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Chapter 1

COLD-WATER CORAL REEFS ALONG THE EUROPEAN CONTINENTAL MARGIN: THE ROLE OF FORAMINIFERA

ANDRES RÜGGEBERG[1,2], SILVIA SPEZZAFERRI[3], CLAUDIO STALDER[3] AND STEPHAN MARGRETH[3]

[1]Renard Centre of Marine Geology, Ghent University, Krijgslaan 281, S8, B-9000 Gent, Belgium.
Email: andres.ruggeberg@ugent.be

[2]GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstrasse 1-3, D-24148 Kiel, Germany.
Email: arueggeberg@geomar.de

[3]University of Fribourg, Department of Geosciences, Chemin du Musée 6, 1700 Fribourg, Switzerland.
Email: silvia.spezzaferri@unifr.ch, claudio.stalder@unifr.ch

INTRODUCTION

To understand the role of foraminifera in cold-water coral ecosystems it is essential to have an overview on their functioning, although these mechanisms are not yet fully understood. Presently, the full extent of cold-water coral reef's geographical distribution is still unknown (Freiwald and others, 2004). They have been documented in Fjords and on the continental shelf off Norway (Fosså and others, 2002; Freiwald and others, 2002), along the upper continental slope from the Faroe-Shetland Channel southwards to central Africa, in the northwest Atlantic from Canada, Florida, the Gulf of Mexico down to Brazil and Argentina, but also in the Indian and Pacific Oceans (Stetson and Squires, 1962; Freiwald and others, 1999; Paull and others, 2000; Heifetz, 2002; Reed, 2002; Freiwald and others, 2004; Gass and Willison, 2005; Mortensen and Buhl-Mortensen, 2005; Schroeder and others, 2005; Reyes and others, 2005; Muñoz and others, 2012). On deep-sea banks cold-water corals have been documented on the Rockall and Porcupine Bank in the northeast Atlantic, on Galicia Bank close to Spain, the Chatman Rise and Campbell Plateau near New Zealand, on several seamounts in the Atlantic and Pacific Oceans (Grigg, 1984; Wilson and Kaufman, 1987; Richer de Forges, 1990, 1993; Grigg, 1993; Probert and others, 1997; Koslow and others, 2001; Andrews and others, 2002; Gubbay, 2003; Baco and Shank, 2005), and on mud volcanoes and ridges in the Gulf of Cadiz and in the Mediterranean (Van Rensbergen and others, 2005; Foubert and others, 2008; Freiwald and others, 2009; Wienberg and others, 2009; Margreth and others, 2011). Peculiar and spectacular cold-water coral settings are the scleractinian coral reef build-ups and carbonate mounds along the European margin from northern Norway to the Mediterranean. The shallowest occurrence has been recorded at 39 m depth in the Trondheimsfjord, the deepest from the New England Seamount chain in the North Atlantic, at 3383 m, and off Morocco, at 2775 m (Zibrowius, 1980). The largest reef complexes of up to 40 km in length have been described along the Norwegian margin (Freiwald and others, 2002; Fosså and others, 2005).

Herebelow, we mainly refer to the cold-water coral reef build-ups of *Lophelia pertusa,* which is the main reef forming scleractinian cold-water coral along the European margin with minor contribution of *Madrepora oculata* and *Desmophyllum* spp. (Freiwald and others, 2004). All these corals are suspension feeders (Messing and others, 1990; Jensen and Frederiksen, 1992) and need to be supplied by a diverse range of food from live zooplankton to particle aggregates of marine snow and resuspended material (Mortensen and others, 2001; Freiwald, 2002; Kiriakoulakis and others, 2004; 2005; Duineveld and others, 2007). In regions where *L. pertusa* is abundant, high primary productivity by surface phytoplankton is observed (Duineveld and others, 2004). This is important to trigger the zooplankton blooms. Strong bottom currents provide the cold-water corals with food, remove the waste products and limit sediment smothering (Klitgaard-Kristensen and others, 1997; Duineveld and others, 2004; Freiwald and others, 2004; White and others, 2007; Thiem and others, 2006).

The biogenic reef frameworks built by the cold-water corals are similar in morphology to their warm-water counterparts, controlled by a complex interaction between biological and geological processes under suitable hydrodynamic conditions. *Lophelia pertusa* may form white, orange or pink bush-like colonies often of several meters in height. A typical cold-water coral reef starts with the settlement of coral larvae on suitable hard substrate such as pre-existing heights, moraine ridges, iceberg plough mark levees (Freiwald and others, 1999; Mortensen and others, 2001), mud breccia extruded from mud volcanoes, or skeletal debris (Roberts and others, 2005; Margreth and others, 2011). Under favourable environmental conditions like permanently or episodically strong currents and food supply, small coral colonies are able to grow (Dons, 1944; Frederiksen and others, 1992). Under stable physical oceanographic conditions in terms of temperature, salinity, food supply and currents, the colonies may continue their growth, colonize larger areas to form coral thickets (Dons, 1944; Freiwald, 2002). These thickets provide support and protection for other organisms, which form together a complex reef biocoenosis (Dons, 1944; Burdon-Jones and Tambs-Lyche, 1960; Jensen and Frederiksen, 1992, Fosså and Mortensen, 1998; Rogers, 1999; Fosså and others, 2000; Freiwald and others, 2004). The continuous growth of the reef results in a separation between the live reef and the dead framework providing different habitats resulting in distinct faunal zonation. Bioeroders, dominantly sponges and fungi, attack the dead corals (Beuck and Freiwald, 2005). This process leads to the formation of extended fields of coral rubble, which provide additional different habitats for distinct fauna but also the substrates for renewed coral settlement supporting horizontal reef growth. The bottom water circulation pattern may produce a facies zonation, which can be identified by the presence of abundant exposed glacial dropstones in the northern regions. This facies harbours distinct communities, different from the more sheltered areas (Mullins and others, 1981; Messing and others, 1990).

The most significant environmental factors controlling cold-water coral distribution and growth, next to the hard substrate required for initial attachment of the coral larvae, are temperature, salinity, and the nutrient supply. *Lophelia pertusa* tolerates a temperature range between 4 and 14 °C (Freiwald and others, 1997; Freiwald and others, 2002) and a salinity range between 32 psu and 38.8 psu (Strømgren, 1971; Taviani and others, 2005). A combination of these two parameters is expressed in the seawater density sigma-theta (σ_θ). Recent studies show that thriving *L. pertusa* coral reefs occur within a density range of sigma-theta (σ_θ) = 27.35 to 27.65 kg m^{-3} in the NE Atlantic Ocean (Dullo and others, 2008; Rüggeberg and others, 2011). However, the Mediterranean occurrences show a special and very narrow sigma-theta (σ_θ) range of 29.1 $\pm$ 0.03 kg m^{-3} (Freiwald and others, 2009).

COLD-WATER CORAL CARBONATE MOUNDS

Providing stable environmental conditions over longer periods (100's of kyr), cold-water coral reefs are able to form several 100-m high carbonate mounds. The known occurrences of cold-water coral carbonate mounds in the North Atlantic are generally confined to the upper and mid-slope of continental margins like the Rockall Bank, the Porcupine Seabight, the Gulf of Cadiz, the Moroccan and Mauritanian margins, the Florida-Hatteras Straight, the Blake Plateau (Florida), the eastern USA and the Gulf of Mexico (e.g., Newton and others, 1987; Colman and others, 2005; De Mol and others, 2005; Grasmueck and others, 2006, Foubert and Henriet, 2009). The growth rate of coral carbonate mounds is relatively high ~0.05–0.1 mm yr^{-1} (= 5–10 cm kyr^{-1}) and up to 5 mm yr^{-1} (~500 cm kyr^{-1}) under favourable conditions compared to off-mound sedimentation rates (Freiwald and others, 1999; Lindberg and others, 2007; Kano and others, 2007; López Correa and others, 2012). For this reason cold-water coral carbonate mounds can be also called 'carbonate factories' (Tucker and Wright 1990; James and Bourque 1992) although most of them occur in mixed carbonate–siliciclastic domains.

During the past decades intensive studies on cold-water coral carbonate mounds were conducted within the Porcupine Seabight and east and west of the Strait of Gibraltar (Gulf of Cadiz, Alboran Sea). These mounds are interpreted to be formed by cyclic development of cold-water corals, which includes a number of processes acting in different ranges of temporal and spatial scales as described in several models (De Mol and others, 2002; Kenyon and others, 2003; De Mol and others, 2005; Dorschel and others, 2005; Huvenne and others, 2005; Kozachenko, 2005; Roberts and others, 2006; Rüggeberg and others, 2007; Huvenne and others, 2009). All these models have a common point, which is the widely accepted mechanism of cold-water coral mound initiation from a cold-water coral reef (Roberts and others, 2009). According to this theory, mounds develop from extended cold-water coral reefs (Williams and others, 2006; Kano and others, 2007) by vertical coral growth on accumulated coral rubble, sediment accumulation of biogenic and authigenic carbonate and sediment baffled in the coral framework. The majority of these models shows also that climatic cycles from interglacial to glacial cause fundamental changes in environmental conditions and sedimentation rates, thus in the coral's development.

Rüggeberg and others (2007) showed that the decrease in temperature, nutrient supply, current speed and increase in sediment input during glacial times produces unfavourable 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 a stronger hydrodynamic regime with consequent removal of the glacio-marine deposits, thus producing again the favourable conditions for cold-water coral growth. In the northern hemisphere glacial/interglacial cycles occurred many times over the last 2.7 Ma (Bartoli and others, 2005). Consequences of this cyclicity are the typical mound sequences with fine-grained sediments accumulated during glacial times and coarser deposits accumulated during interglacials/interstadials (Dorschel and others, 2005; Rüggeberg and others, 2007; Huvenne and others, 2009). Cyclic sedimentation is also responsible for the accumulation of thick mound deposits. When mounds reach a certain size, their top may become isolated from bedload transport, thus they cannot longer expand and they may result embedded within sediment drifts whose accumulation rate is higher than the mound growth rate (Van Rooji and others, 2003, 2007a, b). Sometimes large mounds can create their own hydrodynamic regime influencing the accumulation and erosion (Wheeler and others, 2005, 2007; White and others, 2005; Dorschel and others, 2007; Huvenne and others, 2003, 2007; Van Rooij and others, 2008).

AIM OF THIS ATLAS

As the field of cold-water coral research has developed during the past decades, an increasing number of publication and unpublished reports identify, describe and analyse these ecosystems with respect to their biology, geology, sedimentology, and habitat characterisation from different settings around the world. Only recently, scientists have started to understand the complex interaction of ecological variables controlling the development of cold-water coral ecosystems.

Further investigations are still needed to obtain a complete picture of cold-water coral reefs and their ecology. It is known that these ecosystems are 'hot-spots' for marine life and host thousands of species of sponges, hydrozoans, mollusks, bryozoans, echinoderms, polychaetes, crustaceans, and fishes with a comparable biodiversity as observed for their warm-water analogues (Dons, 1944; Burdon-Jones and Tambs-Lyche, 1960; Jensen and Frederiksen, 1992, Fosså and Mortensen, 1998; Rogers, 1999; Fosså and others, 2000; Freiwald and others, 2004). Until now, studies on cold-water coral associated faunas mainly focused on the mega- and macrofauna (e.g., Jensen and Frederiksen, 1992; Costello and others, 2005; Henry and Roberts, 2007) or microfauna (e.g., Penn and others, 2006; Neulinger and others, 2009; Schöttner and others, 2009).

The study on benthic foraminifera associated to cold-water coral reefs has just started and publications related to these organisms are only a few (Table 1.1, Figure 1.1). Cedhagen (1994), Freiwald and Schönfeld (1996), and Beuck and others (2008) focused on the single parasitic foraminifera *Hyrrokkin sarcophaga* living attached to corals. Jensen and Frederiksen (1992) described foraminiferal fauna attached to *L. pertusa*; Hawkes and Scott (2005) investigated benthic foraminifera associated to an 'octocoral garden' at the east coast of Canada. Wisshak and Rüggeberg (2006) performed a colonization experiment on artificial substrates next to a *Lophelia* reef and Rüggeberg and others (2007) focused on fossil benthic foraminiferal assemblages in sediment cores on a carbonate mound in the Porcupine Seabight. Successively Margreth and others (2009; 2011), Schönfeld and others (2011), Morigi and others (2012), and Spezzaferri and others (2013) studied Recent benthic foraminiferal assemblages from different *Lophelia* reef sites (Porcupine Basin and Rockall region, Alboran Basin). Remia and Taviani (2005), Rüggeberg and others (2007), Rosso and others (2010), Margreth and others (2011), Raddatz and others (2011), Smeulders and others (2014), and Stalder and others (2014) focused on fossil species or assemblages from this ecosystem.

The aim of this Atlas is:

1) To summarize our results acquired over ∼12 years of research on Recent, sub-Recent and Holocene benthic foraminifera associated to scleractinian

Table 1.1. List of published studies on benthic foraminifers associated to cold-water coral reefs.

Study	Area	Comments
1. Burdon-Jones and Tambs-Lyche (1960)	Norway	Recent assemblages
2. Jensen and Frederiksen (1992)	Faroe	Foraminifera attached to *Lophelia*
3. Cedhagen (1994)	Norway	*Hyrrokkin sarcophaga*
4. Freiwald and Schönfeld (1996)	Norway	*Hyrrokkin sarcophaga* on live *Lophelia*
5. Hawkes and Scott (2005)	Nova Scotia	Foraminifera attached to *Primnoa*
6. Remia and Taviani (2005)	Tuscan Archipelago	Single foraminiferal species, 11 kyr BP
7. Wisshak and Rüggeberg (2006)	Skagerrak	Colonization experiment at *Lophelia* reefs
8. Rüggeberg and others (2007)	Porcupine	Fossil assemblages, 0–300 kyr BP
9. Beuck and others (2008)	Norway, Porc., Med.	*Hyrrokkin sarcophaga*
10. Margreth and others (2009)	Rockall, Porcupine	Recent assemblages
11. Rosso and others (2010)	Ionian Sea	Recent, dead assemblages
12. Margreth and others (2011)	Alboran Sea	Fossil assemblages, 3–15 kyr BP
13. Raddatz and others (2011)	Porcupine	Single foraminiferal species, ~2.5 Myr BP
14. Schönfeld and others (2011)	Porcupine, Biscay	Recent assemblages
15. Morigi and others (2011)	Rockall Bank	Recent assemblages
16. Spezzaferri and others (2013)	Norway	Recent assemblages
17. Smeulders and others (2014)	Rockall, Porcupine	Fossil assemblages, sub-Recent
18. Stalder and others (2014)	Norway	Fossil assemblages, 2–15 kyr BP

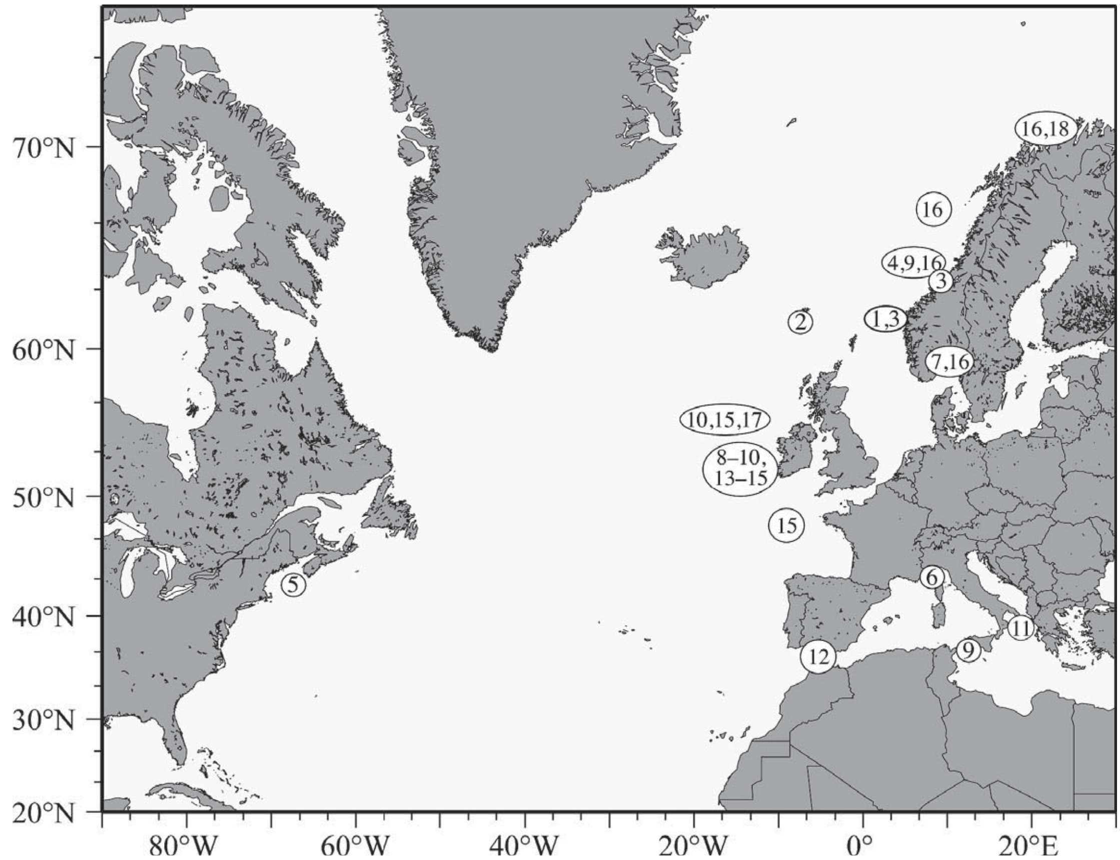

Figure 1.1. Studies on benthic foraminifera related to cold-water coral reefs. Numbers indicate studies: 1. Burdon-Jones and Tambs-Lyche (1960), 2. Jensen and Frederiksen (1992), 3. Cedhagen (1994), 4. Freiwald and Schönfeld (1996), 5. Hawkes and Scott (2005), 6. Remia and Taviani (2005), 7. Wisshak and Rüggeberg (2006), 8. Rüggeberg and others (2007), 9. Beuck and others (2008), 10. Margreth and others (2009), 11. Rosso and others (2010), 12. Margreth and others (2011), 13. Raddatz and others (2011), 14. Schönfeld and others (2011); 15. Morigi and others (2012); 16. Spezzaferri and others (2013), 17. Smeulders and others (2014), 18. Stalder and others (2014).

cold-water coral reef ecosystems along the European continental margin.

2) To illustrate sub-Recent benthic foraminiferal distribution patterns and abundances along the Norwegian margin, the Porcupine Seabight and the Rockall Bank.
3) To compare two fossil examples, (a) the buried cold-water coral reef developed in the Holocene on mud-volcanoes in the Alboran Sea, Western Mediterranean, and (b) the Holocene cold-water coral reef record from the Lopphavet (Northern Norway) to show their eventual similarities and differences in space and time.
4) To give an overview of their ecological preferences in cold-water coral reefs in relation to sedimentary facies and oceanographic parameters.
5) To highlight the potential of these organisms to serve as a tool for identifying these ecosystems in the geologic record, when the corals may be dissolved.

Three hundred ~~seventy three~~ species of benthic foraminifers including some species poorly documented in the literature have been selected to represent different sedimentary facies associated to cold-water coral reefs. They are documented in 37 plates, which will serve as a basis for integration in further studies on the subject.

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