Quaternary Science Reviews 78 (2013) 98–107

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

# Late Holocene ice-flow reconfiguration in the Weddell Sea sector of West Antarctica☆

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ARTICLE INFO

*Article history:*
Received 24 April 2013
Received in revised form
29 July 2013
Accepted 9 August 2013
Available online 3 September 2013

*Keywords:*
Marine ice sheet
Internal layers
Ice rise
Ice sheet stability

ABSTRACT

Here we report Late Holocene ice sheet and grounding-line changes to the Weddell Sea sector of West Antarctica. Internal radio-echo layering within the Bungenstock Ice Rise, which comprises very slow-flowing ice separating the fast-flowing Institute and Möller ice streams, reveals ice deformed by former enhanced flow, overlain by un-deformed ice. The ice-rise surface is traversed by surface lineations explicable as diffuse ice-flow generated stripes, which thus capture the direction of flow immediately prior to the creation of the ice rise. The arrangement of internal layers can be explained by adjustment to the flow path of the Institute Ice Stream, during either a phase of ice sheet retreat not longer than ~4000 years ago or by wholesale expansion of the grounding-line from an already retreated situation not sooner than ~400 years ago. Some combination of these events, involving uplift of the ice rise bed during ice stream retreat and reorganisation, is also possible. Whichever the case, the implication is that the ice sheet upstream of the Bungenstock Ice Rise, which currently grounds over a >1.5 km deep basin has been, and therefore may be, susceptible to significant change.


## 1. Introduction

Ice within the West Antarctic Ice Sheet (WAIS), which is grounded on a bed predominantly below sea level, flows across a ‘grounding line’ into the ocean either directly or via peripheral floating ice shelves. The ice sheet is thought to be susceptible to change as a consequence of ocean-induced ice-shelf melting, which leads to inward migration of the grounding line (Pritchard et al., 2012). This process could result in grounded ice loss, which potentially would raise global sea level by >3 m (Bamber et al., 2009a). Critical to assessing the likelihood of future change is an awareness of significant past changes and an identification of regions susceptible to change.

Although the post-LGM retreat of the WAIS is understood broadly, Holocene adjustments are less well known. These changes are more critical to how the ice sheet may change in the immediate future, since the environmental conditions and ice sheet configuration that led to Holocene change are comparable to today. One location where Late Holocene information is absent is the Weddell Sea sector of the WAIS, where airborne radio-echo sounding (RES) has recently revealed the ice sheet grounding line to be positioned at a major steep reverse bed slope (Ross et al., 2012) making it potentially susceptible to mass loss (e.g. Hellmer et al., 2012).

Here we analyse RES and satellite remote sensing data from the Bungenstock Ice Rise (BIR), a small slow-flowing ice dome that currently separates the fast flowing Institute (IIS) and Möller (MIS) ice streams in the Weddell Sea sector of the WAIS. By analysing the englacial layering and surface form of the ice rise we characterise its glacial history. The consequence of this local glacial history to wider ice sheet changes in the Weddell Sea sector is then discussed.

## 2. RES, internal layers and ice rises

Ice sheet internal layers, measured by RES, occur as a consequence of contrasts in permittivity arising from density changes in the upper few hundred meters of the ice sheet, and in conductivity due to discrete acidic layers of ice that incorporate the aerosol product of volcanic activity deposited on the snow surface (Paren et al., 1975). In slow flowing central regions of ice sheets, and in ice rises that separate ice streams, layering is commonly conformable and continuous over several tens of kilometres (e.g. Siegert, 2003; Siegert and Payne, 2004; Cavitte et al., 2013). Such


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http://dx.doi.org/10.1016/j.quascirev.2013.08.003

layering, as it has a meteoric origin, is thought to be isochronous (Siegert, 1999). In contrast, in fast flowing ice streams layering becomes buckled due to increased englacial stress gradients caused by differential motion, convergent flow, and flow around subglacial obstacles (Jacobel et al., 1993; Siegert et al., 2003; Leysinger Vieli et al., 2007; Ross et al., 2011). Many ice rises, which by definition possess flow divides, contain only conformable layering. If the flow divide remains in the same position, the layering under the divide will take the form of a stack of Raymond Arches (Raymond, 1983; Conway et al., 1999; Vaughan et al., 1999), which are seen in ice rises in parts of the Weddell Sea sector (Hindmarsh et al., 2011). The englacial layering within an ice rise is therefore of value in assessing whether current regional glaciological conditions have prevailed (Martín et al., 2009).

## 3. Bungenstock ice rise and airborne geophysical data

While most ice rises are crossed by a clear divide ridge, the divide over the BIR is only obvious from satellite data over its 'inland' half (Fig. 1a and b). Bordering the ice shelf, the BIR has a lobate apron-like form with no divide ridge (Fig. 1b). Ice velocities across the BIR are very low, rising from 0 m $a^{-1}$ at its centre to ~5 m $a^{-1}$ at the margin (Rignot et al., 2011) (Fig. 1d).

The BIR has been surveyed on several occasions by airborne RES since the late 1970s (e.g. Janowski and Drewry, 1981; Lambrecht et al., 1999, 2007; Ross et al., 2012), revealing that ice thickness ranges from ~1000 m near the grounding line to >2000 m where it adjoins the MIS. Bed topography is noticeably smooth, with depths of 830–1600 m b.s.l. (Fig. 1c). Loose, unconsolidated basal sediments are likely present beneath the BIR, judging by the very low bed roughness, which is similar to that observed across the Siple Coast region (see supplementary information in Ross et al., 2012).

The most recent two RES surveys of the BIR were undertaken by the British Antarctic Survey (BAS) using a coherent system with a carrier frequency of 150 MHz, a bandwidth of 12 MHz and pulse-coded waveform acquisition at a rate of 312.5 Hz. In these surveys, aircraft position was obtained from differential GPS, and the surface elevation of the ice sheet was derived from radar/laser altimeter terrain-clearance measurements. Doppler processing was used to migrate radar-scattering hyperbola in the along-track direction. The onset of the received bed echo was picked in a semi-automatic manner using PROMAX seismic processing

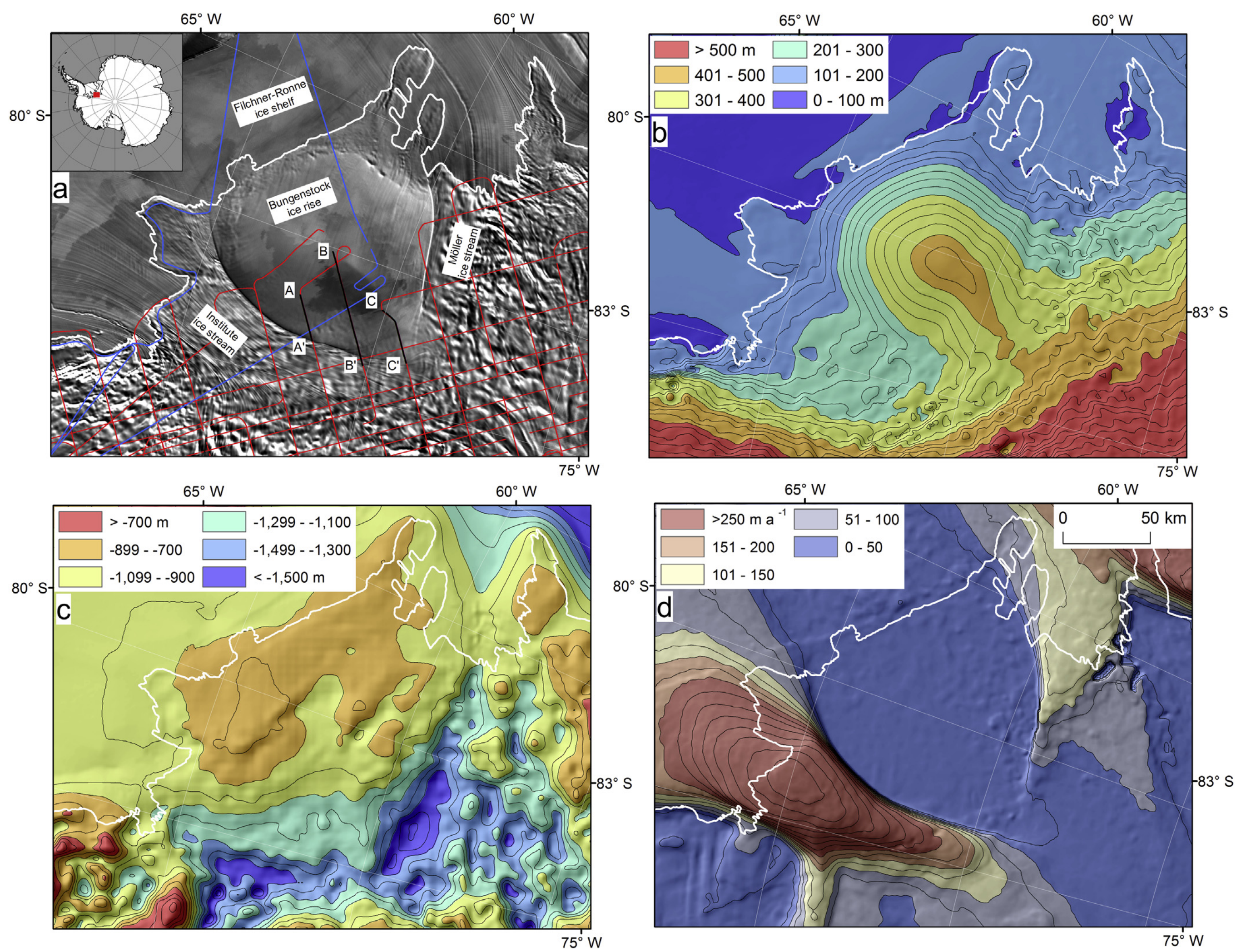


**Fig. 1.** The Bungenstock Ice Rise (BIR). (a) Location of the BIR, existing BAS RES data and MODIS Mosaic of Antarctica (MOA) ice surface imagery (Haran et al., 2006). White line is the existing ice sheet grounding line from the MODIS MOA, blue lines are RES data collected in 2006/7, red lines are RES data collected in 2010/11. The black sections of RES lines are RES transects given in Fig. 2. (b) Ice surface elevation (data from Bamber et al., 2009b). (c) Subglacial topography (data from Fretwell et al., 2013). (b) and (c) are referenced to the WGS84 geodetic system. (d) Ice surface velocity (data from Rignot et al., 2011).