C-14 age control of pre- and post-LGM events using *N. pachyderma* preserved in deep-sea sediments (Ross Sea, Antarctica)

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Summary Biogenic carbonates in Antarctic marine sequences are critical to constrain reliable chronologies for Late Quaternary glacial/interglacial events. Increased amounts of iceberg rafted debris (IBRD) in ice-proximal sediments are proxies for climate-induced disruption of the Ross Ice Shelf system. However, ice rafting events seen in deep-sea sediments from this region lack age control because they are typically barren of calcareous microfossils. We document here evidence of carbonate preservation in three out of eight cores collected from the Ross Sea continental slope (2058-3360 m-depth). AMS-C-14 dates from *N. pachyderma*-rich IBRD range between 28.2 ka and 17.2 ka before present (B.P.), and between ~19 ka and 14.4 ka B.P. suggesting that deep Ross Sea sediments can retain a record of pre- and post- LGM events involving massive destabilization of the Ross Ice shelf-sea ice system. These events occurred at a regional scale and were possibly linked to global sea-level rise from meltwater pulse (MWP) events e.g., 19-kyr MWP.

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Introduction

Ice rafting events seen in Ice-proximal sediments are proxy records for variations in volume and extension of the Antarctic ice sheet throughout glacial–interglacial times. Deep-sea cores conveniently located along the Antarctic margin can retain their original sedimentary environment deposited during late Quaternary climate-shifts (pre- and post-Last Glacial Maximum, or LGM) involving possible contributions of the West and East Antarctic ice sheets to pulses of global sea level rise. Changes in the IBRD flux to the Ross Sea correspond to those seen in cores from the Weddell Sea (Heroy and Anderson, 2005). These ice rafting events, herein referred as to "Ross Sea Events" appear to have occurred at a regional scale, and with analogs in the northern hemisphere seas. They may represent therefore climate events occurring at global scale.

C-14 Age control in the Ross Sea

While planktonic foraminifera-based chronologies of ice rafting events have been produced for high-latitudes (e.g. Elliot et al., 1998; deMenocal et al., 2000), the record for South of the Antarctic Polar Front (APF), in particular the Ross Sea, remains quite incomplete. Ice rafting events seen in deep-sea cores cannot be chronologically constrained by radiogenic dating because calcareous microfossils are not preserved.

Radiocarbon dating of acid insoluble organic (AIO) matter from high latitude glaciated sediments is subjected to several confounding factors. The Ross Sea continental margin is strongly affected by recycled organic debris from the East and West Antarctica (Truswell and Drewry, 1984; Andrews et al., 1985; Domack et al., 1999). A large number of AMS C-14 data (Smith, and Licht, compilers, 2000) confirm the presence of hiatus (Domack et al., 1999; Bonaccorsi et al., 2000), age reversal (e.g., Licht, 1999), and unusual older ages for top cores. Furthermore, old-age top cores can be affected by reworked, and radiogenically "dead" carbon, associated with a high geographical variability (Andrews et al., 1999). In fact, core tops from the western Ross Sea and from sites east of the Ross Bank differ by about 2000 years with respect to the mean surface sediment age.

In this paper we focus on the discovery of discrete levels of calcareous microfossil (*Neogloboquadrina pachyderma*) preserved in IBRD levels within deep seas cores from the Ross Sea. To date, these carbonate-rich layers are unique for the Ross Sea, although intervals of enriched $CaCO_3$ content (up to 30%) have been reported for sites further to the north in the Ross Gyre (Chase et al., 2003). We outline possible mechanisms for preservation of calcareous tests. Finally, we interpret the presence of the planktonic foraminifera assemblages within the old siliciclastic units in term of sea ice-associated habitats and provenance, and outline the implication for their preservation in pre- and post- LGM deposits. Deep biogenic carbonates found in the Ross Sea are key elements for age control of late Pleistocene climate events involving the cryosphere-ocean-land-atmosphere Antarctic system.

Study area

Cores were collected during the 1991, 1995 and 1999 Summer cruises of the Italian "Programma Nazionale di Ricerche in Antartide" (PNRA) from the Central Eastern sector (ANTA95-89C, ANTA99-c20, and ANTA99-c22), the Central Western sector (ANTA99-c23), and the North-Western sector (ANTA91-02, ANTA91-08, ANTA99-c24, and ANTA99-c26) of the Ross Sea slope. Core ANTA95-89C, a 404 cm-long gravity core, was taken from the outer slope of the Ross Sea (74° 29.100'S – 175° 34.059'W) at a water depth of 2058 meters from the lateral gentle slope (rise environment) off the Glomar Challenger Basin. In this part of the continental margin a very steep bottom morphology strongly controls sedimentary processes and oceanographic factors. The shelf break has a water depth of between 500 and 600 m; the slope is dissected by large submarine canyons, which were particularly active during the Quaternary when sediments were pushed out of the shelf break by the bulldozing from an advancing ice sheet.

Material and methods

Cores lithostratigraphy and IBRD events were constrained on the whole cores by comparison between physical properties logs e.g., Wet Bulk Density, Magnetic Susceptibility and X-rayed lithofacies (Bonaccorsi et al., 2000).

AMS C-14 dating

Accelerator mass spectrometer (AMS) C-14 ages were performed at the Woods Hole/NOSAMS facility. Three measurements were made on well-preserved tests of *N. pachyderma.* Monospecific samples were hand picked from the >150µm-sized fraction isolated at 213-239cm core depth herein and referred as to "Level 12" (Bonaccorsi et al. 2000). Only well-preserved individuals e.g., with no evidence of dissolution, or coating, were chosen to obtain ~11 mg-sized samples for analysis. Tests were cleaned by gentle sonication in double distilled water (DDW) to remove residual clay fractions, weighted and oven-stabilized overnight at ~40 C.

Results

Carbonate-rich layers were found in three out of eight cores collected in the Ross Sea continental slope. Carbonate-rich IBRD layers containing variable amount of planktonic and benthic foraminifera were recovered in cores ANTA91-02 (3360 m-depth), ANTA91-08 (2383 m-depth), and ANTA95-89C (2058 m-depth).
AMS C-14 dating of calcareous horizons including *Neogloboquadrina pachyderma* (Figure 1) and *Melonis zaandamae*, suggest a glacial deposition occurred between 25.9 ka and 16.0 ka BP., in Core ANTA91-08, and between 26.0 ka and 14.4 ka B.P. in Core ANTA91-02 (Quaia and Cespuglio, 2000).

Core ANTA95-89C consists of alternating coarse-grained to fine-grained IBRD layers. One of these, Level 12 (216.5-238 cm-depth) is a 22-cm thick level of glacial-marine diamicton, almost entirely dominated by *N. pachyderma* and benthic species. AMS C-14 age and textural composition of the IBRD are shown in Table 1 and Table 2, respectively. In general, the sand-size fraction decreases while the gravel content increases up core.

Tests of *N. pachyderma* appear to be well-preserved, and very likely not reworked (neither oxidized, nor fragmented). Their morphologies and size indicate the occurrence of both juveniles and adult forms together with typical sea ice forms (*in-situ* deposition). A typical sea-ice associated diatom (*Eucampia antarctica*), which is

Table 1. AMS C-14 (uncorrected) ages in Levels 12a and 12c

Level	*Depth (cm)*	*Lab. Code*	*AMS C-14 age (yr BP, uncorrected)*
12a	**216.5-218**	0S-24143	17,200 ± 190
12c	**229-230**	0S-27146	24,300 ± 130
12c	**237-238**	0S-24144	28,200 ± 380

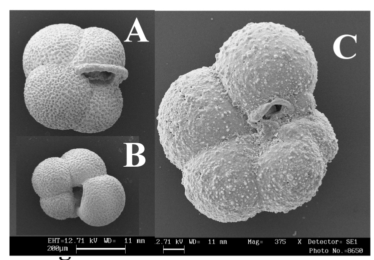

Table 2. Level 12: Abundance of *N. pachyderma* in the sand fraction and summary statistic

Level	*Depth (cm)*		*N. pachy Vol. %*	*Gravel (Wt %) >2 mm*	*Sand (Wt %) (2000-62.5µm)*	*Mud (Wt %) (<62.5µm)*
12a	**216.5-223**	**Range**	25-35	11.3 – 42.7	7.21 - 30.7	39.4 - 69.3
		Avg.		*25.9 ± 13.4*	*21.3 ± 9.3*	*52.4 ± 13.1*
12b	**223-229**	**Range**	0-15	2.5 – 23.2	29.9 – 39.9	46.9 - 58.3
		Avg.		*9.3 ± 8.3*	*37.4 ± 4.2*	*53.4 ± 4.3*
12c	**229-238**	**Range**	75-90	0.0 - 4.0	10.8 – 65.7	32.3 - 89.2
		Avg.		*2.2 ± 1.5*	*50.5 ± 22.5*	*47.3 ± 23.7*

commonly found with increasing IBRD (Burckle and Cooke, 1983; Anderson et al., 2003), was also recognized in these levels. Figure 1 shows SEM microphotographs (Leica Stereoscan 430i) of *N. pachyderma* (left-coiling), umbilical view. Adult form (A). Juvenile type (B). Not-encrusted juvenile specimen (sea-ice form) (375□) (C).

Discussion

Preservation mechanisms

Chemical and physical properties of water masses implicated in the oceanic thermohaline circulation represent the main factors controlling the preservation of deep-sea polar carbonates and are affected by bottom topography (Prasada, 1996).

Clearly, deep sea cores from the Ross Sea show a Pacific-Type preservation of $CaCO_3$ (high during glacials/ deglaciations, and lower to absent during interglacials), whereas those studied at sites in the Antarctic Circumpolar Current (e.g., Chase et al., 2003) have an Atlantic type opposite pattern (poor $CaCO_3$ preservation during glacials and maximum preservation during interglacials/ deglaciation) (Hodell, et al., 2001 and references therein). Likely, a higher alkalinity of bottom water at the end of LGM favored the high preservation of planktonic foraminifera in these cores. The fragmentation degree of calcareous tests in sediments is a proxy for variations in carbonate preservation at depth of lysocline caused by changes in deep water alkalinity (Berger, 1970; Hodell et al., 2001).

The present day (interglacial) preservation of calcareous foraminifera in the Ross Sea bottom sediment is limited to continental shelf above 350-550 m-depth (Fillon, 1974; Taviani et al., 1993). However, recent benthic foraminifera assemblages were described in the Ross Sea continental slope sediments at water depths >1,800 m (Osterman and Kellogg, 1979). Carbonates in deep-sea sediments can be affected by chemical-physical e.g. water saturation in calcium carbonate, and bottom water oxygenation, and biological factors e.g., primary productivity, microbial activity (Barbieri et al., 1999), and by sedimentation rates (Anderson et al., 1991).

According to Grobe and Mackensen (1992) Antarctic Margin interglacial sediments lack carbonates although the productivity is enhanced. The high flux of organic matter produced during interglacial periods, in fact, increases the CO_2 content in water masses flowing downslope and in interstitial waters, rising the Carbonate Compensation Depth (CCD) and enhancing carbonate solution. During glacials surface productivity is suppressed, causing the CCD to deepen and enabling deep-sea carbonate accumulation.

Relatively rapid decoupling of the ice sheet can occur during glacial terminations (Thomas and Bentley, 1978; Grobe and Mackensen, 1992) and lead to rapid disintegration of the ice sheet and calving events, with delivery of freshwater masses and high fluxes of IBRD to the bottom sediment.

In our cores *N. Pachyderma*-rich levels are clearly associated to variable amounts of IBRD with a petrology highly diversified with respect to that of the other IBRD levels analyzed. This suggests that an increase in flux of lithics from a variety of sources occurred at the end of the last glacial cycle (Bonaccorsi et al., 2000). Highest amount of IBRD from climate-induced ice shelf calving can be released along wide portions of the Ross Sea continental margin ice (Kellogg and Kellogg, 1988; Anderson et al., 1991) resulting in rapid burial rates.

Furthermore, the reduction of the sea ice cover at the end of LGM may have involved an increased deep waters ventilation (decreased partial pressure of CO_2, or pCO_2) and higher bicarbonate ion concentration ($[HCO^-_2]$) with preservation of carbonates. In contrast, an extended sea ice cover during the LGM, when the APF shifted Northward, would have reduced the deep-water ventilation (the exchange between deep and Antarctic surface water) trapping CO_2 in the areas of deep water formation. This would have increased the partial pressure of CO_2 (Stephens and Keeling, 2000; Sweeney, 2002), and lowered the $[HCO^-_2]$ causing $CaCO_3$ to dissolve.

Sea ice source of N. pachyderma

Levels 12a and 12b contain the two variants of *N. pachyderma* including the large tests and the tiny four-to-four and one half chambered form (Figure 1), which are typical sea-ice/juvenile types (Lipps and Krebbs, 1974; Spindler et al., 1990; Dieckmann et al, 1991). The left-coiling *N. pachyderma* (Ehrenberg, 1861) in these cores suggest that sea-ice conditions (Webb and Strong, 1998; Bonaccorsi and Melis, 2000) and floating ice masses (Anderson et al., 1991) were synchronously persistent along the Western and Central sides of the Antarctic continental margin (latitudes 70° and 74° S) prior to and at the end of the LGM.

Living *N. pachyderma* can be found in basal levels of Antarctic sea-ice (Spindler et al., 1990; Palmisano and Garrison, 1993) as they are embedded during the initial dynamical stage of sea-ice growing (Lipps and Krebbs, 1974; Dieckmann, 1991). This species is also capable of surviving within granular-frazil ice and under hyper-saline and low temperature, e.g., –9.6°C, conditions (Spindler, 1996). As a result, individuals are both protected from predators and can feed on other sea-ice microbiota such as bacteria and diatoms (Stoecker et al., 1997). In a few days, during spring ice melting, *N. pachyderma* returns to the water column to resume pelagic life, feed and reproduce. At the end of its life cycle this species can become part of the sedimentary record if preserved from dissolution.

Links with global climate events

AMS C-14 dates of 28.2 ka and 17.2 ka BP, and ~19 ka and 14.2 ka BP for massive ice rafting events in the Ross Sea suggest that deep sediment from this region have the potential to retain relevant climate events. These events occurred during a period of time bracketing the LGM and probably involved massive disruption of the Ross Ice shelf-sea ice system on a regional scale e.g., Antarctic Peninsula Ice Sheet Retreat (Heroy and Anderson, 2005). In particular, the fossil-rich IBRD layers dated at about 19 ka and at 14.2 ka were deposited at the same time the 19-kyr Meltwater Pulse event and the 14.5-Kyr MWP1A occurred (Alley et al., 2005; Fig. 2a-d) contributing to a global sea level rise (e.g., Clark et al., 2004). The 19-kyr MWP was associated with an abrupt rise in sea level triggered from meltwater contributions from the Northern and Southern Hemisphere ice sheets. This event has been recognized in sediments from the North hemisphere i.e., Irish Sea basin (Clark et al., 2004) and as IBRD layers possibly associated with post-LGM Ice Sheet instability and retreat in the Antarctic Peninsula (e.g., Heroy and Anderson, 2005).

Conclusions

Several levels of *N. pachyderma*-rich coarse-grained-IBRD, or "Ross Sea" layers, were recognized in three cores sampled from the outer slope, making possible the age control of palaeoclimate-relevant events. Their confirmed pre- and post-LGM-age, match the 19-kyr and the 14-kyr globally recorded MWP events.

Importantly, for the first time a global event, which lead to sea level rise, can be identified in ice-proximal cores from the Ross Sea Embayment, the southernmost sector of the Southern Pacific Ocean. In Core ANTA95-89C the "Ross Sea" layers are different from other types of glacial marine sediment, e.g., highest flux, likelihood of distinctive provenance, and unusual amount of planktonic and benthic foraminifera mixed with IBRD.

More work is needed to a) find further evidence of deep carbonates in the Ross Sea; b) model the mechanisms triggering deposition, and preservation of ice-proximal deep-sea carbonates; and c) tie short-lived changes in the dynamic of the Ross Sea Ice Sheet-ice shelf system to well-recognized global sea level rise events.

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