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The presence of polynyas in the Weddell Sea during the Last Glacial Period with implications for the reconstruction of sea-ice limits and ice sheet history

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ABSTRACT

Cores from a contourite drift on the continental slope in the NW Weddell Sea, Antarctica, contain up to four sandy foraminifer-rich layers (WA1–4), with dispersed ice-rafted debris (IRD), interbedded with silty–clayey sands and sandy muds. Accelerator Mass Spectrometry (AMS) ^{14}C dating on *Neogloboquadrina pachyderma* from the foraminifer-rich layers WA2 and WA3 yielded ages spanning the Last Glacial Maximum (LGM) and Marine Isotope Stage (MIS) 2 (20,319–28,543 cal yr BP) and the middle part of MIS 3 (41,349–43,242 cal yr BP), respectively. We attribute the high abundances of planktonic and benthic foraminifera to deposition in a seasonally open-marine environment. Given that the NW Weddell Sea shelf was covered by grounded ice at the LGM (and probably during MIS 2 and MIS 3) and that diatom-based reconstructions place the northern limit of winter and summer sea-ice coverage to the north of the core sites during the Last Glacial Period, our results document the presence of a seasonal or perennial polynya in the NW Weddell Sea. The polynya may have been formed by katabatic winds blowing off the Antarctic Peninsula Ice Sheet (APIS) when it was grounded at the continental shelf break, although polynya formation through upwelling of deep water cannot be ruled out. In addition we argue that previously published data from the southern, southeastern and southwestern Weddell Sea as well as the Ross Sea may indicate the widespread occurrence of polynyas along the Antarctic continental margin during the Last Glacial Period. The widespread occurrence of polynyas could help explain how (i) AABW formation (through brine rejection) continued throughout the LGM, and (ii) Antarctic shelf benthos survived glacial periods. The presence of polynyas through glacial periods also has implications for sea-ice reconstructions from ice core records, possibly biasing the signal towards a reduced sea-ice cover. Finally we propose that the fringes of the APIS, which probably influence the presence or absence of polynyas in the NW Weddell Sea, are sensitive to changes in Antarctic temperature that may be related to a reduction in oceanic heat transport from the North Atlantic.

1. Introduction

The formation of Antarctic sea-ice plays a key role in the production of dense, saline waters (brines). Together with super-cooled water masses formed below ice shelves predominantly in the Weddell Sea, these dense brines are the precursors of Antarctic Bottom Water (AABW) (e.g. Keeling and Stephens, 2001; Mackensen, 2001; Stössel et al., 2002; Nicholls et al., 2003; Foldvik et al., 2004; Tamura et al., 2008). Since AABW is one of the principal components of the global thermohaline circulation (e.g., Broecker, 1997; Rahmstorf, 2002) any change to its production rate has the potential to influence global climate.

Of particular importance to the production of brines are polynyas (Grigg and Holbrook, 2001; Tamura et al., 2008). Two types of polynyas exist: coastal polynyas are temporary, spatially isolated open-ocean areas (up to a few 100 km across) within the sea-ice belt around the fringes of the Antarctic ice sheets (e.g. Martin, 2001; Renfrew, 2006). Coastal polynyas result from the offshore advection of pack ice by strong katabatic winds blowing downslope off the ice sheets. The oceanward driven sea-ice is continuously replaced by upwelling water, which rapidly freezes to form new sea-ice (Markus et al., 1998). According to a recent study, around 10% of Southern Ocean sea-ice is produced in such polynyas (Tamura et al., 2008). In contrast, open-ocean polynyas are formed by the upwelling of relatively warm deep water, often over morphological obstacles to deep water flow, such as seamounts (e.g., Holland, 2001; Martin, 2001). In both instances polynyas are regions of enhanced primary and secondary productivity as well as other biogeochemical processes (e.g. Zielinski and Gersonde, 1997; Becquevort and Smith, 2001; Martin, 2001; Arrigo and van Dijken, 2003) that may even have helped to sustain higher trophic life on the Antarctic continental margin during glacial periods (Thatje et al., 2008). In addition, it has been proposed that polynyas were the main “factories” for AABW production during glacial periods, although there are conflicting

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hypotheses as to where the dense precursor water masses of AABW were produced (i.e., on or off the shelf) (cf. Mackensen et al., 1996; Paillard and Parrenin, 2004).

However, despite considerable efforts to reconstruct palaeo-sea-ice cover using diatoms in marine sediments (e.g. Crosta et al., 1998; Gersonde and Zielinski, 2000; Gersonde et al., 2003, 2005; Armand et al., 2005) and, more recently, chemical proxies in ice cores (Wolff et al., 2006; Abram et al., 2007; Fischer et al., 2007) the presence of polynyas has rarely been considered. To date, only a limited number of studies have documented the presence of polynyas and leads during glacial times (e.g., Mackensen et al., 1989) making their distribution around the Antarctic margin poorly constrained. The presence of polynyas is not only important for the production of brines and thus deep water formation, but their distribution also has important implications for sea-ice reconstructions, particularly those based on chemical proxies in ice. Traditionally, concentration of sea-salt in ice cores has been viewed as a proxy for aeolian transport to the Antarctic continent and storminess, being higher during phases of reduced sea-ice cover (i.e., interglacials) and lower during phases of expanded sea-ice cover (i.e., glacials) (Welch et al., 1993; Wolff et al., 2003; 2006). More recently, concentrations of methanesulfonic acid (MSA) have been proposed as potential proxies for sea-ice. MSA is ultimately derived from marine phytoplankton productivity at the sea-ice margin (Kawaguchi et al., 2005). Since this is the only known source of MSA in Antarctic ice cores, it has been suggested that MSA records from near-coastal ice cores can be used to reconstruct biological productivity at palaeo-sea-ice margins and thus palaeo-sea-ice extent (Saigne and Legrand, 1987; Curran et al., 2003). However, the observation that increased sea-salt concentrations occur in Antarctic ice cores during modern winter months, and during glacial periods, led to the suggestion that sea-salt may instead reflect the formation of brine and frost flowers on top of newly formed sea-ice and/or within leads and polynyas (Rankin et al., 2002; Wolff et al., 2003). Similarly, the presence of leads and polynyas within the perennial sea-ice zone may significantly bias MSA based palaeo-sea-ice reconstructions towards a reduced sea-ice signal.

Here we use previously undated glaciomarine sedimentary sequences recovered from a contourite drift in the NW Weddell Sea to document the presence of a polynya within the perennial sea-ice belt of the Last Glacial Period, i.e. during Marine Isotope Stage (MIS) 2, (29 to 14 kyr), and the middle part of MIS 3 (57 to 29 kyr) (timescale of Lisiecki and Raymo, 2005). We then set our observations into context with additional, previously published marine sedimentary records and show that polynyas may have been common around Antarctica during the Last Glacial Period. We also discuss their implications for Antarctic Ice Sheet dynamics and possible links to global climatic events.

2. Oceanography and sediments in the NW Weddell Sea

The NW Weddell Sea (Fig. 1) lies on the western margin of the clockwise-flowing Weddell Gyre, a region in which the formation of dense water masses contributes between ~50% and 70% to the total production of AABW (e.g. Orsi et al., 1999; Naveira Garabato et al., 2002; and references therein). AABW and its parent water masses are mainly produced under ice shelves and in polynyas on the shelf of the southern Weddell Sea (e.g. Gordon et al., 2001; Mackensen, 2001; Nicholls et al., 2003; Foldvik et al., 2004). The newly formed AABW then flows in a generally northward direction as a contour current along the continental margin east of the Antarctic Peninsula (Foster and Middleton, 1980; Naveira Garabato et al., 2002).

Sediment cores PD60, KC85, KC88 and KC89 were recovered from a contourite drift formed on the continental slope in the NW Weddell Sea (Fig. 1B and Fig. 2; Table 1), just to the south of the modern average summer sea-ice edge, but north of the minimum summer sea-ice edge (Fig. 1A) (Pudsey, 2002). The four cores show a compositional and textural cyclicity between two distinct facies types (Gilbert et al., 1998; Pudsey, 2002) (Fig. 3). Facies A is characterised by fine-grained sands and silty sands, dispersed gravelly ice-rafted debris (IRD), planktonic foraminifera (*Neogloboquadrina pachyderma* left coiling) and benthic foraminifera (for detailed assemblage data see Gilbert et al., 1998), and presence of some diatoms and radiolarians indicating a Quaternary age of the sediments. Interbedded Facies B is characterised by terrigenous silty–clayey sands and sandy muds (Fig. 3). On the basis of the foraminiferal assemblage data and the content of gravel and/or sand Gilbert et al. (1998) attributed Facies A, which also includes the core-top sediments, to “warm” climate conditions (i.e. similar to the present interglacial) and Facies B to cool climate conditions. Without having precise age control for the sediment cores, the authors speculated that the alternation of Facies A with Facies B reflects either interglacial–glacial cyclicity on orbital time scales or short-term climatic fluctuations, possibly related to local ice sheet and sea-ice variability and/or fluctuations in AABW outflow. Gilbert et al (1998) favoured the latter hypothesis and argued that the coarser-grained Facies A sediments were deposited contemporaneously with strong AABW flow, whilst the finer grained Facies B sediments were deposited during periods of weak AABW flow. This conclusion is supported by the sharp basal contacts of Facies A that may point to current-induced erosion (Gilbert et al., 1998; Pudsey, 2002).

The sediment cores contain up to four units of Facies A, which we refer to as Weddell A1 to Weddell A4 (WA1 to WA4, Fig. 3). Units WA1 and WA3 can be correlated between all four sites (unit WA4 was only recovered at site KC88), whilst unit WA2 occurs in KC85, 88 and 89 but is not present in PD60. The texture and benthic foraminiferal assemblages of units WA1 to WA4 display subtle variations. Unit WA1 consists of poorly sorted sand and silty sand with 5–20% gravel and is dominated by agglutinated foraminifers (mainly *Portatrochammina antarctica wiesneri*). Unit WA2 consists of normally graded sand with 1–2% gravel and a benthic foraminiferal assemblage dominated by the calcareous species *Epistominella exigua* and *Globocassidulina crassa*. Units WA3 and WA4 consist of gravelly sand. The benthic foraminiferal fauna of unit WA3 is characterised by the calcareous species *Ehrenbergina glabra*, *G. crassa* and *Trifarina angulosa*, while that of unit WA4 is dominated by *E. exigua*. Our cores contain up to three units of Facies B, which we refer to as Weddell B1 to Weddell B3 (WB1 to WB3, Fig. 3).

3. Methods

Detailed core information (visual descriptions, grain-size, magnetic susceptibility and carbonate analysis) and foraminifer counts were previously published in Gilbert et al. (1998) and Pudsey (2002). To establish a reliable chronostratigraphy for the glaciomarine sediments from the NW Weddell Sea, we performed accelerator mass spectrometry (AMS) ^{14}C measurements on mono-specific planktonic foraminifera tests (*N. pachyderma* l.c.). The foraminifera were hand-picked from 17 samples taken from units WA1 to WA4, (15 samples with replicate analysis on two sub-samples, Table 2). The sand size fraction 250–355 µm was used, and a sample of 25–40 mg of foraminifera was sent for analysis. All samples yielded sufficient carbon for analysis (Table 2). Units WA1 to WA3 could not be dated independently in every core, because some WA units did not contain enough calcareous foraminiferal tests for ^{14}C dating. However, one ^{14}C date could be obtained from planktonic foraminifera tests in unit WB2 at site KC88 (Fig. 3). Ages were calibrated using the Fairbanks0107curve (Fairbanks et al., 2005) which extends back to 50,000 yr BP (Fig. 4). Ages are reported as conventional (i.e. uncorrected) ^{14}C years before present (BP; relative to AD 1950) and calibrated years BP (cal yr BP). In accordance with other studies (e.g. Anderson et al., 2002; Anderson et al., 2009), we corrected all our ^{14}C dates by subtracting the marine reservoir effect of 1300 years, which is typical for the Antarctic continental margin today (e.g. Berkman et