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New constraints on the timing of West Antarctic Ice Sheet retreat in the eastern Amundsen Sea since the Last Glacial Maximum

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ABSTRACT

Glaciers flowing into the Amundsen Sea Embayment (ASE) account for >35% of the total discharge of the West Antarctic Ice Sheet (WAIS) and have thinned and retreated dramatically over the past two decades. Here we present detailed marine geological data and an extensive new radiocarbon dataset from the eastern ASE in order to constrain the retreat of the WAIS since the Last Glacial Maximum (LGM) and assess the significance of these recent changes. Our dating approach, relying mainly on the acid insoluble organic (AIO) fraction, utilises multi-proxy analyses of the sediments to characterise their lithofacies and determine the horizon in each core that would yield the most reliable age for deglaciation. In total, we dated 69 samples and show that deglaciation of the outer shelf was underway before 20,600 calibrated years before present (cal yr BP), reaching the mid-shelf by 13,575 cal yr BP and the inner shelf to within ca. 150 km of the present grounding line by 10,615 cal yr BP. The timing of retreat is broadly consistent with previously published radiocarbon dates on biogenic carbonate from the eastern ASE as well as AIO ^{14}C ages from the western ASE and provides new constraints for ice sheet models. The overall retreat trajectory – slow on the outer shelf, more rapid from the middle to inner shelf – clearly highlights the importance of reverse bedslopes in controlling phases of accelerated groundling line retreat. Despite revealing these broad scale trends, the current dataset does not capture detailed changes in ice flow, such as stillstands during grounding line retreat (i.e., deposition of grounding zone wedges) and possible readvances as depicted in the geomorphological record.

1. Introduction

Assessing the duration, timing and forcing of past ice sheet retreat is essential if we are to fully understand the controls on recent ice sheet changes and predict their future behaviour (Bentley et al., 2014). Accurately dated ‘retreat trajectories’ are particularly needed for the Amundsen Sea sector of the West Antarctic Ice Sheet (WAIS), where glaciers have accelerated and thinned dramatically and now account for >35% of its total discharge (Rignot, 1998; Rignot et al., 2008; Shepherd et al., 2012). These changes have been accompanied by a rapid inland retreat of the grounding line (GL) of Pine Island Glacier (PIG) (Joughin et al., 2010) and Thwaites Glacier (Tinto and Bell, 2011) raising concern that large-scale collapse is possible on human timescales (Katz and Worster, 2010; Gladstone et al., 2012; Favier et al., 2014; Joughin et al., 2014). Complete collapse of the glaciers in this region would raise global sea level by ~1.5 m and although this remains a possibility, recent estimates suggest that melting of PIG alone will contribute 3.5–10 mm over the next 20 years (Favier et al., 2014). The coherent thinning of glaciers across the Amundsen Sea Embayment (ASE) has been attributed to the melting of the floating ice shelves by warm Circumpolar Deep Water (CDW) upwelling onto the continental shelf (Jacobs et al., 1996, 2011,; Shepherd et al., 2004; Walker et al., 2007), with modelling studies showing that this imbalance is propagated upstream thus affecting the whole ice stream system (Payne et al., 2004).

This work has focussed attention on when the imbalance was initiated, and whether it represents a recent change related to variations in the delivery of CDW onto the shelf (Thoma et al., 2008; Steig et al., 2012) or some other internal or external trigger (i.e., topography, ice dynamics) that occurred sometime in the recent geological past, e.g. following deglaciation from the LGM (19–23 kyr). According to Larter et al. (2014) the rates of change currently observed in the ASE are too high

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to be a simple continuation of deglaciation from the LGM as such high modern retreat rates (i.e., 0.95 ± 0.09 km yr^{-1} between 1992 and 2011; Park et al., 2013) would have resulted in deglaciation of the entire continental shelf within 500 years, which is in conflict with recent marine geological data (e.g., Smith et al., 2011). There is also a growing body of geomorphological evidence that ice sheet retreat following the LGM was oscillatory with periods of rapid change punctuated by periods of relative stability (Graham et al., 2010; Jakobsson et al., 2011).

However, despite recent progress in dating the timing of ice sheet retreat in the ASE (see recent review by Larter et al., 2014) much of the detail, including oscillations in GL positions and the duration of still-stands, is yet to be fully resolved. This reflects two fundamental, but persistent problems: (1) lack of data from key areas of the shelf owing to the logistical challenges of working in the ASE, both in terms of distance from Antarctic research stations and persistent sea ice coverage; and (2) significant challenges associated with dating marine sediments on the Antarctic continental shelf. In this context, the scarcity of calcareous (micro-)fossils in combination with the large and variable input of reworked fossil organic carbon from the hinterland has hampered efforts to establish detailed retreat histories, especially when attempting to constrain the subglacial to glacier-proximal transition. Notwithstanding these problems, recent studies from the Bellingshausen Sea and western ASE shelf have demonstrated that with a careful sampling strategy guided by detailed sedimentological information, reliable deglacial chronologies can be produced using the acid insoluble organic (AIO) fraction (Hillenbrand et al., 2010a; Smith et al., 2011). This approach requires a local reservoir correction, achieved by dating the surface sediments (usually obtained from box cores) and subtracting this age from down-core ages (cf. Andrews et al., 1999), alongside sufficient down-core dates to identify major steps in ^{14}C age progression (so-called ^{14}C dog-legs). In the western ASE the validity of this approach has been verified by other independent dating methods (relative palaeomagnetic intensity (RPI) and paired carbonate–AIO dating; e.g., Hillenbrand et al., 2010b; Smith et al., 2011) illustrating that with careful sample selection, reliable deglacial chronologies can be obtained even when biogenic carbonate is sparse.

The current paper presents a new AIO-based deglacial chronology for the eastern ASE, which complements and significantly expands upon the largely carbonate-based deglacial ages recently published by Kirshner et al. (2012) and Hillenbrand et al. (2013) and provides a key dataset for the ice sheet modelling community. Whilst our new deglacial framework further demonstrates the utility of a careful AIO-based dating strategy, the lack of core material from key areas as well as a highly variable input of reworked fossil organic carbon, particularly in the central part of Pine Island-Thwaites Palaeo-Ice Stream Trough (PIT) trough continues to represent challenges. We discuss these limitations in the context of geomorphological data which shows a stepped retreat across the outer to mid-shelf and summarise what we can (and cannot) say about the trajectory of ice sheet retreat in the eastern ASE.

1.1. Study area and previous work

The glacial history of the ASE has recently been reviewed by Larter et al. (2014) so it is only briefly described here. The gross bathymetry of the ASE is characterised by cross-shelf bathymetric troughs which mark the former pathways of ice streams that advanced to, or close to, the continental shelf edge during Late Quaternary glacial periods (Fig. 1) (Evans et al., 2006; Nitsche et al., 2007; Graham et al., 2009; Larter et al., 2009; Graham et al., 2010; Kirshner et al., 2012). Geomorphological mapping of the inner-mid-shelf showed that the Pine Island and Thwaites glaciers converged to a single palaeo ice stream (PITPIS) as the WAIS advanced across the shelf (Fig. 1). PITPIS was topographically constrained on the inner to mid-shelf by the main Pine Island Trough (PIT). The main trough then bifurcates on the outer shelf into western and eastern branches referred to as Pine Island Trough West (PITW) and East (PITE) (Evans et al., 2006; Graham et al., 2010; Jakobsson et al., 2012). Streaming ice was also concentrated along the eastern coastline (Cosgrove–Abbot Trough) (Fig. 1) with a connection to ice flowing out of Ferrero Bay in the south (Fig. 1) but separated from PITPIS by an area of slower moving ice around Burke Island (Klages et al., 2013; Klages, 2014). Well-developed grounding zone wedges (GZWs) occur along the PITE and main trough axis (GZW1–5; Graham et al., 2010) with extensions in the Cosgrove–Abbot troughs (GZWa-c; Kellogg & Kellogg, 1987; Klages, 2014) suggesting a stepwise and uniform retreat across the entire eastern ASE (Fig. 1). Jakobsson et al. (2012) also described a series of regular 1–2 m-high corrugated ridges seaward of GZW3 associated with and transverse to curvilinear–linear furrows (Jakobsson et al., 2011, 2012). The ridges have been interpreted as impressions resulting from the grounding of tidally-influenced icebergs that were calved directly from the GL during an ice shelf collapse from a GL position seaward of GZW3.

The timing of GL retreat is still poorly known, particularly on the outer and mid shelf areas. Kirshner et al. (2012) showed that glaciomarine sediments had started to accumulate seaward of GZW1 sometime before 16.4 cal kyr BP (core PC07) and also argued that grounded ice had retreated seaward of GZW5 before 12.3 cal kyr BP. The authors also speculated that this was followed by a second phase of ice shelf presence (12.3–10.6 cal kyr BP; KC19) and break-up (KC23) (Kirshner et al., 2012). Inland of GZW5, Hillenbrand et al. (2013) demonstrated that inner Pine Island Bay (PIB) was free of grounded ice by 11.2 cal kyr BP in core PS75/214-1 (NB: age recalibrated using MRE of 1300 ± 70 years). Larter et al. (2014) has recently questioned whether the ages published in Kirshner et al. (2012) and Hillenbrand et al. (2013) are compatible as they would imply (1) very rapid retreat across the mid to inner shelf (i.e., between KC19 and PS75/214-1, Fig. 1); and (2) a large ice shelf extending more than 200 km from the GL after its retreat into inner PIB. According to Larter et al. (2014) the apparent inability to accommodate the published chronological data with the geomorphological record could suggest that one of the age-datasets or facies interpretations is misleading. In addition, Graham et al. (2013) has also suggested that the corrugations may have been formed by other non-collapse bed-forming processes leaving room for an alternative deglaciation model for the eastern ASE. In light of these uncertainties, new chronological data is required to improve our understanding of the glacial history of this rapidly changing area.

2. Methods

Gravity cores (GC) and vibro-cores (VC) were recovered during expeditions JR141 and JR179 with RRS *James Clark Ross* and ANT-XXIII/4 and ANT-XXVI/3 with RV *Polarstern* to reconstruct the glacial history of the eastern ASE (Gohl, 2007; Larter et al., 2007; Enderlein and Larter, 2008). Undisturbed seabed surface sediments were collected with (giant) box corers (GBC or BC). Core sites were focused along transects in the main PIT, PITE, and Abbot and Cosgrove troughs (Fig. 1) with locations identified using an acoustic sub-bottom profiler. Physical properties (magnetic susceptibility, wet bulk density (WBD), and P-wave velocity) were measured on whole cores using GEOTEK multisensor core loggers (MSCL) at the British Ocean Sediment Core Research Facility (Southampton, UK) and at the Alfred Wegener Institute (AWI, Bremerhaven, Germany). The core sections were split at AWI and British Antarctic Survey (BAS) and shear strength was measured every 10–20 cm with a hand-held shear vane. Lithology, colour and sedimentary structures were described visually on the split cores and supplemented using smear-slides and X-radiographs. Individual sediment sub-samples (1 cm-thick slices) were then taken every 5–20 cm to determine contents of water, total carbon (TC), organic carbon (C_{org}) and total nitrogen (N_{tot}) and to analyse grain-size composition using techniques outlined in Smith et al. (2011). The relative contents of the clay minerals smectite, illite, chlorite and kaolinite were determined on an aliquot of the <2 μm fraction using standard X-ray diffraction