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High-resolution facies zonation within a cold-water coral mound: The case of the Piddington Mound, Porcupine Seabight, NE Atlantic

Aaron Lim[a,*], Andrew J. Wheeler[a,b], Aurélien Arnaubec[c]

[a] School of Biological, Earth and Environmental Sciences, University College Cork, Distillery Fields, North Mall, Cork, Ireland
[b] Irish Centre for Research in Applied Geosciences, University College Cork, Ireland
[c] Unité Systèmes sous-Marins, Centre de Méditerranée, Ifremer, Zone Portuaire de Brégaillon, CS 20330, 83507 La Seyne/Mer Cedex, France

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ABSTRACT

Framework-forming cold-water corals (CWC's) such as *Lophelia pertusa* and *Madrepora oculata* generate positive topographic features on the seabed called CWC mounds. In the North East Atlantic, CWC mounds have been studied in detail and reveal heterogeneous spatial on-mound organisation of coral patches. Many of these studies are limited by a paucity of remotely-sensed and video imagery at an appropriate resolution and coverage. This study is the first attempt to video mosaic an entire CWC mound (the Piddington Mound of the Moira Mounds, Porcupine Seabight, Irish margin). The mosaic is divided into 18,980 0.25 m^2 cells with a manual classification applied to each within a geographic information system (GIS). Geospatial analysis shows that cell distribution is not random but clustered significantly across the mound surface. These clusters of cells make up a ring-like facies pattern. A model for the processes that lead to this facies pattern is suggested based on contemporary environmental controls. Parallels to shallow-water reef atolls are also drawn which subsequently has implications for interpreting fossil coral outcrops.

1. Introduction

Framework-forming, scleractinian cold-water corals (CWCs) are sessile, filter-feeding organisms that can baffle current-suspended sediment and biogenic material between their framework (Roberts et al., 2006). *Lophelia pertusa*, the most common framework-forming CWC in the NE Atlantic, has been found as shallow as 39 m water depth and as deep as 4000 m water depth (Freiwald et al., 2004; Roberts et al., 2006). In general, it occurs in temperatures between 4 and 13 °C (Freiwald, 2002) and has proven to be tolerant of a wide range of salinities, from 31.7–38.8‰ (Davies et al., 2008). As the coral framework grows, it baffles sediment which can help to generate topographic features on the seabed called CWC reefs and, through successive periods of reef development, CWC carbonate mounds (Freiwald, 2002; Roberts et al., 2009). Here, we refer to mound-shaped, positive topographic features developed by CWC's as CWC mounds. CWC mounds are common in the NE Atlantic (Wheeler et al., 2007), specifically where internal waves concentrate food particles (phytodetritus) which is delivered to CWCs by enhanced bottom currents (Dullo et al., 2008; Mienis et al., 2009; White and Dorschel, 2010).

Habitat mapping has proved to be a valuable, efficient and cost-effective tool in understanding the marine environment (e.g. Huang et al., 2011; Lamarche et al., 2011) including CWC habitats (Savini et al., 2014). Multibeam Echosounder (MBES) bathymetry and backscatter have been used extensively to characterise current dynamics and their influence on CWC mound morphology and development e.g. in the Straits of Florida, W Atlantic (Correa et al., 2012a; Correa et al., 2012b) and the midslope Moira Mounds, Porcupine Seabight, NE Atlantic (Foubert et al., 2011). Recently, more advanced approaches to MBES surveying have imaged CWC habitats in deep water using ROV-borne MBES (Dolan et al., 2008; Foubert et al., 2011), on submarine terraces using AUV-borne MBES (Correa et al., 2012a) and on vertical cliff faces in submarine canyons using forward-facing ROV-borne MBES (Huvenne et al., 2011).

In the absence of adequate multibeam data, other studies (e.g. Dorschel et al., 2007; Wheeler et al., 2008) avail of current data, sediment types, video data and/or side scan sonar (SSS) surveying integrated within a Geographical Information System (GIS) to highlight the role of currents and sediment supply on CWC mounds. Seabed sediment samples are an effective way of studying CWC mounds although limited by the spatial representation of the sample (e.g. Day grab, < 0.5 m^2). Video surveys can discriminate the seabed across substantial areas and are widely used in CWC habitat inspections (Foubert et al., 2005; Huvenne et al., 2005; Vertino et al., 2010). Recent advances in

* Corresponding author.
E-mail address: aaron.lim@ucc.ie (A. Lim).

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underwater imaging have made high-resolution underwater imagery with accurate positioning in deep water environments possible (Kocak and Caimi, 2005). As a result, since 2005, the utilisation of ROV-based observations for facies information from CWC mounds has increased dramatically (e.g. De Mol et al., 2007; Foubert et al., 2008; Guinan et al., 2009; Hebbeln et al., 2014; Heindel et al., 2010; Huvenne et al., 2016; Purser, 2015; Wienberg et al., 2013). Huvenne et al. (2005) demonstrate the variability between entire mound provinces along the Irish Margin highlighting both the frequency and variability of CWC mounds within the Belgica Mound Province. Later, Dorschel et al. (2007) observed a correlation between living coral and enhanced bottom currents in the Belgica Mound Province and outlined the influence of contour currents, tidal currents and local topography on the distinct coral facies distribution across the Galway Mound. Results from other ROV-based facies mapping also highlight the strong relationship between local currents and facies distribution across a mound surface. For example, the Franken Mound, a CWC mound in a state of "mound retirement" at the western Rockall Bank, shows a distinct facies distribution across the mound with living coral dominating the summit region (Wienberg et al., 2008). Many other uses for ROV-based facies observations were realised. Heindel et al. (2010) test, for the first time, a method of spatial prediction mapping (maximum likelihood classification) on a CWC ecosystem providing detailed aerial estimates of CWC-typical facies. ROV-based facies observations were utilised to show that *L. pertusa* is restricted to longer term, stable conditions while *Madrepora oculata* is more tolerant towards environmental fluctuations (Wienberg et al., 2009). Furthermore, its need as a tool in marine reserve designation and implementation is now recognised (Roberts et al., 2005).

In addition, advances in image processing have led to the application of video mosaicking to marine habitat mapping (Rzhanov et al., 2000). For example, Lirman et al. (2007) accurately characterise a tropical coral reef in shallow water using an entire reef-scale video mosaic. However, no such study has been carried out on an entire CWC mound although small parts of CWC habitats have been manually photo mosaicked (Wheeler et al., 2011).

The need for more local-scale studies and data sets of equal resolution have previously been highlighted (Dolan et al., 2008). This study presents the first attempt of video mosaicking an entire cold-water coral mound and subsequent analyses providing an in-depth facies mapping exercise allowing to discuss facies organisation and potential facies organisational influences.

1.1. Study site

The Belgica Mound Province (BMP), partly enclosed with a Special Area of Conservation (SAC) designated under the EU Habitats Directive, is located on the eastern flank of the Porcupine Seabight, NE Atlantic (see Fig. 1) (Beyer et al., 2003; Dorschel et al., 2007; Huvenne et al., 2002). It contains an abundance of (giant) CWC mounds, including the well-studied Galway Mound, Thérèse Mound and Challenger Mound (De Mol et al., 2007; Dorschel et al., 2007; Eisele et al., 2008; Huvenne et al., 2009; Kano et al., 2007; Thierens et al., 2010; Titschack et al., 2009; Wheeler et al., 2005). Two distinct CWC mound chains have been identified, orientated roughly N-S (parallel to depth contours) (Wheeler et al., 2005). Pre-existing bathymetry highlights their slight elongate to conical morphology and typical dimensions (approx. 1 km across and 100 m tall) (Beyer et al., 2003). To the east, these large CWC mounds are enclosed by the continental shelf and to the west, the Arwen Channel runs through the BMP (Murphy and Wheeler, 2017; Van Rooij, 2004). Towards the south and south-west, the Porcupine Seabight exits out to the abyssal plain (Dorschel et al., 2010) while the north shallows to 500 m, outside the typical depth range for CWC growth on the Irish continental margin (Dullo et al., 2008; White and Dorschel, 2010).

The Moira Mounds are small-type CWC mounds (approx. 30 m across and 10 m tall) found throughout the BMP, occurring between 800 and 1100 m water depth (Wheeler et al., 2005). While no definitive dating has confirmed their age, it is speculated that they are Holocene features based on their size, seismic profiles and the surrounding seabed substrate (Foubert et al., 2011; Huvenne et al., 2005; Kozachenko, 2005). The Moira Mounds in the BMP can be further subdivided into 4 areas or chains of mounds based on the distribution of approx. 256 Moira Mounds; the "up-slope area", the "mid-slope area", the "down-slope area" and the "northern area" (Wheeler et al., 2011) (see Fig. 1). While the number of Moira Mounds in the northern and the up-slope areas are relatively sparse, the main focus of research has been carried out on the mid- and down-slope areas. The mid-slope area occurs between the chain of large CWC mound structures. The Moira Mounds here are thought to represent mound formation under "stressed" conditions due to high sediment input (Foubert et al., 2011). The down-slope area is unique as it occurs within the Arwen Channel. Unlike the other areas, the CWC's on the Moira Mounds are predominantly growing, are actively trapping sands (Wheeler et al., 2011) and occur outside the influence of other large mound structures.

2. Materials and methods

2.1. ROV-borne multibeam echosounder (MBES)

ROV-borne MBES data was collected over the Piddington Mound and the surrounding seabed during the QuERCi survey (2015) on board *RV Celtic Explorer* with the *Holland 1 ROV* (cruise number CE15009: Wheeler et al. (2015). A high-resolution Kongsberg EM2040 MBES was integrated with a sound velocity probe and mounted on the front-bottom of the ROV. Data were acquired at a frequency of 400 kHz while the ROV maintained a height of 30 m above the seabed with a survey speed of approximately 2 knots. This achieved a swath width of ~160 m. Positioning and attitude were obtained using a Kongsberg HAINS inertial navigation system, ultra-short baseline (USBL) system (Sonardyne Ranger 2) and doppler velocity log (DVL). Data acquisition was carried out using SIS software, where calibration values, sensor offsets, navigation and attitude values were incorporated. Two adjacent 170 m long MBES lines were collected over Piddington Mound and the surrounding seabed. MBES data were stored as *.all and *.wcd files and were processed using CARIS HIPS and SIPS v9.0.14 to apply tidal corrections and clean anomalous data spikes. The cleaned data were saved as a single *.xyz and gridded to a 10 cm ArcView GRID.

The 10 cm MBES grid was imported into ArcMap 10.2 and projected in UTM Zone 29N. A 1 m contour *.shp file was generated using the Arc Toolbox Spatial Analyst Contour tool. Slope (degrees) and aspect were derived from the bathymetry using the Arc Toolbox Spatial Analyst tools.

2.2. ROV-video data collection

ROV-video data was collected over Piddington Mound during the VENTuRE survey (2011) on board *RV Celtic Explorer* with the *Holland 1 ROV* (cruise number CE11009: Wheeler and Shipboard Party, 2011). A downward-facing, high-definition camera was mounted on the bottom of the ROV. Positioning and navigation were achieved using a USBL (Sonardyne Ranger 2) and RDI Workhouse DVL. The ROV altimeter recorded and logged the height of the ROV from the seabed. The ROV recorded downward-facing HD video during a series of transects across the mound < 2 m off the seabed/mound surface.

2.3. Georeferenced video mosaic generation

A georeferenced video mosaic has been generated using the IFREMER in-house *Matisse* software where the raw video data was imported and from which images have been extracted at a rate of 1 per second. Poor quality imagery, possibly due to an excessive fly height, and/or with a poor navigational lock were not included. The associated