Estuarine, Coastal and Shelf Science 92 (2011) 90–102

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

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

Deep-sea benthic foraminifera, carbonate dissolution and species diversity in Hardangerfjord, Norway: An initial assessment

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ARTICLE INFO

Article history:
Received 16 April 2010
Accepted 13 December 2010
Available online 25 December 2010

Keywords:
Bathyal silled fjord
foraminiferal dispersal
turbidites
taphonomy
carbonate dissolution
biodiversity

ABSTRACT

This is the first record of live (stained) deep-sea benthic foraminifera in the 850 m deep silled Hardangerfjord, the second deepest fjord in Western Norway. Estimates of organic carbon flux ($\sim$2.5 g Cm^{-2} y^{-1}) show that the fjord-values are comparable to similar depths on the continental slope. Accordingly, although these first samples only provide relative abundance data, the low proportion of live to dead individuals in the top cm of the sediment suggests a low foraminifera biomass. Another similarity with the deep sea is that the abiotic environment of the deep basins is stable even though the deepest basins are isolated from the open deep sea by the continental shelf and sills in the outer parts of the fjord suggesting that the deep-sea species are introduced as propagules during deep-water renewals. There is evidence of an increase in dissolution of fragile calcareous tests (e.g., *Nonionella iridea*) especially in the innermost part of Hardangerfjord since the 1960s and this has led to a relative increase in dead agglutinated assemblages. The presence of larger forms with tests >1 mm provides substrata for the attachment of smaller forms and therefore an increase in species diversity. Indeed, the diversity is comparable both to that of the open deep sea and that of reported macrofauna from the same sites, reflecting similar ecological status. Holtedahl (1965) suggested that there may be some down-slope transport of sediment into the deep basins with the deposition of turbidites. Despite some evidence of transport, no major recent disturbance due to turbidite deposition seems to have occurred and hence Hardangerfjord presents a unique environment with elements of deep-sea faunas in a land-locked setting.

1. Introduction

Fjords are typical high latitude, deep estuaries excavated or modified by land-based ice and western Norwegian ones are often long, narrow, steep-sided, and deep, commonly with a sill at the entrance, which may hamper deep-water exchange with the open ocean (Syvitski et al., 1987). “It is a quite peculiar feature of our coast’s nature that the greatest depths are normally not, as one would expect, to be found furthest out on the sea-margin among the outer skerries but, on the contrary, by preference in the fjord arms, carved deeply into the land and there, commonly in the innermost part” (translated from Sars, 1872). He described how deep-sea dredging in Norwegian fjords using small simple-equipped fjord-steamers differed from British efforts where larger ocean-going naval ships were needed. The results of both groups yielded important information about the occurrence and distribution of organisms, including some benthic foraminifera, at depths which only recently had been discovered to be habitable. Today, over a century later, there is still limited knowledge of benthic foraminifera in the deep inland fjords and the method of colonisation of deep-sea taxa by crossing shallow coastal areas. Since sediment accumulation rates commonly are higher than in open shelf and deep-sea settings, cores from fjord sediments may yield high-resolution, high quality data for interpretations of naturally (e.g., Husum and Hald, 2002; Norgaard-Pedersen and Mikkelsen, 2009) as well as anthropogenically (e.g., Alve et al., 2009) induced environmental change over recent millennia to centuries. Benthic foraminifera have the potential to play a key role in such interpretations. Additionally, the fact that some steep-sided fjords (e.g., Hardangerfjord, Holtedahl, (1965)) experience slope failure, leading to deposition of turbidity sequences in the deep basins, makes them ideal places to study community- and colonisation processes.

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doi:10.1016/j.ecss.2010.12.018

There are similarly few publications on the dynamics and community structures of benthic deep fjord macrofaunal assemblages and their links to those of the deep sea. We need to improve our understanding of these deep fjord ecosystems through the current focus on cold-water corals (*Lophelia pertusa*), which are common on the Norwegian continental shelf but also occur in the sill areas around the entrance to Hardangerfjord (Fosså and Skjoldal, 2010), an increasing awareness that human activities impact the ecological quality of unique fjords like Sognefjord, Western, Norway (Manzetti and Stenersen, 2010), and the possible installation of underwater electricity cables in parts of Hardangerfjord.

An environmental monitoring cruise in Hardangerfjord in May 1996 collected sediment samples for soft-bottom macrofauna and geochemical analyses (reported by Rygg and Skei, 1997). Analysis of foraminiferal assemblages was not part of the original sampling programme but, as there are few published data on benthic foraminifera from deep Scandinavian fjords, material was collected for an initial assessment. Owing to a lack of time, it was only possible to subsample (a few cm^3) surface sediment samples collected for other purposes rather than proper quantitative subsamples. Although our material is not ideal for carrying out a detailed analysis of the living (stained) and dead benthic foraminiferal assemblages, it has provided new insights into the foraminiferal assemblages of this deep fjord, and especially the presence of deep-sea species. It also provides the possibility to look for oceanic deep-sea species distributions and hence to study dispersal mechanisms.

2. Hydrography

With a length of 165–180 km (Cone et al., 1963, Ervik et al., 2008), the Hardangerfjord, western Norway (Fig. 1), is the third largest fjord in the world (see Syvitski et al., 1987). During the last glaciation, the fjord was filled with ice and Holtedahl (1965) suggested that sediments accumulated during interglacial and glacial stages prior to the last glaciation are unlikely to have been preserved in the fjord. The Hardangerfjord system consists of several silled basins and slumping and turbidity currents were probably important mechanisms transporting sediments into the fjord basins during postglacial times (Holtedahl, op. cit.). The deepest basin now reaches about 850 m depth and the main path for deep, open coastal water to enter the fjord is across the generally <200 m deep inner continental shelf and across the140 m deep Valevåg sill. After being transported some tens of kilometres from the coastline, past one 260 m or one 170 m deep sill, some water may also pass a sill at 190 m near Huglo (Ervik et al., 2008; Jan Aure, written com., 2010). The shallow water above sill depth is usually stratified throughout the year, with the most pronounced stratification in summer. Sills generally separate the deep, stable (salinity 35; temperature 6.4–6.8 °C) but well-oxygenated (80–90% saturation) fjord water from the coastal water (Saelen, 1967). Little is published on the deep-water hydrography of Hardangerfjord but deep-water renewals are known to commonly occur every spring/early summer (Jan Aure, pers. com., 2010). The north–south

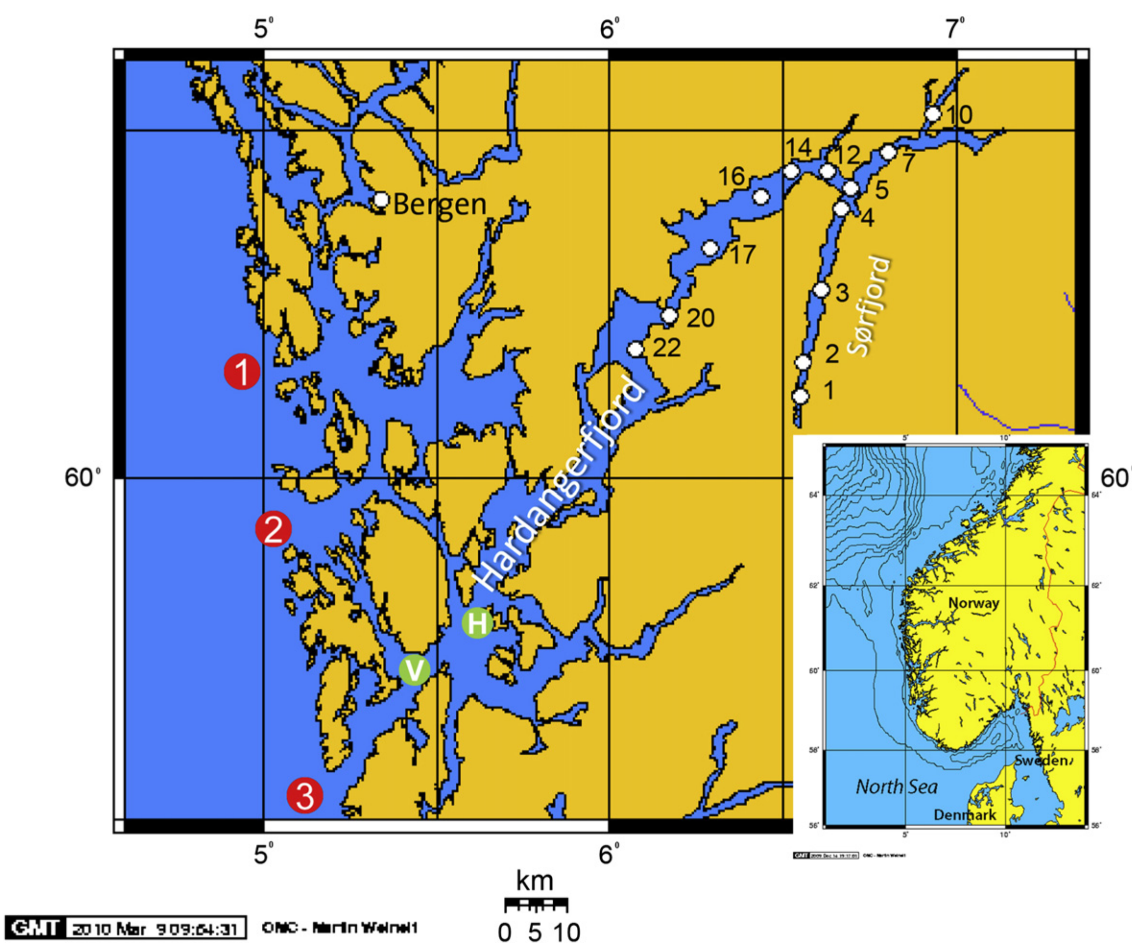

Fig. 1. Map of the Hardangerfjord system with location of sampling sites. Depth contours on inset map are 200 m. The maps are produced through http://www.aquarius.ifm-geomar.de/. Red dots are coastal sill areas; 1 = Korsfjorden (260 m), 2 = Selbjørnsfjorden (170 m), 3 = Sletta (150 m). Green dots are sills in Hardangerfjord; V = Valevåg (140 m), H = Halsnøy/Huglo (~ 190 m). Sill positions/depths from Ervik et al. (2008). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).