice-free conditions comes from the radiocarbon dates marking the onset of lake sedimentation in one basin on the Tønsberg Peninsula, close to Husvik, at 18,621–19,329 cal yr BP (Rosqvist et al., 1999). Most other basal dates from lake sediments and peat sequences provide minimum ages for ice-free conditions from the start of the Holocene (Table 1 in Hodgson et al., 2014b).

To test the two differing hypothesis of extensive (maximum) or restricted (minimum) ice limits during the LGM we develop two sets of ice models that simulate extensive (shelf based) or restricted (island only) glaciation that we input into a GIA model, the outputs of which we compare to the geomorphological evidence of former relative sea levels (RSL) from the island. The results have implications for understanding of sub-Antarctic glaciation, ongoing patterns of land-level displacement and the climate of the Southern Ocean.

2. Study area

South Georgia is 170 km long and its width varies from 2 to 40 km (Fig. 1). It is dominated by a central spine of mountains rising to nearly 3000 m (Mount Paget is the highest peak at 2935 m). The axis of the island hosts a series of linked icefields from which numerous outlet glaciers descend. Most terminate as tidewater fronts but a few have terrestrial margins. The glaciers have eroded deep fjords that dominate the South Georgia coastline and at the head of most of these is a large outlet glacier. South Georgia currently has a cool climate (mean annual temperature 2 °C) with a strong maritime influence (Smith, 1960). The regional equilibrium line altitude (ELA) on the north-east of the island was estimated by Smith (1960) to be 460 m above sea level (asl). Much of the data reported here is focused on the north-east coast of the island where there are several ice-free peninsulas between the fjords which can be logistically accessed, and on which is located a rich geomorphological record of glacial landforms and raised coastal features (Bentley et al., 2007; Clapperton et al., 1989; Stone, 1974; Sugden and Clapperton, 1977). The south-west coast is data-poor since it is largely glaciated down to sea level, difficult to access, and has limited present and raised marine features (Hansom, 1979).

3. Field data

To test the hypothesis of extensive versus restricted ice extent during the LGM we compiled a dataset of geomorphological evidence of the elevation of past sea level (Figs. 1–3), to compare against the GIA model outputs. There is widespread and consistent evidence of the postglacial marine limit on South Georgia and a small number of dated sea-level index points.

3.1. Raised marine features

There is a wide range of raised marine features around the island, most of which have been identified along the north-east coastline where previous work and our own mapping has focussed (Fig. 1, Tables 1 and 2). These can be divided into two main groups: raised beaches and rock platforms. The raised beaches consist of an assemblage of common landforms that are always found below 10 m asl, though are found above modern beach level either due to relative sea-level fall and/or long-term tectonic uplift (Figs. 1 and 2). They typically consist of raised gravel beaches and terraces cut into existing glacial or slope deposits (e.g. Gordon and Hansom, 1986). The deposits are usually crudely bedded gravels,