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Foraminiferal assemblages from ice-proximal paleo-settings in the Whales Deep Basin, eastern Ross Sea, Antarctica

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ABSTRACT

Reconstructions of Ross Sea paleoenvironments based on foraminifera are hindered by the dearth of actualistic data, especially from below the Ross Ice Shelf. To fill this gap, we used a recently developed well-resolved deglaciation record from the Whales Deep Basin of the eastern Ross Sea to understand the ecological affinities of different foraminiferal assemblages. During open-water conditions similar to the present, two benthic foraminiferal communities are strongly dominated by agglutinated species. However, in the underlying sediments that represent sub-ice-shelf and grounding-zone proximal settings on the outer continental shelf, we identified five different assemblages of calcareous foraminifera. By Antarctic margin standards, these calcareous assemblages are periodically truly abundant. Along with assemblages dominated by benthic calcareous species that are well known from many Antarctic settings, *i.e.*, *Globocassidulina biora*, *Trifarina earlandi*, and *Astrononion echolsi*, two important assemblages are dominated by a heretofore undescribed pustulose morphotype of *G. biora* and poorly known spinose morphotype of *T. earlandi*. Based on our correlations to the deglacial record, these two assemblages live near the grounding line or in environments with especially intense bottom water currents. As grounded and floating ice retreated south to the middle continental shelf, these later sub-ice-shelf and grounding-zone proximal settings were largely devoid of calcareous foraminifera and instead were inhabited by agglutinated taxa. This improved understanding of foraminiferal assemblage distributions from a variety of environments within the eastern Ross Sea may contribute to better use of foraminiferal data to investigate the evolution of environmental changes in grounding-line proximal environments.

1. Introduction

Direct observations of benthic communities below modern ice shelves are sparse. However, benthic foraminifera have already been documented from below the present-day Ross Ice Shelf by Lipps et al. (1979). They discovered foraminiferal tests under 400 m of floating ice 400 km south of the calving front but unfortunately, provided only a few taxonomic details. More recently, Pawlowski et al. (2005) described allogromiid foraminifera and gromiids from the ANDRILL HWD-2 site, 10 km south of the calving front. They interpreted the presence of the rather diverse living protist community as a result of advected phytodetritus that was apparently lacking at the site investigated by Lipps et al. (1979). Thus, it might have been assumed tacitly that below ice shelves and far away from calving front, harsh conditions, such as low temperatures and, most of all, lack of a sufficient food source, precluded the establishments of rich benthic communities. This assumption has to be abandoned because recent results from the WISSARD project (NSF press release from March 2015) showed that a diverse ecosystem exists below the modern ice shelf at a site located several hundred km away from open water.

During the last decade or so, several studies from the western Ross Sea have been published (*e.g.*, Brambati et al., 1999; Salvi et al., 2006; Melis and Salvi, 2009), suggesting that foraminifera can be useful for paleoenvironmental reconstruction in that area. Unfortunately, data presented provided only limited support for environmental interpretations because of a poor knowledge of their modern analogues especially those from below the Ross Ice Shelf that could have strengthened interpretation of ecological affinities. Subsequently, Bart et al. (2016) showed that calcareous foraminifera from Grounding Zone Wedges (GZWs) of Ross Sea can be used for radiocarbon dating marine diamicts; however, they must be selected with considerable care. One of the keys was the recognition of the paleoenvironmental setting of the source of material intended for analyses. All these issues collectively call for recognition of apparently distinct benthic communities living beneath the vast Ross Ice Shelf from calving front to grounding line.

The prospects for such investigations were further encouraged by

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reports of calcareous foraminifera associated with ice shelves from other parts of Antarctica. Abundant planktonic foraminifera were described from beneath the present-day Amery Ice Shelf, reflecting sub-ice-shelf circulation (Hemer et al., 2007). Other reports from the Antarctic Peninsula and Pine Island Bay include calcareous foraminifera from pre-modern sediments interpreted as sub-ice-shelf facies (Ishman and Szymcek, 2003; Hillenbrand et al., 2017; Kilfeather et al., 2011; Kirshner et al., 2012; Minzoni et al., 2017). These confirm the probability of finding rich late-Quaternary foraminiferal assemblages in areas that are recently largely devoid of biogenic carbonates and exhibiting their usefulness for paleoenvironmental reconstructions and radiocarbon dating.

During the NBP15-02B cruise, our shipboard analyses revealed that several cores recovered from the Whales Deep Basin in the eastern Ross Sea contain rich assemblages of both diatoms and foraminifera. Importantly, unlike in the western Ross Sea (*e.g.*, Kellogg et al., 1979; Webb and Strong, 1998; Melis and Salvi, 2009; Prothro et al., 2018), apparently reworked foraminiferal specimens were not encountered. This situation provided a rare opportunity to study *in situ* assemblages. Here, our study aims to document foraminiferal assemblages from a variety of paleoenvironments including those from below the paleo ice-shelf and proximal to the paleo grounding zone. We aim to answer the question of what were the benthic foraminiferal assemblages living during open marine and sub-ice-shelf conditions and during ice shelf break-up, and on GZW foresets. The goal is to understand what conditions were critical in supporting calcareous microfossil communities so that they may provide (1) paleoenvironmental information, and (2) material for radiocarbon dating.

Our biostratigraphic analyses relied on robust framework of two recent studies of the Whales Deep Basin deglaciation. The first study used seismic, multibeam, and chirp data to demonstrate that the WAIS occupied seven grounding-line positions within 60 km of the continental shelf edge (Bart et al., 2017a). Those positions are interpreted from GZWs, four of which are exposed over broad areas of the seafloor. The second study used a regional transect of cores (Fig. 1) from the basin (McGlannan et al., 2017). The cores showed successive changes from grounding-zone proximal, sub-ice-shelf, to open-marine settings (Fig. 2), and the correlation with the grounding-line position data demonstrated that the WAIS did not experience significant back and forth oscillations as grounded and floating ice vacated the trough. We use the McGlannan et al. (2017) paleoenvironmental framework to analyze foraminiferal data. Due to an abundant recovery of foraminifera and the apparent lack of reworked specimens, the results of this study may serve as a model for the relation between Ross Sea environments, sediment facies, and foraminiferal assemblages. If applied in future studies, this model may not only strengthen paleoenvironmental interpretations but also help to identify core intervals with the best potential for acquiring carbonates for radiocarbon dating, thus allowing for more robust deglacial reconstructions.

2. Background

2.1. Regional setting

The Ross Sea continental shelf is characterized by deep troughs up to 1200 m deep separated by much shallower banks (Fig. 1A). These erosional features were shaped by repeated advance and retreat of ice streams, which during glacial times reached the continental shelf break (*e.g.*, Shipp et al., 1999; Anderson et al., 2002; Mosola and Anderson, 2006). The modern Ross Ice Shelf has a surface area of half of the entire Ross Sea, covering almost 500,000 km^2, including the southern part of the Whales Deep Basin. The Whales Deep Basin is in the eastern Ross Sea (Fig. 1A and B) and is > 250 km long and ~100 km wide. It extends from the outer continental shelf in the north and is bound by the Hayes and Houtz banks. The basin continues south below the Ross Ice Shelf calving front to the mouth of the Bindschadler Ice Stream (Fig. 1B), which is an important component of the West Antarctic Ice Sheet.

The Whales Deep Basin can be divided into the inner- (the part below the Ross Ice Shelf), middle-, and outer-continental shelf parts. The divide between middle and outer continental shelf is at the crest of a prominent bathymetric saddle just north of 77°S latitude. This high is a compound GZW (Fig. 1C) that was formed after the Last Glacial Maximum. The GZW is composed of an overlapping stack of at least seven GZWs that are estimated to represent ~3000 years of sedimentation at the paleo grounding line of the paleo-Bindschadler Ice Stream (Bart et al., 2017b). The water depth (mwd) of the middle and outer continental shelf ranges from 470 to ~600 m. At least four individual GZW foreset surfaces were identified on the northward slope of the compound GZW (Bart et al., 2017b). These GZWs are labeled GZW1, −2, −3 and −7, as seismic data indicates that three additional GZWs (GZWs 4, −5 and −6) are buried by GZW7 (Bart et al., 2017b and Fig. 1C). Mega Scale Glacial Lineations (MSGLs) that extend to the shelf edge are partially buried by GZW1 while progressively younger MSGLs mold the tops of GZWs 1, 2 and 3. A set of small-scale back-stepping moraine ridges (Fig. 1C) mantle the topset surface of GZW7 in the southern part of the middle continental shelf, *i.e.*, just to the north of the modern Ross Ice Shelf calving front.

The Ross Sea is an area where some of the coolest waters on the planet exist with temperatures less than −2 °C. These waters originate below the Ross Ice Shelf (Jacobs et al., 1979) and in the Ross Sea polynya formed by strong katabatic winds from the south that push sea ice to the north. Cold and saline water is dense and sinks contributing to Antarctic Bottom Water. The currents of the Ross Sea are characterized by a gyre-like circulation, which seems to extend under the Ross Ice Shelf, although details of this sub-ice-shelf circulation are poorly known (Smith et al., 2007). Deep canyons at the continental shelf break are pathways for cold deep water moving northwards, and periodic intrusions of Modified Circumpolar Deep Water impinging onto the shelf (Smith et al., 2007).

2.2. Previous foraminiferal studies

The majority of investigations employing foraminifera in the Ross Sea shelf area have focused on fossil assemblages of Pliocene and older ages (*e.g.*, Leckie and Webb, 1986; Ishman and Webb, 1988; Webb, 1988; Coccioni and Galeotti, 1997; Webb and Strong, 2006; Patterson and Ishman, 2012), and on assemblages from surface sediments representing the youngest Holocene (McKnight Jr., 1962; Pflum, 1966; Kennett, 1968; Osterman and Kellogg, 1979; Ward et al., 1987; Bernhard, 1987; Gooday et al., 1996; Violanti, 1996). The latter works focused on modern material from accessible areas, so they do not describe assemblages south of the present-day calving front. Kennett (1968) noted that most calcareous assemblages in the Ross Sea are limited to relatively shallow water depths, while at depths > 430 m, assemblages are dominated by agglutinated taxa, which he linked to the position of the Carbonate Compensation Depth (CCD) at ~500 m. The agglutinated assemblages include rather fragile taxa that deeper in the subsurface are poorly preserved. Thus, they are of little use for paleoenvironmental studies and useless for radiocarbon dating. Given the additional problem of widespread reworking in ice-proximal settings, it is understandable that foraminifera have not contributed as much as they could have to our understanding of the Ross Sea deglaciation history, despite several hundred cores (Anderson et al., 2014) that have been previously collected in the area.

Only a couple of foraminiferal studies targeted modern sediments from below the Ross Ice Shelf (Lipps et al., 1979; Pawlowski et al., 2005) but they have not revealed the presence of living calcareous foraminifera, possibly due to patchiness of scarce food resources. On the other hand, the few studies that targeted subsurface deposits (*e.g.* Brambati et al., 1999; Salvi et al., 2006; Melis and Salvi, 2009) showed a discontinuous presence of calcareous foraminifera in pre-modern