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Late Quaternary grounded ice extent in the Filchner Trough, Weddell Sea, Antarctica: new marine geophysical evidence

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ABSTRACT

The Last Glacial Maximum (LGM; ca 23–19 ka BP) extent of grounded ice in the Filchner Trough, a major cross shelf trough extending seaward from the Filchner Ice Shelf in the southern Weddell Sea, has been much debated. Here we present data from the first extensive multibeam swath bathymetry and sub-bottom acoustic profiling surveys in the Filchner Trough that include several parallel survey lines with overlapping swaths. We interpret these new data, combined with published observations and radiocarbon dates from sediment cores, as indicating that the grounding line in the Filchner Trough during the LGM advanced beyond the middle shelf, probably to within 40 km of the shelf break, and possibly reached the shelf break. Three different hypotheses are discussed that could reconcile this interpretation with interpretations, based on ice coring and surface exposure age data, that LGM ice surface elevations in areas draining into the Filchner and Ronne ice shelves were no more than a few hundred metres higher than today: (1) ice plain conditions extended along most of the Filchner Trough; (2) the ice shelf advanced and thickened so that it "touched down" on the continental shelf for a short period; (3) LGM ice drainage pathways in the interior of the Weddell Sea embayment were different from those observed today.

1. Introduction

Almost a quarter of the area of the grounded Antarctic Ice Sheet (AIS) drains through the Filchner and Ronne ice shelves into the Weddell Sea (Fig. 1; Rignot et al., 2011). Therefore, constraining the changes that have taken place in this sector of the ice sheet since the LGM is essential for quantifying the overall contribution of the AIS to the global sea-level lowstand of ca -130 m at the LGM. Knowledge of such changes is also important for determining the potential for this region to have contributed to global meltwater pulses during the last deglaciation (Bassett et al., 2007; Bentley et al., 2010; Deschamps et al., 2012), as well as for understanding the sensitivity of the AIS to changing climate, and hence predicting its future contribution to sea-level rise. Furthermore, the past configuration of glacial ice on the southern Weddell Sea continental shelf has implications for the production of deep and bottom water masses that constitute an essential component of the global thermohaline circulation (e.g. Rahmstorf, 2002). Today, 50–70% of all Antarctic Bottom Water (AABW) is produced in the Weddell Sea (Naveira Garabato et al., 2002; Nicholls et al., 2009). If the grounding line extended to the shelf edge all along the southern Weddell Sea margin, there would have been no sub-ice-shelf cavity with a landward-dipping sea bed, a situation thought to be necessary for formation of the Ice Shelf Water that is an important pre-cursor of AABW today (Foldvik and Gammelsrød, 1988).

The Filchner Trough extends more than 450 km beyond the 2011 Filchner Ice Shelf front to the continental shelf edge in the southern Weddell Sea (Fig. 1). It has typical characteristics of a glacially-carved Antarctic shelf trough, its axial depth decreasing from >1200 m at the ice front to 630 m at the shelf edge. Its width also decreases with distance from the ice front, from 175 to 125 km, measured at the 500 m depth contour. However, there is debate about when the trough was carved and whether or not it was filled by grounded ice during late Quaternary glacial periods. Hein et al. (2011) considered that the trough may have been carved by an expanded Antarctic Ice Sheet in the Middle Miocene, about 14 million years ago, and that subsequently its great depth has limited grounding line advances. Other authors have also concluded that the grounding line did not advance far along the trough during the LGM and that it was covered by an ice shelf (Bentley et al., 2010; Le

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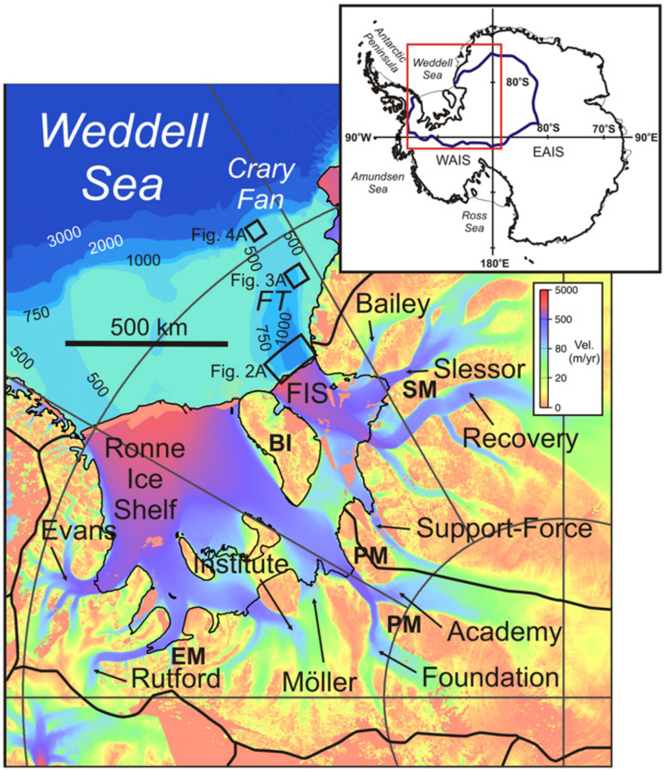

Fig. 1. Location and general physiography of the Filchner Trough (FT). Regional bathymetry from GEBCO 2003 dataset (IOC, IHO and BODC, 2003) depicted by colour changes at 250 m intervals shallower than 1000 m and at 1000 m intervals in deeper water. Areas shown in Figs. 2A, 3A and 4A are marked by boxes. Contemporary ice flow velocity data from Rignot et al. (2011) are shown in ice sheet and ice shelf areas. Black lines on the ice sheet mark the main ice drainage divides. Major ice streams are labelled, with their locations indicated by arrows. On inset, red box shows location of main map and blue line marks limit of ice drainage basins from which ice flows into the Filchner and Ronne ice shelves. FIS – Filchner Ice Shelf; BI – Berkner Island; SM – Shackleton Mountains; PM – Pensacola Mountains; EM – Ellsworth Mountains; EAIS – East Antarctic Ice Sheet; WAIS – West Antarctic Ice Sheet. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Brocq et al., 2011). In contrast, Hillenbrand et al. (2012) reviewed available sedimentological data and radiocarbon dates from shelf sediment cores and considered them to be consistent with ice-sheet grounding across the entire Weddell Sea shelf at the LGM. Some earlier studies had also concluded that the Filchner Trough was covered by grounded ice at the LGM (Elverhøi, 1981), or that grounded ice extended to the outer shelf within the trough (Bentley and Anderson, 1998). In a recent paper, however, Stolldorf et al. (2012) reclassified some of the diamictons, which had been recovered in cores from the shelf within and to the east of the Filchner Trough and which had been previously interpreted as subglacial tills, as glaciomarine sediments and presented new radiocarbon dates from these sediments. The authors concluded from the ages that the last grounded ice advance in this area occurred before ca 30.5 ka BP and thus pre-dated the LGM, but they also pointed out that that the age of tills in Filchner Trough itself remains unconstrained.

Berkner Island ice core data and surface exposure ages from the Shackleton and Ellsworth mountains (Fig. 1) have been interpreted as indicating that LGM ice surface elevations in areas draining into the Filchner and Ronne ice shelves were, at most, only a few hundred metres higher than today (Fogwill et al., 2004; Mulvaney et al., 2005; Bentley et al., 2010; Hein et al., 2011). These interpretations imply that if grounded ice did extend far onto the continental shelf it must have had a very low surface gradient (Hillenbrand et al., 2012).

Until recently, little evidence from marine studies had been published pertaining to the extent of grounded ice in the Filchner Trough during late Quaternary glacial periods (Elverhøi, 1981; Melles and Kuhn, 1993; Bentley and Anderson, 1998). However, Hillenbrand et al. (2012) reviewed data from marine sediment cores and acoustic sub-bottom profiles collected in the southern Weddell Sea, including previously unpublished findings. The available evidence suggested that ice had been grounded even on the outer shelf and in the deepest parts of the Filchner and Ronne troughs at the LGM (cf. Bentley and Anderson, 1998). Hillenbrand et al. (2012) also highlighted the need for detailed bathymetric data to determine the presence or absence of subglacial bedforms, particularly on the outer shelf and in the deepest parts of the Filchner and Ronne Troughs. Spatially limited multibeam data collected directly in front of the Filchner and Ronne Ice Shelves were recently published by Stolldorf et al. (2012). These data revealed subglacial lineations on the deeper parts of the shelf and iceberg furrows on the shallower parts.

In this paper, we present multibeam swath bathymetry data and sub-bottom acoustic profiles collected in three areas within the Filchner Trough: one near the ice front, one mid-way along the trough, and the third near the shelf edge. Due to the great extent of the trough, only a fraction of it could be surveyed during a single research cruise, so we targeted these three areas in order to constrain the past extent of grounded ice. Sea ice coverage was also a factor that influenced the precise locations of the areas surveyed. We interpret the bedforms and acoustic stratigraphy revealed by these data and, in the light of the available sediment core data, discuss their implications for LGM grounded ice extent and dynamic behaviour.

2. Methods

In February 2011, on RRS *James Clark Ross* Cruise JR244, we collected multibeam swath bathymetry data and sub-bottom acoustic profiles over the Filchner Trough (Fig. 1). The multibeam echo sounding system was a Kongsberg EM120, with 191 beams, each $1^\circ \times 1^\circ$, in the frequency range 11.25–12.75 kHz. The system corrects for vessel roll, pitch and yaw using real-time electronic beam steering based on data supplied by a Seatex Seapath 200 motion sensor unit. Maximum beam angles used were 66° from vertical. Vertical measurement accuracy is 0.2% of root mean square depth (manufacturer's specifications). Horizontal accuracy is <5 m for small beam angles. Although horizontal uncertainty is expected to increase with increasing beam angle, the fact that mismatches are not evident in sea-floor features crossing overlapping swath edges provides confidence that uncertainty remains smaller than the scale of features imaged.

Sub-bottom echo sounder profiles were collected along all survey lines using a Kongsberg TOPAS PS 018 system, transmitting two primary frequencies around 18 kHz to generate 10 to 15 ms-long secondary chirp pulses with frequencies ranging from 1300 to 5000 Hz and a $5^\circ \times 5^\circ$ beam width. In this configuration, the TOPAS can image acoustic layering in unconsolidated sediments to a depth of more than 50 m below the sea floor with a depth resolution of better than 1 m. Data were digitally recorded at a sampling rate of 20 kHz. Traces were cross-correlated with the secondary transmission pulse signature and instantaneous amplitude records derived from the correlated output were displayed as variable density traces. Navigation data were acquired using a Seatex GPS receiver.

In two of the Filchner Trough areas surveyed, some multibeam swath bathymetry data had been collected previously using the