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# Holocene glacial and climate history of Prince Gustav Channel, northeastern Antarctic Peninsula

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ABSTRACT

The Antarctic Peninsula is one of the most rapidly warming regions on Earth, as evidenced by a recent increase in the intensity and duration of summer melting, the recession of glaciers and the retreat and collapse of ice shelves. Despite this, only a limited number of well-dated near shore marine and lake sediment based palaeoenvironmental records exist from this region; so our understanding of the longer-term context of this rapid climate change is limited. Here we provide new well-dated constraints on the deglaciation history, and changes in sea ice and climate based on analyses of sedimentological proxies, diatoms and fossil pigments in a sediment core collected from an isolation basin on Beak Island in Prince Gustav Channel, NE Antarctic Peninsula (63°36′S, 57°20′W). Twenty two radiocarbon dates provided a chronology for the core including a minimum modelled age for deglaciation of 10,602 cal yr BP, following the onset of marine sedimentation. Conditions remained cold and perennial sea ice persisted in this part of Prince Gustav Channel until c. 9372 cal yr BP. This was followed by a seasonally open marine environment until at least 6988 cal yr BP, corresponding with the early retreat and disintegration of the ice shelf in southern Prince Gustav Channel. Following isolation of the basin from 6988 cal yr BP a relatively cold climate persisted until 3169 cal yr BP. A Mid-late Holocene climate optimum occurred between 3169 and 2120 cal yr BP, inferred from multiple indicators of increased biological production. This postdates the onset of the Mid-late Holocene climate optimum in the South Shetland Islands (4380 cal yr BP) and the South Orkney Islands (3800 cal yr BP) suggesting that cooler climate systems of the Weddell Sea Gyre to the east of the Peninsula may have buffered the onset of warming. Climate deterioration is inferred from c. 2120 cal yr BP until 543 cal yr BP. This was followed by warming. Superimposed on this warming trend, the instrumental record of recent warming at nearby Hope Bay is mirrored by a recent increase in the lake's primary production and a shift in the diatom communities in the uppermost 3 cm of sediments, suggesting that this is amongst the first records to show an ecological response to recent rapid temperature increase. These new constraints on glaciological and climate events in Prince Gustav Channel are reviewed in the context of wider changes in the Antarctic region.



## 1. Introduction

The Antarctic Peninsula (AP) is particularly sensitive to climate change. Currently it is one of the most rapidly warming regions on Earth, with temperatures rising at six times the global mean (0.6 ± 0.2 °C) during the 20th century (Houghton et al., 2001; Vaughan et al., 2003). This warming has resulted in an acceleration in the intensity and duration of summer melting by up to 74% since 1950 (Vaughan, 2006), the recession of snowfields and glaciers (Cook et al., 2005), and a reduction in the duration of sea ice cover (Parkinson, 2002). It has also been linked to the retreat and collapse of ice shelves (e.g., Vaughan and Doake, 1996; Rott et al., 1998; Scambos et al., 2003; Hodgson, 2011) causing increased flow velocities of their feeder glaciers (De Angelis and Skvarca, 2003; Scambos et al., 2004).

In order to better understand the longer-term context of these anomalies, ice, marine, and lake sediment cores, together with geomorphological evidence, are being used to reconstruct palaeoenvironmental changes through the Holocene. To date, most ice

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cores from the AP region only span a few thousand years, although a new ice core extracted from James Ross Island is predicted to span the late glacial and Holocene (Mulvaney et al., 2007). Therefore, investigations of the deglaciation of the Antarctic Peninsula Ice Sheet from its Last Glacial Maximum (LGM) limits, and the regional Holocene climate evolution have largely been derived from marine sediment cores, for example in Marguerite Bay (Ó Cofaigh et al., 2005), Lallemand Fjord (Taylor et al., 2001), Bismark Strait (e.g., Domack, 2002) and Bransfield Strait (e.g., Barcena et al., 1998). On land, records have been derived from lake sediment cores, for example from Alexander Island (e.g., Bentley et al., 2005; Smith et al., 2007; Roberts et al., 2008), Horseshoe Island (Wasell and Håkansson, 1992), the western and northern islands of the Antarctic Peninsula (e.g., the South Shetland Islands; Björck et al., 1993), James Ross Island (e.g., Björck et al., 1996), and the South Orkney Islands (Jones et al., 2000; Hodgson and Convey, 2005). Well-dated terrestrial and near shore marine records spanning the entire Holocene are however still rare, particularly along the northeastern margin of the AP, the Weddell Sea margin, and the western margin of the AP between the South Shetland Islands and Marguerite Bay (Bentley et al., 2009; Hodgson et al., 2009).

Although the deglaciation of the Antarctic Peninsula Ice Sheet since the LGM, and Holocene environmental and climate changes are poorly constrained in some areas, attempts have been made to formulate a regional consensus (e.g., Hjort et al., 2003; Ingólfsson et al., 2003; Bentley et al., 2009; Hodgson et al., 2009). However, the limited number of records from the AP means that there are still considerable gaps in understanding, for example of the differences in the climate and glaciological history of the east vs. the western margin of the AP, and between the AP and other regions of Antarctica.

In this paper, we analyse the record of palaeoenvironmental change from sediments that have accumulated in an isolation basin on Beak Island in northern Prince Gustav Channel (Figs. 1 and 2). We integrate a radiocarbon dated stratigraphy, sedimentological, fossil diatom and pigment analyses to reconstruct and constrain the timing of the main glaciological and palaeoclimate events occurring there during the Holocene.

## 2. Site description

Beak Island (63°36′S, 57°20′W) is a partially emerged periphery of an inactive volcanic caldera situated in Prince Gustav Channel between Vega Island and the Tabarin Peninsula (Figs. 1 and 2a). The island is composed of Miocene volcanic rocks, mainly porphyritic basalt, hyaloclastites and pillow lavas, belonging to the James Ross Island Volcanic group (Bibby, 1966). Beak Island is currently free of permanent snow fields, ice caps or glaciers, and is assumed to have a similar continental climate regime to the Tabarin Peninsula (28 km to the northeast) where mean annual temperatures are −5.3 °C and mean annual precipitation 60.53 mm (Data from Base Esperanza, Hope Bay). The regional climate is influenced by (1) the westerly storm tracks bringing humid, warm air from the northwest, and by (2) the cold barrier winds bringing arid air-masses from the south and southwest (i.e., the Weddell Sea) (Björck et al., 1996). The region is influenced by the rain shadow effect of the mountains of the Antarctic Peninsula. Snowfall periodically occurs during summer, followed by rapid melting and long dry periods.

Several lakes and ponds occur on the island (Fig. 2a, b). Beak Lake 1 (63°36′38″S, 57°20′20″W, the name is unofficial) is the largest and deepest lake (c. 24 m), it is near circular, with a diameter of c. 400 m and occupies a depression created by a secondary eruption vent. The current retaining sill height is 10.95 ± 10 cm above the present high tide mark and is lower than the 14.91 ± 10 cm m a.s.l. Holocene marine limit (Fig. 2a; Roberts et al. 2011). The lake is flanked by a >10 m rock cliff 200 m to the west and northwest, and is bordered by periglacially patterned ground to the north, east and south. Moss banks occur on the north-western shores of the lake, and are dissected by a series of small, braided meltwater streams emanating from a snow bank on the adjacent slope (Fig. 2b). Beak Lake 1 has a single outflow to the southwest, which discharges to the sea via a series of ponds and raised shorelines. The outflow is vegetated by thick orange and green microbial mats and was nearly inactive at the time of sampling (January 2006). Ice cover is likely to persist for 8–9 months per year.

## 3. Methods

### 3.1. Lake sediment coring

Following routine limnological measurements (cf. Hodgson et al., 2001), core sites were selected on the basis of bathymetric mapping with a hand-held echo sounder along static lines. Sediment cores were collected at 20 m water depth using a Livingstone corer (Wright, 1967). One core sequence (sections BK 1E and BK 1D) was sectioned at 0.5 cm resolution in the field, sealed in sterile Whirlpack bags and stored frozen; a duplicate core (BK1G) was retained intact for high resolution, non-destructive core scanning.

### 3.2. Geochronology

A chronology for the sediment sequence was established by AMS radiocarbon ($^{14}C$) dating of macrofossils of the aquatic moss *Cratoneuropsis Chilensis* (also referred to as *Cratoneuropsis relaxe subsp. minor*) (Ochyra, 2008, Ochyra pers. comm.), and macrofossils of lacustrine cyanobacteria. Bulk (inorganic) sediments were dated in 7 samples where no macrofossils were present. Paired cyanobacterial mat and moss macrofossils were analysed at 15.5–16 cm, and overlaps between core sections were independently dated at 73–74 cm.

Macrofossils were hand-picked from frozen bulk material, after overnight defrosting at 5 °C, immersed in ultra-pure (18.2 m Ohm) water, sealed and placed in an ultrasonic bath for an hour and then refrozen and stored. Samples were sent frozen to the Scottish Universities Environmental Research Centre (SUERC) and Beta Analytic (Miami, Florida) for accelerator mass spectrometry (AMS) radiocarbon dating. SUERC-samples were heated in 2 M HCl (80 °C for 8 h), rinsed in deionised water, until all traces of acid had been removed, and dried in a vacuum oven. Inorganic sand and rock fragments in samples SUERC-12947, 12574, 12575, 12576, 12577 were removed by sieving/hand-picking and set aside from finer organic bearing material before combustion. Moss samples dated by Beta Analytic (BETA 288864-67) were leached with a 0.5M–1.0M HCl bath to remove carbonates, heated to 70 °C for 4 h. Leaching was repeated until no carbonate remained, followed by rinsing to neutral 20 times with deionised water, then placed in 0.5%–2% solution of NaOH for 4 h at 70 °C and rinsed to neutral 20 times with deionised water. The process was repeated until no additional reaction (typically indicated by a colour change in the NaOH liquid) was observed. Samples were then leached again in a 0.5M–1.0M HCl bath to remove any $CO_2$ absorbed from the atmosphere by the NaOH soakings and to ensure initial carbonate removal was complete, and then dried at 70 °C in a gravity oven for 8–12 h.

Dates are reported, in years AD for 'modern' moss macrofossils, as conventional radiocarbon years BP ($^{14}C$ yr BP) $\pm 1\sigma$, and as calibrated years BP (cal yr BP relative to AD 1950). For the 'modern' radiocarbon samples calibration was carried out using CALIBomb with the SH1 compilation of Southern Hemisphere datasets (Hua and Barbetti, 2004; Reimer et al., 2004b). The remaining dates were calibrated in CALIB v6 (Reimer and Reimer, 2011) using the SHCal04 $^{14}C$ atmosphere dataset (McCormac et al., 2004; Reimer et al., 2004a) for freshwater samples, the MARINE09 calibration curve (Reimer et al., 2009) for marine samples, and a mixed MARINE09-SH04 curve (50% marine) for samples at the marine–lacustrine transition.