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Deep-sea coral and hardbottom habitats on the west Florida slope, eastern Gulf of Mexico

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ABSTRACT

Until recently, benthic habitats dominated by deep-sea corals (DSC) appeared to be less extensive on the slope of the Gulf of Mexico (GOM) than in the northeast Atlantic Ocean or off the southeastern US. There are relatively few bioherms (i.e., coral-built mounds) in the northern GOM, and most DSCs are attached to existing hard substrata (e.g., authigenically formed carbonate). The primary structure-forming, DSC in the GOM is *Lophelia pertusa*, but structure is also provided by other living and dead scleractinians, antipatharians (black corals), octocorals (gorgonians, soft corals), hydrocorals and sponges, as well as abundant rocky substrata. The best development of DSCs in the GOM was previously documented within Viosca Knoll oil and gas lease blocks 826 and 862/906 (north-central GOM) and on the Campeche Bank (southern GOM in Mexican waters). This paper documents extensive deep reef ecosystems composed of DSC and rocky hard-bottom recently surveyed on the West Florida Slope (WFS, eastern GOM) during six research cruises (2008–2012). Using multibeam sonar, CTD casts, and video from underwater vehicles, we describe the physical and oceanographic characteristics of these deep reefs and provide size or area estimates of deep coral and hardground habitats. The multibeam sonar analyses revealed hundreds of mounds and ridges, some of which were subsequently surveyed using underwater vehicles. Mounds and ridges in < 525 m depths were usually capped with living coral colonies, dominated by *L. pertusa*. An extensive rocky scarp, running roughly north-south for at least 229 km, supported lower abundances of scleractinian corals than the mounds and ridges, despite an abundance of settlement substrata. Areal comparisons suggested that the WFS may exceed other parts of the GOM slope in extent of living deep coral coverage and other deep-reef habitat (dead coral and rock). The complex WFS region warrants additional studies to better understand the influences of oceanography and geology on the occurrence of DSC and associated organisms. Protection measures are being considered to ensure the long-term integrity of this diverse ecosystem.

1. Introduction

Until recently, benthic habitats dominated by deep-sea corals (DSC) appeared to be more scattered and less extensive in the Gulf of Mexico (GOM) (Brooke and Schroeder, 2007; Schroeder and Brooke, 2011) than on the slopes of the northeastern Atlantic Ocean (Hall-Spencer et al., 2007) or off the southeastern United States (SEUS) (Ross and Nizinski, 2007; Reed et al., 2013). In contrast with other regions of the North Atlantic, relatively few coral bioherms (elevations mostly created by successive coral growth, senescence and sedimentation) were known from the GOM slope, although extensive cold-water coral mounds were recently described from the Campeche Bank in the southern GOM (Hebbeln et al., 2014). Instead of building mounds, GOM DSCs were usually observed attached to abundant exposed hard substrata (Brooke and Schroeder, 2007), mostly authigenic carbonate blocks on the north-central GOM slope (Cordes et al., 2008; Schroeder and Brooke, 2011) and emergent carbonate and phosphorite hardgrounds on the slope of the eastern GOM (Brooks and Holmes, 2011). The main structure-forming DSC in the GOM is the branching scleractinian *Lophelia pertusa*, but complex structure is also provided by other living and dead scleractinians (e.g., *Madrepora oculata*, *Enallopsammia profunda*), antipatharians (e.g., *Leiopathes* sp.), octocorals (e.g., *Keratoisis flexibilis, Callogorgia americana*), hydrocorals (e.g., *Stylaster* sp.) and sponges, as well as the non-living rocky substrata (Schroeder and Brooke, 2011). Whether composed mostly of DSC or rock, collectively these complex deep reefs sustain similar ecological functions as shallow reefs, providing structure for the development of diverse benthic communities (Roberts et al., 2009; Lessard-Pilon et al.,

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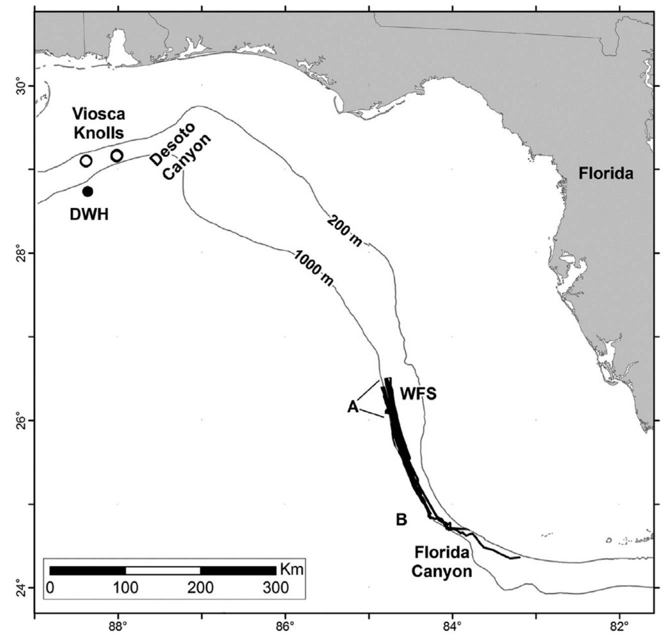

Fig. 1. North-central and eastern Gulf of Mexico illustrating locations of the two Viosca Knoll deep reef sites, the Deep-Water Horizon (DWH) well site, and the West Florida Slope (WFS) study area. Area A at the north end of the WFS study area was mapped with multibeam sonar by the NOAA ships *Nancy Foster* and *Okeanos Explorer*, was surveyed by several underwater vehicles, and is presented in greater detail in this paper. The strips (B) south of A were mapped by the M/V *Lost Coast Explorer* and the *Okeanos Explorer*.

2010). Over the last decade research programs directed toward DSC ecosystems in the GOM indicated that DSC reefs are most abundant in 300 to about 600 m depths and support distinct communities (Continental Shelf Associates, 2007; Cordes et al., 2008; Ross et al., 2012; Brooks et al., 2015).

GOM oil and gas lease blocks Viosca Knoll 826 (VK826, 415–480 m depths) and Viosca Knoll 862/906 (VK862/906, 310–440 m depths) in the north-central GOM, approximately 37 km apart (Fig. 1), were previously reported to exhibit the most extensive DSC accumulations in the GOM (Schroeder and Brooke, 2011). These sites are characterized by *L. pertusa* bioherms and carbonate blocks colonized by corals and sponges, interspersed with shell hash, coral rubble and soft sediments (Schroeder et al., 2005; Brooke and Schroeder, 2007; Continental Shelf Associates, 2007; Davies et al., 2010). Based on several years of video surveys at the VK sites, we conservatively estimated (not previously published) the areas most heavily covered by DSC (living and dead) and rocky bottom to be about 412,500 m^2 (0.413 km^2) at VK826 and about 562,500 m^2 (0.563 km^2) at VK862/906 (Supplemental Fig. 1), but note that these estimates include some non-reef, soft-bottom habitat that is not separable at this scale. A newly discovered DSC region on the Campeche Bank, dominated by *E. profunda* and L. *pertusa*, reportedly surpasses the VK region in aerial extent (4,000,000 m^2 or 40 km^2) of coral habitat (Hebbeln et al., 2014).

This paper describes extensive areas of hard substrata and DSC, some recently discovered, on the West Florida Slope (WFS) in the eastern GOM and provides the oceanographic and geological context for these sites. Associated fauna will not be described except for major sessile species which contribute to benthic habitat structure. The midpoint of this study area is about 478 and 460 km southeast of the VK deep reefs and the Deep-Water Horizon oil spill site, respectively (Fig. 1), and about 362 km northeast of the Campeche Bank deep coral mounds. Numerous small topographic highs with stands of mostly dead L. *pertusa* were described previously for part of the WFS area (Newton et al., 1987; Reed et al., 2006; Hübscher et al., 2010). Recent multibeam sonar surveys of the WFS and subsequent visual surveys revealed widespread living coral colonies capping large ridges and numerous putative DSC bioherms. The living DSC and complex habitat in this area is perhaps the most extensive in the GOM and may represent an important bridge for DSC communities between the Caribbean, the north-central GOM, and the rest of the North Atlantic. Regardless of the area's role in connectivity, the WFS is an important reservoir of upper slope biodiversity.

2. Methods

2.1. Research cruises

Six research cruises provided data for the WFS region. During 20–22 October 2008, the NOAA ship *Nancy Foster* used multibeam sonar to map areas likely to contain DSC and hard bottom habitats. Guided by these maps, the R/V *Seward Johnson* and the *Johnson Sea-Link II* submersible (JSL, Harbor Branch Oceanographic Inst., Florida Atlantic Univ.) surveyed the WFS (16–17 September 2009). The first 2010 cruise (28 September-2 October) addressed multidisciplinary research objectives using the R/V *Cape Hatteras* and the remotely operated vehicle (ROV) *Kraken II* (Univ. Connecticut). The NOAA ship *Ronald H. Brown* and ROV *Jason II* (Woods Hole Oceanographic Inst.) conducted one dive on the WFS (10 November 2010). Multibeam sonar mapping was conducted by the *Lost Coast Explorer* (7–10 November 2010). During 20–22 March 2012, the NOAA ship *Okeanos Explorer* conducted multibeam mapping and two dives with the ROV *Little Hercules* in the WFS study area. The area mapped during the 2008 cruise (Fig. 1, Area A) is emphasized because more extensive data were collected there.

2.2. Multibeam sonar surveys

Part of the WFS (Fig. 1), centered on a previously described (Newton et al., 1987; Reed et al., 2006) hardground area, was surveyed during the 2008 *Nancy Foster* cruise using a Kongsberg-Simrad EM1002 (95 kHz frequency, 111 beams per ping) multibeam sonar. An additional single track line of multibeam sonar, attempting to follow the long scarp described below, was collected south of the 2008 survey by the *Lost Coast Explorer*, using a Kongsberg EM710 (70–100 kHz frequency, 400 beams per ping) multibeam system. During the *Okeanos Explorer* cruise additional multibeam sonar data were collected using a Kongsberg EM302 (30 kHz frequency, 432 beams per ping) to fill in deeper areas not mapped in previous cruises. Raw data were corrected and post-processed using CARIS HIPS and SIPS (v. 6.1) to produce georeferenced color-shaded bathymetric maps (in ArcGIS v. 9.31, ESRI) gridded to 8 m (2008 survey), 3 m (2010 survey), and 10 and 25 m (2012 survey) resolutions.

Features of the prominent scarp were described as follows. The highest points along the top edge of the scarp were traced on the GIS map. The base of the scarp was more difficult to discern because it often exhibited slumping, multiple terraces, and boulder fields. To resolve the scarp base, the slope of each map cell (8×8 m or 10×10 m) in the raster dataset was calculated using ArcGIS, and we identified the base of the scarp as those cells where the slopes either obviously changed direction (as in boulder fields) or became flat. The scarp base was then also traced on the GIS map, and the scarp face was defined the area between the top and base lines. Vertical relief of the scarp was measured only in the 2008 survey area approximately every 50 m by subtracting the depth at the top of the scarp from that at the base. The width of the scarp was measured at the same places using the two-dimensional distance between the top and the base. The angular slopes of the scarp face were calculated at the 50 m intervals by taking the arctangent of scarp relief divided by its width.

Objectively identifying the numerous topographic highs (mounds and ridges) west of the scarp was more difficult because these features varied greatly in size and shape, were often not continuous (unlike the scarp), and geological features are frequently described in relative