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Late Quaternary environmental changes in Marguerite Bay, Antarctic Peninsula, inferred from lake sediments and raised beaches

Dominic A. Hodgson [a,*,1], Stephen J. Roberts [a,1], James A. Smith [a], Elie Verleyen [b], Mieke Sterken [b], Minke Labarque [b], Koen Sabbe [b], Wim Vyverman [b], Claire S. Allen [a], Melanie J. Leng [c], Charlotte Bryant [d]

[a] NERC British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK
[b] Department of Biology, Section of Protistology and Aquatic Ecology, University of Ghent, Krijgslaan 281 S8, 9000 Gent, Belgium
[c] NERC Isotope Geosciences Laboratory, British Geological Survey, Keyworth, Nottingham NG12 5GG, UK
[d] NERC Radiocarbon Facility, Scottish Enterprise Technology Park, Rankine Avenue, East Kilbride, Scotland G75 0QF, UK

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A B S T R A C T

The Antarctic Peninsula is one of the fastest-warming regions on Earth, but its palaeoenvironmental history south of 63° latitude is relatively poorly documented, relying principally on the marine geological record and short ice cores. In this paper, we present evidence of late-Quaternary environmental change from the Marguerite Bay region combining data from lake sediment records on Horseshoe Island and Pourquoi-Pas Island, and raised beaches at Horseshoe Island, Pourquoi-Pas Island and Calmette Bay. Lake sediments were radiocarbon dated and analysed using a combination of sedimentological, geochemical and microfossil methods. Raised beaches were surveyed and analysed for changes in clast composition, size and roundness. Results suggest a non-erosive glacial regime could have existed on Horseshoe Island from 35,780 (38,650–33,380) or 32,910 (34,630–31,370) cal yr BP onwards. There is radiocarbon and macrofossil evidence for possible local deglaciation events at 28,830 (29,370–28,320) cal yr BP, immediately post-dating Antarctic Isotopic Maximum 4, and 21,110 (21,510–20,730 interpolated) cal yr BP coinciding with, or immediately post-dating, Antarctic Isotopic Maximum 2. The Holocene deglaciation of Horseshoe Island commenced from 10,610 (11,000–10,300) cal yr BP at the same time as the early Holocene temperature maximum recorded in Antarctic ice cores. This was followed by the onset of marine sedimentation in The Narrows, Pourquoi-Pas Island, before 8850 (8480–9260) cal yr BP. Relative sea level high stands of 40.79 m above present at Pourquoi-Pas Island and 40.55 m above present at Calmette Bay occurred sometime after 9000 cal yr BP and suggest that a thicker ice sheet, including grounded ice streams, was present in this region of the Antarctic Peninsula than that recorded at sites further north. Isolation of the Narrows Lake basin on Pourquoi-Pas Island shows relative sea level in this region had fallen rapidly to 19.41 m by 7270 (7385–7155) cal yr BP. *Chaetoceros* resting spores suggest high productivity and stratified surface waters in The Narrows after 8850 (9260–8480) cal yr BP and beach clasts provide evidence of a period of increased wave energy at approximately 8000 yr BP. Lake sediment and beach data suggest an extended period of regional warming sometime between 6200 and 2030 cal yr BP followed by the onset of Neoglacial conditions from 2630 and 2030 cal yr BP in Narrows Lake and Col Lake 1, respectively. Diatom and $\delta^{13}C$ vs C/N and macrofossil evidence suggest a potential increase in the number of birds and seals visiting the Narrows Lake catchment sometime after 2100 (2250–2000) cal yr BP, with enhanced nutrient enrichment evident after 1150 (1230–1080) cal yr BP, and particularly from c. 460 (540–380) cal yr BP. A very recent increase in *Gomphonema* species and organic carbon in the top centimetre of the Narrows Lake sediment core after c. 410 (490–320) cal yr BP, and increased sedimentation rates in the Col Lake 1 sediment core, after c. 400 (490–310) cal yr BP may be a response to the regional late-Holocene warming of the Antarctic Peninsula.

* Corresponding author. Tel.: + 44 1223 221635.
E-mail address: daho@bas.ac.uk (D.A. Hodgson).
[1] These authors contributed equally to this research.

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1. Introduction

The Antarctic Peninsula is one of the fastest-warming regions on Earth. With a rate of temperature increase of 3.7 ± 1.6 °C century^{-1}, it is warming at several times the global mean of 0.6 ± 0.2 °C century^{-1} (Vaughan et al., 2003). This has resulted in shifts in species distributions, changes in lake ecology (Quayle et al., 2002), catastrophic disintegration of seven ice shelves (Hodgson et al., 2006; Cook and Vaughan, 2010; Hodgson, 2011) and accelerated discharge of 87% of continental glaciers (Cook et al., 2005). These processes look set to accelerate given IPCC predictions that future anthropogenic increases in greenhouse gas emissions will lead to a 1.4–5.8 °C rise in global temperatures by 2100 (IPCC, 2007), and climate modelling studies that show anthropogenic forcing of the Southern Hemisphere Annular Mode has played a key role in driving the local summer warming (Marshall et al., 2006). Warming is set to accelerate further once the buffering effect of the 'ozone hole' declines (Turner et al., 2009; Marshall et al., 2010).

Palaeoenvironmental records from this region are therefore urgently required to understand (1) the degree to which these recent changes fall outside of the range of natural variability, (2) how the ice sheets, relative sea level and ecosystems in the region have developed to their present status, and (3) how they might respond to the effects of continued increases in temperature. The key palaeoenvironmental datasets from the southern Antarctic Peninsula (South of 63° latitude) are those from ice cores, marine and lake sediments coupled with cosmogenic isotope exposure age dating of glacially-emplaced boulders and scoured bedrock, which, combined, constrain the retreat of the Last Glacial ice sheet (Bentley et al., 2006, 2009, 2011).

Ice cores from the Antarctic Peninsula have been limited in length due to the relatively rapid flow of ice from its mountainous spine (see Mosley-Thompson and Thompson, 2003, and references therein). New ice cores collected from more stable ice accumulation sites on the north-eastern Peninsula, for example at James Ross Island (64.21° S, 57.63° W) (Mulvaney et al., 2012), partially address this issue, but most ice cores from central and southern parts of the Peninsula typically span periods of only 1–2000 years. Some of these contain evidence of the rapid temperature changes seen in instrumental data over the last two decades (Thomas et al., 2009).

There is a reasonable distribution of marine sediment records from the region which document the deglaciation of the continental shelf (Ó Cofaigh et al., 2005; Kilfeather et al., 2011; Graham and Smith, 2012), bays and fjords (Taylor et al., 2001) and, in some cases changes in sea ice extent, ocean circulation, biological production and ecology (Domack, 2002; Allen et al., 2010). Some of these are reliably-dated using radiocarbon ages from discrete calcareous macrofossils whose marine reservoir effects are well-constrained by modern specimens (e.g., Domack et al., 2001; Allen et al., 2010).

On land, cosmogenic isotope exposure dating is beginning to constrain the onset of deglaciation (Bentley et al., 2006, 2011) (Fig. 1e). Epishelf lake sediments have provided records of ice shelf retreat (Bentley et al., 2005b; Hodgson et al., 2006; Smith et al., 2007a; Roberts et al., 2008), and geomorphological and palaeolimnological studies, evidence of the deglaciation and emergence of a former subglacial lake (Hodgson et al., 2009a, 2009b). However, to date, lake sediment records documenting environmental changes in the region between 63 and 70° South are limited (e.g., Wasell and Håkansson, 1992), and lake sediment proxies that reveal important information about changes in temperature (as a result of its influence on lake ice cover and within lake production), deglaciation, and sea level change (Hodgson et al., 2004; Hodgson and Smol, 2008) have been under exploited.

To address this, we present detailed multi-proxy analyses of two lake sediment cores from islands within a small archipelago in northern Marguerite Bay on the southern Antarctic Peninsula; one from a freshwater lake on Horseshoe Island and one from a coastal isolation basin on Pourquoi-Pas Island. This is supplemented by information on relative sea level change and marine conditions from surveys of raised beaches at three different locations within Marguerite Bay.

2. Site descriptions

All field sites are located in Marguerite Bay (68° 30′ S, 068° 30′ W), which is the most extensive embayment on the west side of the Antarctic Peninsula, bounded to the north by Adelaide Island and the Arrowsmith Peninsula and to the south by Alexander Island and George VI Sound (Fig. 1). From north to south it measures approximately 270 km and from east to west, 150 km. Outlet glaciers from the Antarctic Peninsula and Alexander Island drain into the northern, eastern and south-western parts of the bay. In the southern part of Marguerite Bay, George VI Ice Shelf, which occupies George VI Sound, discharges north into Marguerite Bay and south into the Bellingshausen Sea. The submarine Marguerite Trough, formed by the earlier grounded ice stream in this location, extends from the George VI Sound, to the edge of the continental shelf. This trough is between 50 and 80 km in width and roughly 370 km in length (Fig. 1c). It is over-deepened from approximately 500 m at the shelf edge to 1500 m in inner Marguerite Bay (Ó Cofaigh et al., 2005; Graham et al., 2011).

2.1. Horseshoe Island

Horseshoe Island (67° 51′ S, 67° 12′ W), one of the larger islands in northern Marguerite Bay, is situated at the entrance to Bourgeois Fjord (Fig. 1c, d). The underlying bedrock consists of foliated granitic gneisses of the Antarctic Peninsula Metamorphic Complex and undifferentiated volcanic rocks of the Antarctic Peninsula Volcanic Group (Matthews, 1983b). There are marked topographic differences between the northern part of the island which consists of low lying topography dominated by Mount Searle (537 m) and the more mountainous southern part dominated by Mt Breaker (879 m) and the Shoesmith Glacier that discharges into Gaul Cove. Between these is a narrow, largely ice-free elevated central col (Figs. 1d and 2a, b), the remnant of a major shear zone of uncertain age (Matthews, 1983b). There are four small lakes located on this central col at altitudes of between c. 80 and 140 m a.s.l. The lake studied, 'Col Lake 1' (unofficial name) (67° 49.870′ S, 67° 13.937′ W; Fig. 2b), is an elongate, shallow clear water lake, 162 m long, 64 m wide and 3.2 m deep situated at an altitude of c. 80 m above sea level.

2.2. Pourquoi-Pas Island

Pourquoi-Pas Island (67° 41′ S, 67° 30′ W) is a mountainous and heavily glaciated island situated to the north of Horseshoe Island (Fig. 1c). Its topography is dominated by Mt Verne 1635 m and Mt. Arronax 1540 m (Fig. 1e). The underlying bedrock consists of undifferentiated volcanic rocks of the Antarctic Peninsula Volcanic Group (Matthews, 1983a). Lower altitude ice-free areas are covered in a thick silty diamict with frost-sorted polygons, whilst bedrock is exposed on the higher ridges. Glacial striations run south-east to north-west, sub-parallel with the topographic axis of The Narrows. The study lake 'Narrows Lake' (unofficial name) is located on the north-eastern ice free coast adjacent to The Narrows (67° 36.054′ S, 67° 12.449′W) (Figs. 1e and 2c, d). The lake is 125 m long, and 6.2 m deep with a sill height of at 19.41 m above the present high water mark in The Narrows.