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Water mass characteristics and sill dynamics in a subpolar cold-water coral reef setting at Stjernsund, northern Norway

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ABSTRACT

The Stjernsund, located in subpolar setting at 70.5°N off northern Norway, hosts a thriving cold-water coral reef community on a morainic sill. Dives with manned submersible JAGO identified the different reef zones and sedimentary facies on top and on the slopes of the sill. Hydrographic investigations indicate different water mass distribution east and west of the sill. Winter Mode Water and Norwegian Coastal Water variability depends on the runoff and freshwater discharge into the fjord. Atlantic Water dynamics are almost entirely tidally driven. High-resolution CTD time series covering a full tidal cycle demonstrate mixing processes occurring east of the sill. Additionally, the different bathymetric distribution of living corals on the western and eastern slope of the sill portrays the dependence on these tidal dynamics. The living corals thrive just below the isopycnal of 27.5 kg m^{-3}, which marks the boundary between Norwegian Coastal Water and Atlantic Water.

1. Introduction

Cold-water coral reefs occur at various sites along the European continental margin, like in the Mediterranean Sea (e.g., Taviani et al., 2005), on carbonate mounds West off Ireland (e.g., Henriet et al., 1998; De Mol et al., 2002; Kenyon et al., 2003; Wheeler et al., 2007), or at shallower depths between 100 and 350 m on the Norwegian shelf (e.g., Mortensen et al., 2001; Freiwald et al., 2004; Fosså et al., 2005). Their occurrence is related to different physical parameters like temperature, salinity, seawater density, dissolved oxygen, and to other environmental parameters such as internal wave activity, nutrient supply, strong currents, which keep sediment input low, etc. (Frederiksen et al., 1992; Rogers, 1999; White, 2007; Dorschel et al., 2007; Dullo et al., 2008).

Along the Norwegian coast, several cold-water coral sites are also known from fjord and sound settings. In these locations, sills play an important role with respect to water mass structure, circulation, sediment transport, and marine life. Fjords are characterized by continuous estuarine circulation patterns (Farmer and Freeland, 1983; Lewis and Thomas, 1986), whereas sounds exhibit a circulation pattern governed by the local wind regime (Klinck et al., 1982; Stigebrandt and Aure, 1989). Tidal forcing and varying seasonal freshwater runoff (snow-melt, ice-melt, rain-storm) have an impact on the current regime (Syvitski et al., 1987). In addition, sounds are characterized by increased through-flow, flushing rate, and reduced residence time of water (Arneborg, 2003).

Our objective during RV POSEIDON cruise P325 was to investigate the facies pattern, geological boundary conditions and characteristics and dynamics of the water masses of the cold-water *Lophelia*-reef structures on Stjernsund-sill, which was first described in the classical comprehensive study by Dons (1932). Since this study, cold-water corals are known to form build-ups or deep-water reefs on the Norwegian margin including spectacular locations such as Oslofjord, Trondheimfjord, Sula Reef, Røst Reef, or Stjernsund (Freiwald et al., 1997, 2002, 2005). However, the controlling factors favouring and maintaining cold-water coral reef growth in subpolar sound-settings have rarely been studied applying swath bathymetry, submersible dives including photo and video surveys, physical oceanography, geology, and biology at one site.

Located at 70.5°N and 22.5°E, the Stjernsund is a 30 km long and up to 3.5 km wide sound connecting the open North Atlantic with the Altafjord (Fig. 1). A deep-seated SW–NE oriented morainic sill with varying depths (203–236 m) splits the more than 400 m deep sound into two troughs. This sill has an asymmetric cross-section with a steep NW slope and a gently inclined SE slope. Living *Lophelia pertusa* dominated reef complexes occur on the NW slope between 235 and 305 m water depths and on the SE slope between 245 and 280 m.

The general surface hydrography in the NE Atlantic and the Norwegian-Greenland Sea is characterized by the northward

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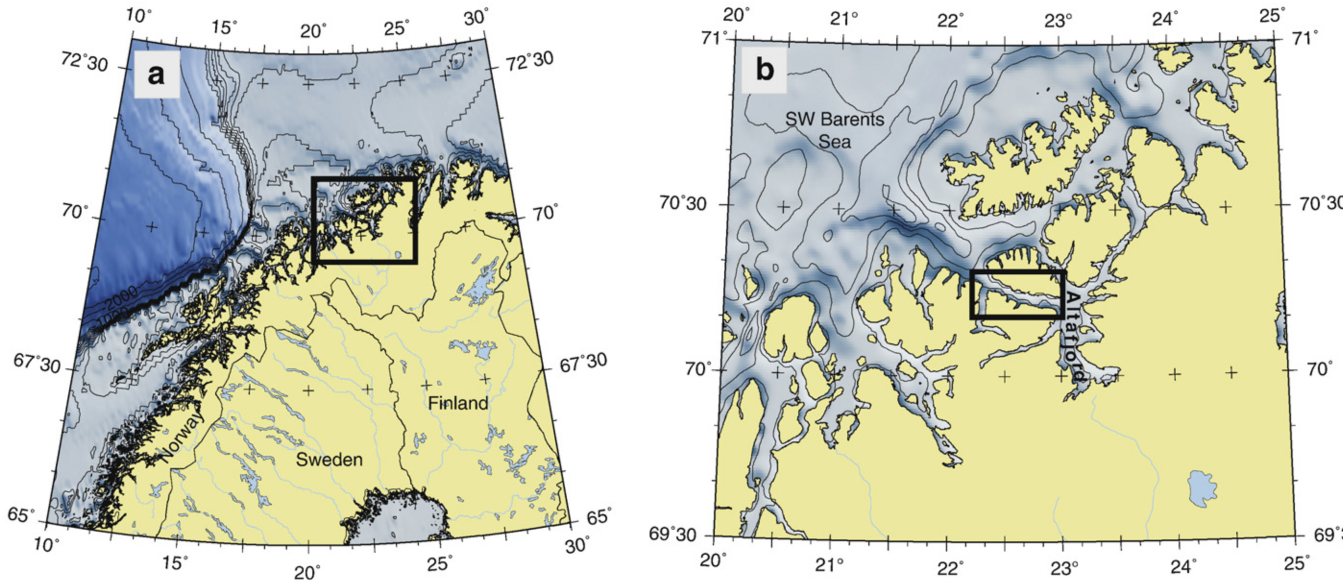

Fig. 1. a) The Finnmark district of northern Norway with b) the study site of Stjernsund (box).

transport of warm subtropical water to high latitudes. Along the Norwegian coast water masses of this surface current regime, the North Atlantic Current (NAC), occur at the relative shallow habitats of living coral reefs (140–380 m; Fosså et al., 2005; Freiwald et al., 2002). The Norwegian Coastal Current (NCC), which originates primarily from the freshwater outflow of the Baltic and the runoff from the mainland flows northwards parallel along the coast and dominates the surface water circulation (Mork, 1981). The main water masses in the study area along the Norwegian coast (Fig. 1b) are of coastal and Atlantic origin. Norwegian Coastal Water (NCW) is part of the NCC with salinities less than 35 psu (Practical Salinity Unit) and stretches like a wedge over the shelf edge merging with Atlantic Water (AW, Skardhamar and Svendsen, 2005). AW is characterized by salinities >35 psu and is present below the low-saline NCW in water depth of >50–250 m. Norwegian Sea Deep Water (NSDW) comprising salinities below 34.95 and potential temperatures less than 0 °C, fills the deep troughs below 800 m water depth west of the study area (l.c., Freiwald et al., 2005). Within the Stjernsund area, the surface water corresponds to NCW with contribution of continental freshwater discharge. The formation of Winter Mode Water (WMW) is a seasonal effect of freshwater discharge, between 100–150 m water depths. It results from the cooling of surface water of the upper few tens of metres during wintertime. NCW comprises the upper 200–250 m while AW is the dominant water mass below.

Due to the maximum ice extent during the last glaciation, several fjords and sounds exhibit a sill structure (moraines) formed by the subsequent retreat of these glaciers. This geomorphological feature separates the sound into troughs and favours the colonization by benthic sessile biota. Furthermore, these bottom thresholds cause flow acceleration, which in turn results in higher nutrient concentrations, a necessary requirement for cold-water coral growth. Advection of water over sills further triggers nutrient and phytoplankton production (Lindahl and Hernroth, 1988) although the advected nutrients represent only a small portion of nutrients over a sill (Aksens et al., 1989). Underwater ridges such as sills affect water turbulence (Huppert, 1980). Processes like internal waves can be generated and add to the complexity of mixing (Murty and Rasmussen, 1980). They can influence nutrient distribution and energy transport. Farmer and Smith (1980), and Xing and Davies (2006) show that narrow sills increase internal mixing on the lee side.

2. Material and methods

2.1. Swath bathymetry

Swath bathymetry was applied to produce the first three-dimensional image of Stjernsund. A 50 kHz Seabeam 1180 swath system with 126 beams with $3 \times 3°$ beam angle was used. The system was installed together with an OCTANS 3000 motion sensor and a sound velocity probe. Sound velocity profiles of the water column were taken from CTD casts. Cruising speed was between 3 and 4 knots. The data were recorded with the *HYDROSTAR ONLINE* software from ELAC-Nautik and edited by *Hydrographic Data Processing/Data Editor*. Digital Terrain Models (DTM) were processed by *Hydrographic Data Processing/Post Processing* and grids of different grid space (3–8 m) were exported as latitude-longitude-depth data in ASCII format. For map visualisation we used *Generic Mapping Tool* (GMT) with WGS84 as reference ellipsoid and Mercator projection. During our field studies, a total of 71 km track lines were recorded. Apart of the 3-D visualisation, the data were used to produce high-resolution maps to identify promising dive sites for video surveys, to locate hydrographic transects for CTD cast and water samples, and to map the extension and geometry of cold-water coral occurrences.

2.2. Submersible dives

"JAGO" is a manned submersible, certified to a maximum operating depth of 400 m. It was designed and built according to the rules for classification and construction of the Germanischer Lloyd. The highly maneuverable vehicle can accommodate two persons, the pilot and a scientist/observer, at atmospheric pressure. The vehicle is equipped with fluxgate compass, Ultra-Short-Base-Line-navigation and tracking system, underwater telephone, sonar, video and photo cameras, oceanographic sensors and a manipulator arm for handling various sampling devices. In total, 30 h were spent underwater on 8 project dives. The *in situ* observations along with video surveys provided the source for the facies mapping of the sill and its slopes.

2.3. Hydrography

A total of thirty-five CTD casts were carried out in the sound (Table 1). CTD profiles were performed West, East, across, and parallel