Deep-Sea Research II 99 (2014) 249–269

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

Late Weichselian deglaciation and early Holocene development of a cold-water coral reef along the Lopphavet shelf (Northern Norway) recorded by benthic foraminifera and ostracoda

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ARTICLE INFO

Available online 27 August 2013

Keywords:
Northern Norway
Foraminifera
Pleistocene–Holocene
Deglaciation
Cold-water corals
Melt-water influxes
Sea-level changes

ABSTRACT

Cold-water coral (CWC) settlement in northern Norway is strongly related to the outlet-glaciers of the Fennoscandian Ice-sheet, and dating of known CWC structures show clearly post-glacial ages. Two gravity cores (POS391 559/2,277 cm long and POS391 559/3,282 cm long) were recovered on a CWC reef in the area of Lopphavet, northern Norway. Detailed investigations on lithology (sediment structures and composition), micropaleontology (foraminifera and ostracoda) and AMS ^{14}C dating on the epibenthic foraminifera *Discanomalina coronata* were performed on the two cores. Phosphorus analyses were performed only on core POS391 559/3. Results indicate that the whole core POS391 559/2 is representative of a CWC reef environment. The base of the core is dated at 10,600 ± 120 cal. yr BP, thus representing one of the oldest ages of a Norwegian coral reef. Core POS391 559/3 documents the passage from a proximal glacier environment characterized by fine silty sediments with intercalation of several dropstone layers to a CWC ecosystem. The transition from the glacial to the interglacial stage is dated as old as 10,725 ± 205 cal. yr BP, whereas the base of the core is dated to an age of 15,300 ± 550 cal. yr BP. Diversity of benthic foraminifera is higher within the CWC, especially in the intervals containing coral framework. Five clusters are identified based on the Bray–Curtis Similarity Term Analyses and the interpretation of data shows that they are related to different ecological settings, e.g., fluctuations of the sea-ice cover; influence of the warmer and more saline Atlantic water masses; transitional to a fully interglacial environment; well oxygenated, nutrient-rich and high current setting being conducive to CWC.

Ostracod assemblages show that these crustaceans may be also used to characterize sedimentary facies on CWC reefs.

1. Introduction

Cold-water corals (CWCs) were first described from Norway in the eighteenth century (Pontoppidan, 1755; Gunnerus, 1768). However, it is only from the last two decades that they have been extensively studied (e.g., Mortensen et al., 1995; Freiwald et al., 1997; Hovland et al., 1998; Rogers, 1999; Freiwald et al., 1999; Fosså et al., 2002; Lindberg and Mienert, 2005).

Recent studies (e.g., Dorschel et al., 2005; Roberts et al., 2006; Mienis et al., 2007; Huvenne et al., 2009; Thierens et al., 2010) have demonstrated a dominant oceanographic control in the development of cold-water coral reefs, mounds and ecosystems in the north Atlantic. The distribution of frame-building scleractinian corals seems to be climatically controlled by a variability of physical, chemical and biological parameters such as water density, temperature, salinity, pressure, currents, oxygen and nutrients availability (Roberts et al., 2006; Rüggeberg et al., 2007; Dullo et al., 2008). In particular $\delta^{15}N$ signatures of CWC tissues (Duineveld et al., 2004), experiments of feeding *Lophelia* in aquaria (Rapp and Sneli, 1999) or in situ observations on Norwegian reefs (Freiwald, 2002) suggest a rather large diversity in food sources. Davies et al. (2009), Thiem et al. (2006) and Mortensen et al. (2001) pointed out the preferential settlement of CWC along topographic highs and/or on locations affected by particularly strong tidal currents producing enhanced vertical flows and remobilization of suspended food particles. Furthermore, Hovland et al. (2012) demonstrated that the occurrence of *Lophelia* reefs on the shelf off mid-Norway are closely linked to pockmarks which

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http://dx.doi.org/10.1016/j.dsr2.2013.07.009

may enhance the primary and secondary productivity through injection of nutrients to the water column and thus contribute to a continuous food supply for the living corals.

Roberts et al. (2006) and Rüggeberg et al. (2007) showed that the decrease in temperature, nutrient supply, current speed and increase in sediment input during glacial times produces unfavorable conditions for cold-water coral growth. They show that the return to interglacial/interstadial conditions is marked by the return to relatively warmer temperatures and by the re-establishment of high speeds in the circulation patterns with consequent removal of the glacio-marine deposits on topographic heights, thus producing again the favorable conditions for cold-water coral growth.

Since the last interglacial stage cold-water coral reef-like structures, dominated by *L. pertusa*, developed along the Norwegian continental shelf, from the inner of fjords to the shelf break (e.g., Dons, 1944; Mortensen et al., 1995, 2001; Freiwald et al., 1997, 1999; Hovland et al., 1997; Hovland and Mortensen, 1999; Fosså et al., 2000; Lindberg et al., 2007).

Pre-existing topographical heights on the sea floor, such as moraine ridges and iceberg plow mark levees control their distribution (Freiwald et al., 1999; Hovland and Mortensen, 1999; Mortensen et al., 2001; Freiwald et al., 2002; Fosså et al., 2005). On the Norwegian margin, from the Oslo fjord to the northernmost reefs near the Nordkapp, living corals generally colonize the top and the upper slopes of these post-glacial structures and thrive at preferential water depths of 110–400 m influenced by Atlantic water masses (Fosså et al., 2002; Freiwald et al., 2004; Hovland et al., 1998; Hovland and Mortensen, 1999). However, CWC reefs do also occur at shallower sites as for instance the Tautra reef complex in the Trondheimsfjord (Dons, 1944; Hovland and Mortensen, 1999; Hovland et al., 2002).

In situ, dead corals characterize the steep flanks of the reefs, while bio-eroded coral rubble accumulates around the base. These reefs provide abundant and diverse microhabitats for benthic organisms (Mortensen et al., 1995).

In Norway, the corals colonized elevated hard substrates building elongated structures that can reach heights of 40 m and lengths of several kilometers (Freiwald et al., 1999; Freiwald et al., 2002).

Radiocarbon ages of *Lophelia* fragments clearly show the development of CWC reefs at least during the last 8000–8700 yr (Hovland and Mortensen, 1999; Hovland et al., 1998) whereas the onset of coral growth in Northern Norway was recently reported around 10,900 cal. yr BP according to López Correa et al. (2012), this latter age corresponds to the onset of the modern oceanographic conditions in the region.

This research focuses on two gravity cores (POS 391 559/2 and POS 391 559/3), which record the transition from glaciomarine sediments to an active cold-water coral reef spanning the interval from 15,300 to 2020 cal. yr BP. The micropaleontological study on benthic and planktonic foraminifera addresses the paleoenvironmental evolution of the Lopphavet region from the Latest Pleistocene to the Holocene and benthic assemblages provide assessments of suitable conditions for coral growth during the last glacial/interglacial transition.

2. Study area and oceanography

Lopphavet is part of the Norwegian Sea located on the shelf north of Tromso (Fig. 1). This area is surrounded by the islands of Arnoya in the south, Loppa in the southeast, and faces the main entrance to the Kaevangenfjord and Altafjord (Fig. 1). The sea-floor morphology at the study area is composed of generally shallow banks (less than 100 m water depth) and deep troughs reaching 380 m water depth (Fig. 1B and C). The bedrock at the core site consists mainly of Caledonian and Precambrian metamorphic rocks whereas further offshore Mesozoic and early Tertiary sedimentary rocks prevail (Fig. 1C, Sigmond, 1992; Winsborrow et al., 2012 and references therein). The Quaternary sediment cover is generally thin on the shelf (< 100 m) but increases towards the shelf break and consists mainly of till deposits and successions of glaciomarine sediments (Vorren et al., 1992; Laberg et al., 2012).

During the Last Glacial Maximum, northern Norway and the continental shelf of the South-Western Barents Sea were completely covered by ice (Winsborrow et al., 2010). The Lopphavet area was at the confluence of the Fennoscandian and Barents Sea ice sheets during the last glaciation. Recent studies showed that this area has experienced intensive ice streaming during the last glacial maximum which lead to the formation of deep cross-shelf troughs on the sea-floor surrounded by moraines and banks (Vorren et al., 1998; Ottesen et al., 2008; Winsborrow et al., 2010, 2012). Lopphavet was intensively influenced by a succession of retreats and advances of three major ice-streams (Hakjerringdjupet, Fulgoybanken and Sørøya through Ice Streams; Fig. 1B) and calving glaciers during the late Weichselian (Winsborrow et al., 2012).

The Late Weichselian deglaciation of Northern Norway was rather rapid, whereas the complexity of ice-streams and the timing of the ice-sheets retreat are still poorly understood (Landvik et al., 1998; Winsborrow et al., 2010). Retreat of the Fennoscandian Ice Sheet (FIS) from the shelf break is thought to have started around 18,000 cal. yr BP (Ottesen et al., 2005; Vorren and Plassen, 2002). Available studies from this region report early glaciomarine conditions by 17,100–14,128 cal. yr BP (Hald et al., 1989; Rasmussen et al., 2007; Vorren and Plassen, 2002; Vorren et al., 1978). From the area of Ingoydjupet (Fig. 1), Junttila et al. (2010) and Aagaard-Sørensen et al. (2010) even report glacier free conditions at about 18,700 and 18,600 cal. yr BP, respectively. According to Winsborrow et al. (2012) glaciomarine conditions prevailed at the outermost Soroya Trough around ca. 15,000 cal. yr BP and at ca. 14,500 cal. yr BP at the outer Altafjorden close to Lopphavet (Fig. 1).

The surface water circulation off Norway is characterized by two northward-trending current systems (Fig. 1), the Norwegian Atlantic Current (NwAC) which is mainly a continuation of the North Atlantic Current (NAC) and the Norwegian Coastal Current (NCC), which has its main source in the Skagerrak region (Hebbeln et al., 2006). The warm and saline Atlantic water (temperature= 6–9 °C, salinity= > 35) enters the Norwegian Sea through two major pathways, from the southwestern part by passing the Iceland–Faroe Ridge and from the southeast along the Faroe–Shetland Channel (Orvik et al., 2001; Orvik and Niiler, 2002). The western branch of the NwAC follows the slope topography of the Vøring Plateau towards Jan Mayen and continues further northward to the Fram Strait. The inflow along the Faroe–Shetland Channel is mainly constraint along the Norwegian shelf edge with a minor stream flowing parallel to the NCC on the shelf and converging again southwest off the Lofoten Islands (Poulain et al., 1996). The lower boundary of the NwAC reaches a water depth ranging between 500 m and 600 m (Blindheim, 1990).

The core of the eastern NwAC branch has an annual mean velocity of 30 cm/s but may reach maximum values up to 117 cm/s on the uneven shelf topography (Orvik et al., 2001). Around the CWC reefs, strong bottom currents prevail with velocities up to 44 cm/s measured at the Sula reef (Eide, 1979).

Further north, the NwAC enters the Barents Sea before dividing into a stream flowing northward (West Spitsbergen Current) to Spitsbergen and a stream bifurcating to the east (North Cap Current) parallel to the northern Norwegian coast (Loeng, 1991).