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Benthic foraminifera as palaeo sea-ice indicators in the subarctic realm – examples from the Labrador Sea–Baffin Bay region

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ABSTRACT

Benthic foraminifera are found in a wide range of environments and may at times be one of few proxies available for the study of palaeoenvironmental conditions. However, the response of benthic foraminifera to changing sea-ice conditions is not well understood. This paper discusses benthic foraminifera as potential sea-ice proxies, with special emphasis on their use in shelf regions of the sub-arctic realm. Four marine sediment records from the Labrador Sea–Baffin Bay region serve as examples; in all four records independent sea-ice proxy will be used for testing the foraminiferal response to changing sea ice conditions. This test suggests that 1) Benthic foraminifera provide information on variations in sea-ice cover, but they are not direct proxies for sea-ice cover and no true sea-ice species has yet been identified. 2) Foraminifera mainly respond to the surplus of food often available at sea-ice edges. 3) Dominance of agglutinated foraminifera may suggest corrosive bottom-water conditions which may at times be linked to seasonal sea-ice cover.

1. Introduction

One of the important questions of today's climate is whether the presently fast-shrinking Arctic sea-ice is a unique and irreversible phenomenon or whether similar fast reductions in sea-ice cover have been common occurrences in the past. It is therefore imperative that we identify and test proxies that may be useful for studying past sea-ice conditions to obtain longer records of sea-ice variability prior to the instrumental and satellite records. As various proxies may be found in different geographical areas and environments and as each proxy may have different thresholds and levels of sensitivity, it is imperative to establish the possibilities and limits of all potential proxies.

Although today dinoflagellate cysts and diatoms and more recently IP_{25} (e.g., de Vernal and Hillaire-Marcel, 2000; de Vernal et al., 2001; Belt et al., 2007; Justwan and Koç, 2008; Weckström et al., 2013), are widely applied as sea-ice proxies, benthic foraminifera have also been used to infer variations in sea ice (e.g. Schröder-Adams et al., 1990a; Jennings et al., 2002; Scott et al., 2008, 2009). High benthic/planktonic foraminiferal ratios have been suggested to indicate perennial sea-ice cover (Scott et al., 1989a) as planktonic foraminifera are only found in low numbers under permanent sea ice (Carstens and Wefer, 1992; Carstens et al., 1997) in the Arctic, while Wollenburg and Mackensen (1998) showed that benthic foraminifera only live in the upper few cm of sediment under perennial sea ice. The former approach is however only viable for the open ocean due to the general absence or low numbers of planktonic foraminifera in coastal and shelf regions, whilst the vertical habitat distribution of the foraminifera below the sea floor cannot at present be traced in palaeo-records. For shelf sites we thus need a different approach.

Benthic foraminifera may potentially be used as a proxy for palaeo sea-ice conditions due to their general sensitivity to food availability and oxygen content. If the sea ice causes a stratified water column, reduced bottom-water oxygen content may severely limit the benthic faunas. In addition, cold bottom waters may have a corrosive effect resulting in carbonate dissolution (e.g., Azetsu-Scott et al., 2010), although well-oxygenated, calcium-rich, relatively warm bottom waters may also be found underneath permanent sea ice (e.g. Schröder-Adams et al., 1990b). However, in particular the high primary productivity related to the ice-edge phytoplankton blooms, especially during ice-edge retreat (e.g. Perrette et al., 2011) and underneath first-year ice (Arrigo et al., 2012), may be of significance for the benthic foraminifera, as they benefit from the increased food supply exported to the sea floor as the algae die. On the other hand this high export productivity may also cause reduced oxygen conditions hostile to benthic foraminifera (Jennings and Helgadottir, 1994; Hald and Steinsund, 1996).

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The aim of this paper is thus to explore and test benthic foraminifera as potential sea-ice proxies, with special emphasis on their use in shelf regions of the sub-arctic realm. Four marine sediment records from the Labrador Sea–Baffin Bay region, three from shelf/coastal sites and one from a deeper-water location, will serve as examples. For all these records an independent sea-ice proxy will be used for comparison. The records will not be discussed in detail with regards to their palaeoceanographic or palaeoclimatic interpretation or implications, as the focus will here alone be on the potential use of selected foraminifera as sea-ice proxies in palaeorecords. Unfortunately, very few such records that combine benthic foraminiferal assemblage studies with independent sea-ice records exist from the shelf and subarctic region (e.g. Lloyd et al., 2007; Seidenkrantz et al., 2007; Andresen et al., 2011) and it was thus necessary to use different types of proxies as independent sea-ice control for the various records.

2. Modern oceanography and sea-ice distribution in the Baffin Bay and Labrador Sea

The surface circulation in the Labrador Sea and Baffin Bay (Fig. 1A), where all four sites are located, is characterized by the advection of both warm, Atlantic water masses and cold, polar water from the Arctic Ocean. The West Greenland Current (WGC) flows northwards along the Greenland coast (Cuny et al., 2005), entraining relatively 'warm' and saline Atlantic subsurface water from the Irminger Current and cold, low-salinity Polar surface water from the East Greenland Current (Fig. 1) as well as freshwater and icebergs from the Greenland Ice Sheet. Before crossing the Davis Strait into the Baffin Bay part of the WGC is advected westward towards the Canadian margin while the remaining water continues north, reaching the northernmost regions of the Baffin Bay (Tang et al., 2004). Arctic Water enters the Baffin Bay from the north through the Canadian gateway (Nares Strait, Jones Sound and Lancaster Sound; Fig. 1A). This cold and relatively low-saline water travels southward along the coast of eastern Canada via the Baffin–Labrador Current system down to Newfoundland, where it meets the northern edge of the Gulf Stream–North Atlantic Current (Fig. 1A) (Drinkwater, 1996).

This circulation pattern affects the present-day sea-ice distribution (Fig. 1B) as the northward flow of warm surface and subsurface waters along the West Greenland coast means that the coastal and western regions of the Labrador Sea are only subject to sea ice for a relatively short period in winter. This ice is to a large extent advected from East Greenland by the Polar component in the West Greenland Current. The western Labrador Sea on the other hand experiences sea ice until spring as sea ice is transported southwards from the Baffin Bay via the Labrador Current.

Much of Baffin Bay is covered by near-continuous sea ice in winter (Fig. 1B) (Tang et al., 2004). In summer, mainly drift ice remains in the central and western parts of the bay due to the relatively warm WGC at the eastern margin of the bay while the western part of Baffin Bay remains ice covered much longer as a consequence of the cold Arctic Water at the surface. This pattern also results in an SW–NE trending ice edge, moving N–S according to seasons (Wang et al., 1994; NSIDC, 2012). In the very north of Baffin Bay, the North Water Polynya (Fig. 1B) characterizes the sound between Ellesmere Island and Greenland with it southern rim reaching the northern Baffin Bay in summer (Dunbar and Dunbar, 1972). Sea-ice cover in the Baffin Bay–Labrador Sea is at its maximum in February–March and its minimum in August–September.

The annual retreat of the ice-edge in spring/summer has a major impact on both planktonic and benthic ecosystems, as phytoplankton blooms are commonly observed along ice edges during ice retreat (Sakshaug and Skjoldal, 1989; Sakshaug, 2004; Perrette et al., 2011). The freshwater input to the surface waters during the break-up and melt of the ice may result in stratification stabilising the newly-formed, nutrient-rich waters in the photic zone (Perrette et al., 2011); also ice-edge upwelling events bringing nutrient-rich waters to the surface have been observed (Mundy et al., 2009). In addition, increased solar irradiance at the surface may also play a role (Perrette et al., 2011). Although these phytoplankton blooms are generally short-lived, they are an important element of the food chain providing a fresh food supply to benthic organisms, including benthic foraminifera (Smetacek et al., 1978; Wassmann, 1984; Dhargalkar, 1988; Grebmeier et al., 1988).

3. Agglutinated vs. calcareous foraminifera

Since the work of among other Phleger (1952), Marlowe and Vilks (1963) and Vilks (1964, 1969, 1989) and later among other Ishman and Foley (1996), who all identified a predominantly agglutinated foraminiferal assemblage in the cold Arctic waters of the Canadian Arctic shelf regions, the presence of a dominantly or solely agglutinated foraminiferal assemblage in Arctic and subarctic shelf areas has been considered an indicator of cold water and possibly sea- ice. However, Schröder-Adams et al. (1990b) reported that while Lancaster Sound in the Canadian Arctic with its seasonal sea-ice cover today is dominated by agglutinated foraminifera, rich calcareous faunas are found below the near-perennial sea-ice cover of the Axel Heilberg shelf, where waters of Atlantic origin penetrate below the ice. Also Scott et al. (1989b) found that in the Quaternary of Baffin Bay, periods of seasonal sea-ice cover were characterized by low bottom-water ventilation making the bottom waters corrosive, similar to the modern and late Holocene Baffin Bay and Labrador Shelf regions (cf. Scott et al., 1984; Schafer and Cole, 1986; Osterman and Nelson, 1989; Knudsen et al., 2008). In contrast, during periods of near-perennial sea-ice cover, influx of episodes of terrigenous calcareous material helped preserve calcareous foraminifera for a short time. Furthermore, Hald and Steinsund (1996) linked carbonate dissolution and dominance of agglutinated foraminifera to the sea-ice margin and the oceanic polar front the in Barents Sea, while Jennings and Helgadottir (1994) found an agglutinate fauna associated with low pH Polar water in East Greenland fjords. These authors thus suggest a general link to increased productivity, high pCO_2 and low pH.

3.1. Agglutinated foraminifera in core 260248-2, Ameralik Fjord, West Greenland

To test the use of agglutinated foraminifera as sea-ice proxies in the subarctic region, an agglutinated foraminiferal record is compared with a diatom-based sea-ice record, defined as the percentage of sea-ice diatoms, in gravity core 248260-2 from West Greenland (Figs. 1 and 2; 64°5.433 N; 51°15.530 W; 674 m water depth; 348 cm long). The core encompasses the last ~4400 cal. yrs.

The present study defines 'sea-ice diatoms' as the cumulative frequency of *Fragilariopsis cylindrus*, *Fossula arctica*, *Detonula confervaceae* resting spore and *Thalassiosira bulbosa*; i.e. the sea-ice record differs somewhat from that of Møller et al. (2006) and Seidenkrantz et al. (2007), who used the percentage of *F. cylindrus* and *Fragilariopsis oceanicus* as a measure for sea ice. This changed definition highlights the general uncertainty in using biological proxies such as diatoms and dinoflagellates as sea-ice indicators, as the ecology of each species is not yet fully understood. Although certain species are often found in connection to sea ice, many of these same species may also be found in other types of environments, e.g. in connection to cold surface waters of decreased salinities and may not always indicate sea ice (e.g.,