

Interpretation of the relationship between benthic fauna, geologic distributions, and methane seeps at Southern Hydrate Ridge, Oregon continental margin

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Abstract

Deposits of methane and their associated seeps are found worldwide along continental margins. These seeps are of importance and increasing interest because their potential as an energy source, their contribution to greenhouse gases, and the unique community of chemosynthetic microorganisms and fauna that they host. One of the best-studied methane seep sites is Southern Hydrate Ridge, located ~90 km west of Newport, Oregon at a water depth of ~780 m. Despite extensive geophysical and biological research completed here, no studies have quantified the relationship of seep sites and seafloor geology to the spatial distribution and abundances of microbial and macrofaunal communities. High resolution, georeferenced photomosaics of the individual seeps and the associated biological communities at this site were collected in 2011, using the remotely operated vehicle *ROPOS*. Detailed analyses of these images has allowed for the quantification and characterization of the diversity and structure of the faunal community coregistered with seafloor substrate. Results show that both the distribution and abundances of seep organisms are highly variable.

Introduction

Submarine methane seeps hosting chemosynthetic communities occur in a variety of geologic settings on both active and inactive continental margins (Sibuet and Olu, 1998). Chemosynthetic microbial communities at these sites are fueled by the flow of methane-rich fluids which, unlike hydrothermal vents, are not elevated in temperature. These environments support sulfide-oxidizing bacteria, symbiont hosting animals such as vesicomid clams and mussels, and a variety of non-symbiotic invertebrate and vertebrate species (MacDonald et al., 1989; Fisher, 1990; Sibuet and Olu, 1998; Sahling et al., 2002). Although poorly quantified, some studies suggest that the productivity of these chemosynthetic communities is comparable to that at hydrothermal vents (Boetius and Suess, 2004). Methane seeps are of significant interest

not only because of the unique biological communities they host, but also because many overlie methane hydrate deposits that, on a global basis, may contain between 500 Gt and 10,000 Gt of methane carbon (Kvenvolden, 1999; Milikov et al., 2003). Therefore, substantial attention has focused on natural gas hydrates and the methane gas that they release as contributors to greenhouse gases and climate change (Lu, 2015), as possible energy reserves (National Academy of Sciences, 2010), and as geo-hazards if hydrate deposits disassociate during earthquake-induced landslides (Bell, 2014; Hovland and Gudmestad, 2001).

Southern Hydrate Ridge (SHR), located ~90 km west of Newport, Oregon (Figure 1) at a water depth of ~780 m, is one of the best-studied methane seeps (Boetius and Suess, 2004). It is part of an accretionary prism formed by the subduction of the Juan de Fuca tectonic plate beneath the North American plate. The compressional forces of this collision as well as microbial fermentation and/or thermal maturation can cause buried organic matter to form hydrocarbon-bearing fluids (Boetius and Suess, 2004). When the escaping fluids and gases come into contact with

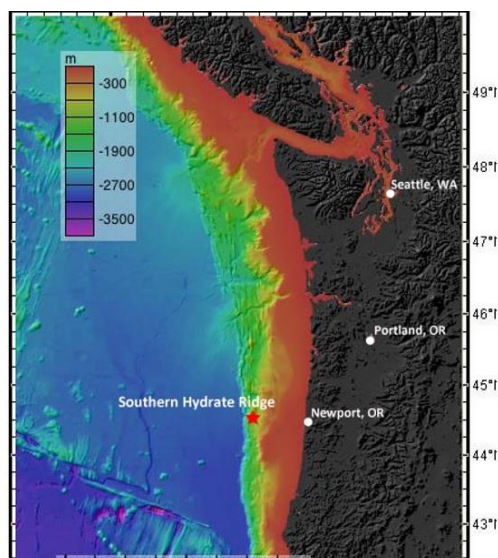


Figure 1. Southern Hydrate Ridge's location and depth in relation to the continental margin

oxidized seawater they may become fuel for chemosynthetic archeal/bacterial consortiums that perform anaerobic oxidation of methane (AOM) (Marlow, 2014). This process is estimated to consume 80-90% of all methane from the seafloor (Reeburgh, 2007). Therefore, the methane released into the overlying water column by these systems is dependent on both the seafloor methane flux and microbial oxidation of methane (Kastner, 2001). The byproducts of this reaction form carbonate deposits and fuel diverse microbial and macrofaunal communities

(Claypool, 2006). A particular set of these organisms include sulfide-oxidizing *Beggiatoa* bacteria and vesicomyid symbiont clams which act as visual indicators of fluid flux on the seep floor (Van Dover et al., 2003; Levin, 2005; Niemann et al., 2013).

Previous studies at SHR have focused on the *Beggiatoa* bacterial mats, vesicomyid clam beds (*Calyptogena pacifica* and *Calyptogena kilmeri*), and their associated micro and meioinfaunal organisms (Sahling et al., 2002; Sommer et al., 2002). Although studies have examined the micro and macrobenthic organisms at other methane seeps (Rybakova et al., 2013, Wagner et al., 2013), detailed documentation of the diversity and structure of the biological community at SHR has not been undertaken. Quantification and habitat mapping of this community is important for understanding the linkages among the biological communities, geochemical gradients, and geological factors; the evolution of these systems; and for sustainable management of this biologically productive area (Degraer, 2008).

The seep community at SHR is associated with areas of focused and diffuse fluid flow and is characterized by hummocky bathymetry. The *Beggiatoa* bacterial mats generally occur on the top of these hummocks, while clam beds are located either surrounding the edges of the mats or occur further away and unassociated with mats (Torres et al., 2002; Sahling et al., 2002; Tryon et al., 2002). Various macrofauna, both sessile and mobile, are also found at the site. There are invertebrates, such as several species of anthozoa, asteroidean, actiniaria, pennatulacea, and decapoda, as well as several species of fish belonging to the groups sebastes, zoarcidae, embassichthys, and myxinidea.

This study provides the first detailed quantification of the spatial distribution of bacterial mats, clam beds, and macrofauna at SHR. The Canadian Scientific Submersible Facility's (CSSF) ROV *ROPOS* was used during the construction phase of the National Science Foundation's (NSF) Ocean Observatory Initiative (OOI) Cable Array in 2011 to collect high-resolution

imagery. High-resolution photomosaics created from these images were used to quantify the seep community and characterize the relationships between fauna, seafloor geology, and chemistry. The seep sites, animal locations, and seafloor geology were overlain on high-resolution bathymetry (< 5 m), collected with Woods Hole Oceanographic Institution's autonomous underwater vehicle (AUV) *Sentry*, to determine if the hummocky bathymetry, fluid flow, and flow-chemical gradients have impacts on animal distributions.

Methods

The initial work at SHR was conducted in 2010 onboard the R/V *Thomas G. Thompson* (TN221) hosting the AUV *Sentry* and ROV *Jason* for detailed bathymetry, mapping, and site characterization. The AUV *Sentry* hosted a Reson 7125 multibeam sonar. It performed a mapping survey at a 20 to 75 m altitude with line spacing of 50 to 225 m. During the VISIONS'11 University of Washington-NSF-OOI cruise aboard the R/V *Thomas G. Thompson*, eight individual seep sites at SHR were imaged to provide detailed photomosaics for cable installation and placement of instruments. The surveys were conducted using the CSSF's ROV *ROPOS* hosting a Nikon D7000 digital still camera mounted facing downward. The total area photo surveyed was 125 m by 110 m, which was covered in 63 tracklines of 270 m length and 5 m spacing. Gaps in the survey were filled in with 18 additional tracklines of 185 m length and 10 m spacing. The altitude during the survey was at 6 m off bottom. Images were taken in 2.1 m intervals and the survey was conducted at an average speed of 0.36 m/s.

The 9,727 georeferenced images were mosaicked using ©Esri ArcGIS software. From this survey of the entire region, eight distinct seep sites and one background site were identified and the images were further processed using ©Adobe Photoshop. The nine fully mosaicked sites were then overlaid onto the general mosaic of the entire area. At the primary site for cable infrastructure installation, called Einstein's Grotto (EG), an area of about 636 m² was surveyed

again at 4 m altitude (8 tracklines, 35 m length, 2.5 m spacing, 123 images) and processed using the same method in Adobe Photoshop (Figure 2).

ArcGIS was used to calculate the individual areas and the areal coverage of *Beggiatoa* bacterial mats of the eight seep sites. This calculation involved the manual delineation of the desired area. Using Adobe Photoshop, the mosaic of each seep was divided into grids with squares roughly 6 m by 6 m. Within these squares all visible fauna were counted and classified into one of ten morphotype categories: (1) Rockfish; (2)

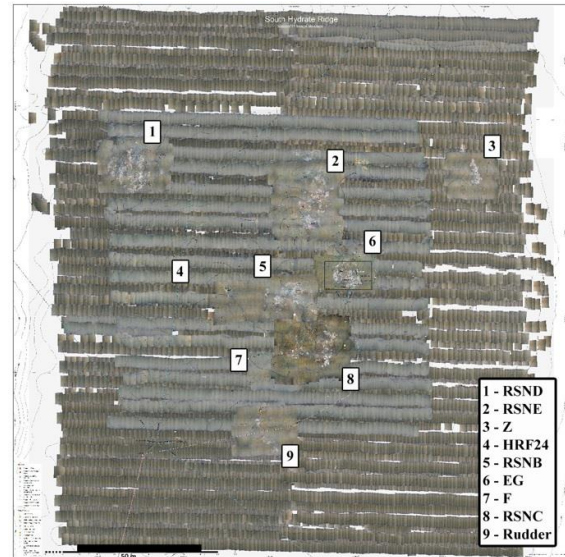


Figure 2. Full mosaic of SHR with the eight seep sites and one background site overlain

Deep Sea Sole; (3) Eelpout; (4) Flatfish; (5) Hagfish; (6) Crab; (7) Sea Star; (8) Anemone; (9) Soft Coral; and (10) Sea Pen (Figure 3). Seep areas varied dramatically (from 1585 m² to 600 m² (Table 1)) depending on the active venting at the site. Because of this, organism counts and the areal extent of the bacterial mats were converted to mean densities (ind. m⁻²) to allow comparisons among the sites. At Einstein's Grotto, it was also noted whether or not the fauna was within in the bounds of the bacterial mat, and mean densities for these different substrate types was calculated.

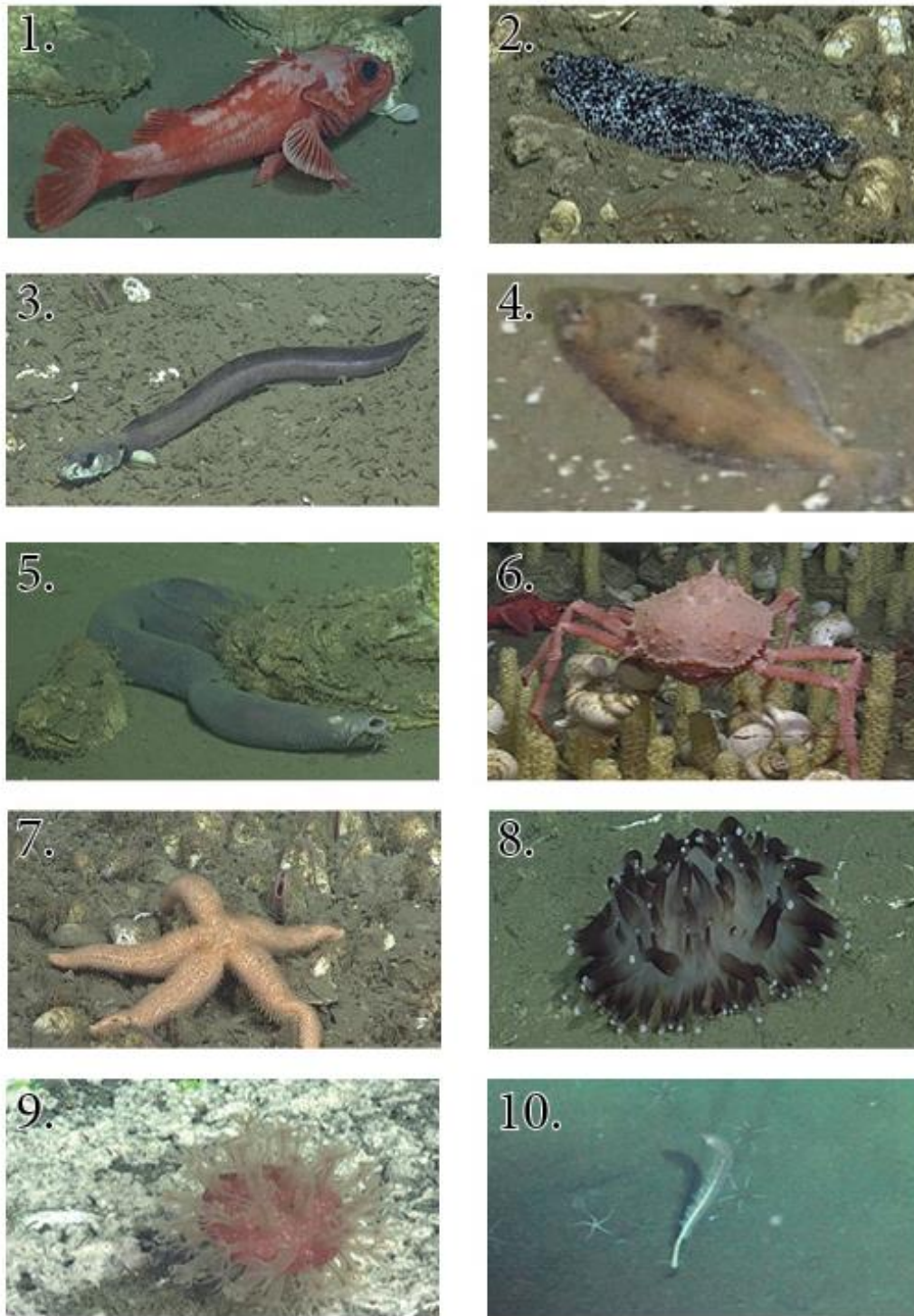


Figure 3. Examples of the ten morphotypes. (1) Rockfish, (2) Deep Sea Sole, (3) Eelpout, (4) Flatfish, (5) Hagfish, (6) Crab, (7) Sea Star, (8) Anemone, (9) Soft Coral, and (10) Sea Pens.

Depth profiles for Einstein's Grotto (EG) were created based on transects across the bathymetry map produced by the AUV *Sentry* 2010 data (Figure 8). The macrofauna and substrate along these profiles was delineated based on visual observation. Four general types of substrate were documented:

bacterial mat; clam bed; carbonate cobbles; and sandy sediment (Figure 4).

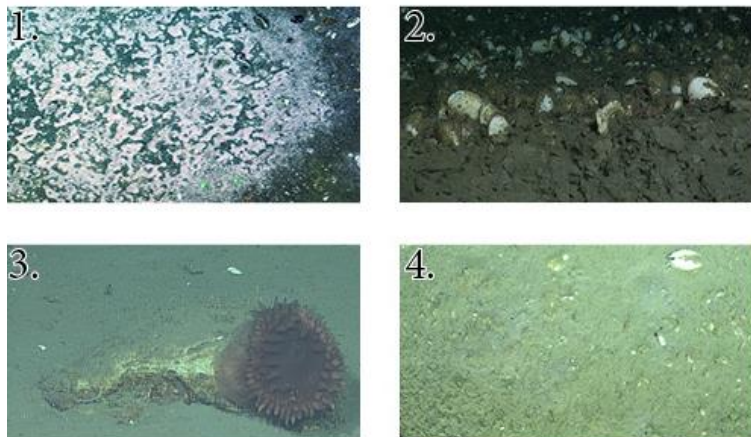


Figure 4. Examples of the four substrate categories identified along depth profiles shown in Figure 9. (1) *Beggiatoa* Bacterial Mat, (2) Vesicomid Clam Bed, (3) Carbonate cobble with an anemone attached, and (4) Sandy Sediment.

Results

All morphotypes except flatfish were observed at all eight seep sites. Flatfish were not observed at Rudder or EG. Sea stars were the dominant morphotypes at six of the eight sites (RSNE, RSNC, RSND, Z, RSNB, and EG) accounting for 17% to 41% of the total abundance of organisms. Rockfish were the next most abundant group at these sites and dominate at the two other sites (Rudder, and HRF24) accounting for 17% to 26% of the total abundance of organisms. Six sites had a total mean density of animals >0.7 ind. m^{-2} (RSNE, RSNC, Z, RSNB, HRF24, EG) (Figure 5).

Site Name	RSNE	RSNC	RSND	Rudder	Z	EG	RSNB	HRF24	F
Total Area	1584.6	1351.0	887.1	870.7	697.3	636.3	620.8	599.9	345.0
Total Bacterial Mat Area	108.4	67.8	123.0	17.9	44.8	61.4	72.9	10.8	0
Total Animal Abundance	1241	1306	504	366	504	567	571	581	199

Table 1. Areal extent of all seep sites and background site (F), along with areal extent of bacterial mats and total faunal abundances.

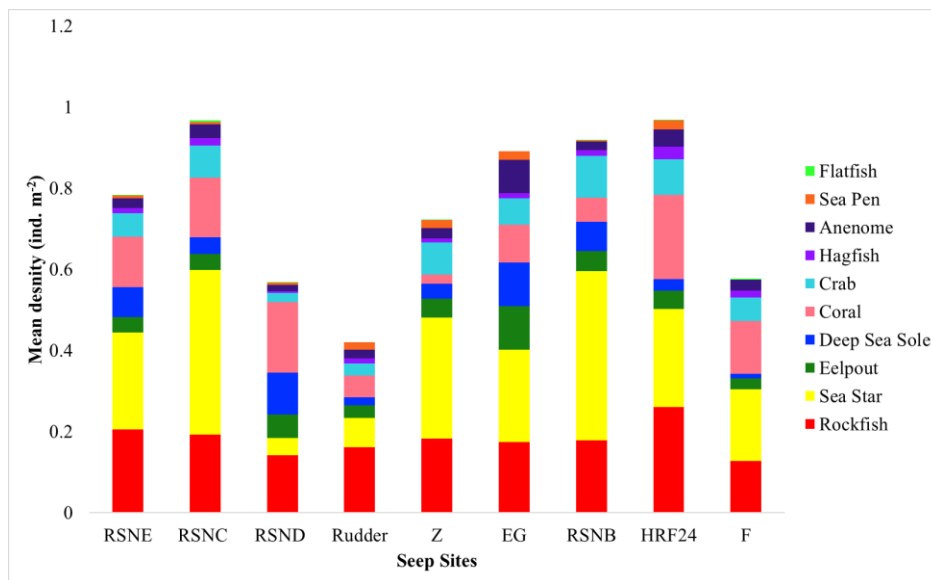


Figure 5. Mean density (ind. m^{-2}) of organisms at the eight seep sites and one background site (F).

At Einstein's Grotto faunal abundances were greater outside of the bacterial mats than within (Figure 6). A paired t-test on the data from EG, indicates that the distribution across substrate types is statistically significant and not a product of chance (P two-tailed = 0.020027, $\alpha=0.05$, $df=9$ t-stat=-2.8206). Some mobile groups such as rockfish, eelpouts, deep sea sole, and hagfish showed no differences in their mean densities inside and outside of the bacterial mat, while sessile organisms such as coral, anemones, and sea pens were much less abundant, and in some cases not present at all, within the bacterial mat.

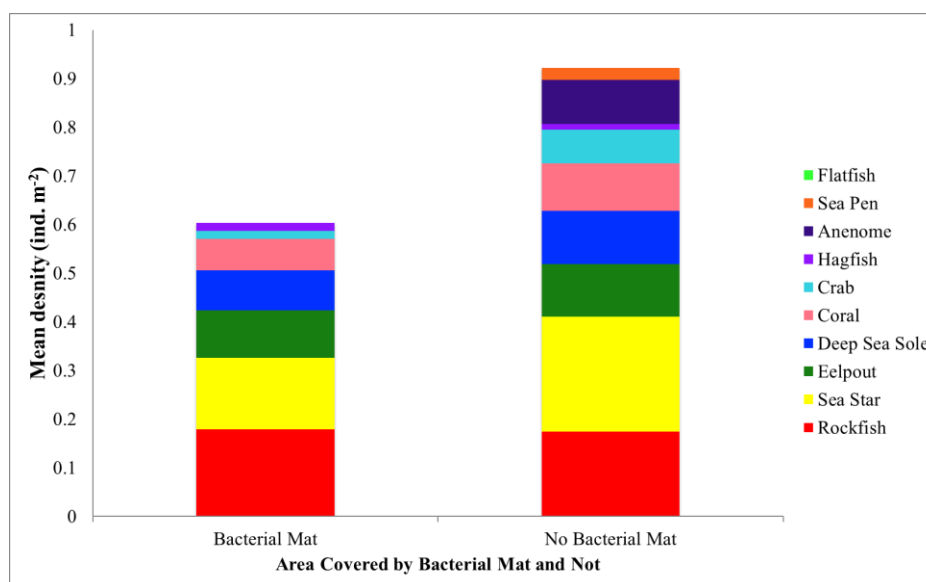


Figure 6. Mean density (ind. m⁻²) of organisms inside and outside of the bacterial mat at Einstein's Grotto.

The spatial distribution of bacterial mats and clam beds at EG was similar across the site, with bacterial mats occurring near or on central highs and clam beds surrounding them. Macrofauna such as rockfish and coral were commonly associated with carbonate cobbles or the sandy substrate outside of the bacterial mats (Figure 9).

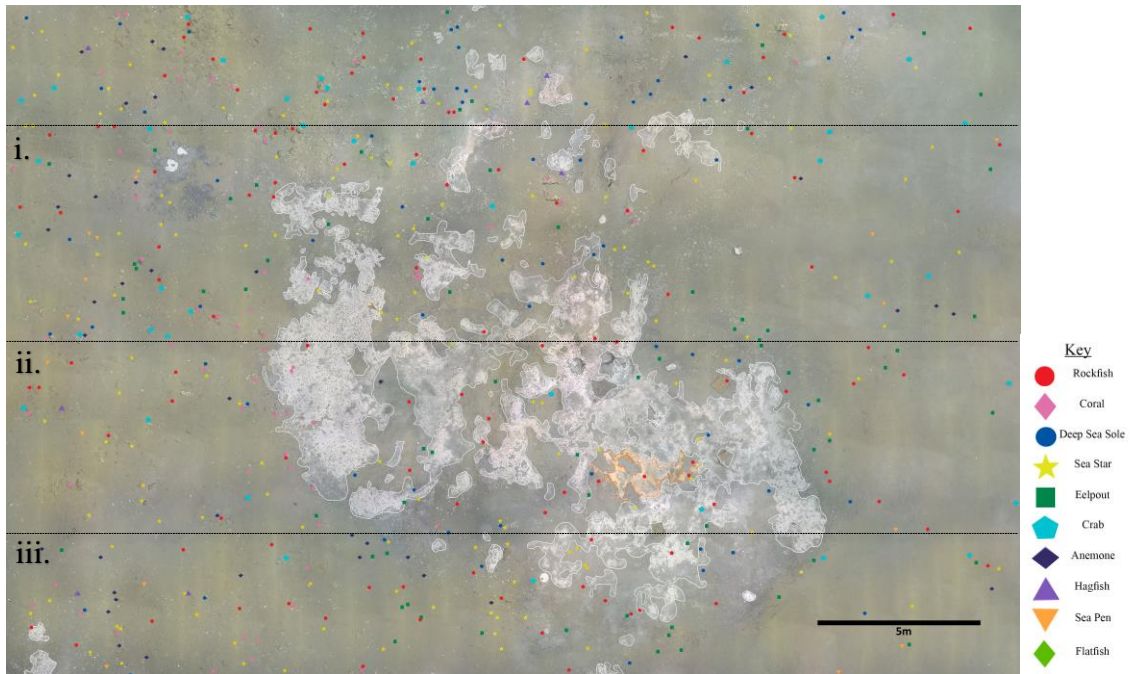


Figure 7. Photomosaic of Einstein's Grotto with morphotypes marked and bacterial mat outlined in white or orange. Dashed lines correspond to vertical profiles in Figure 9.

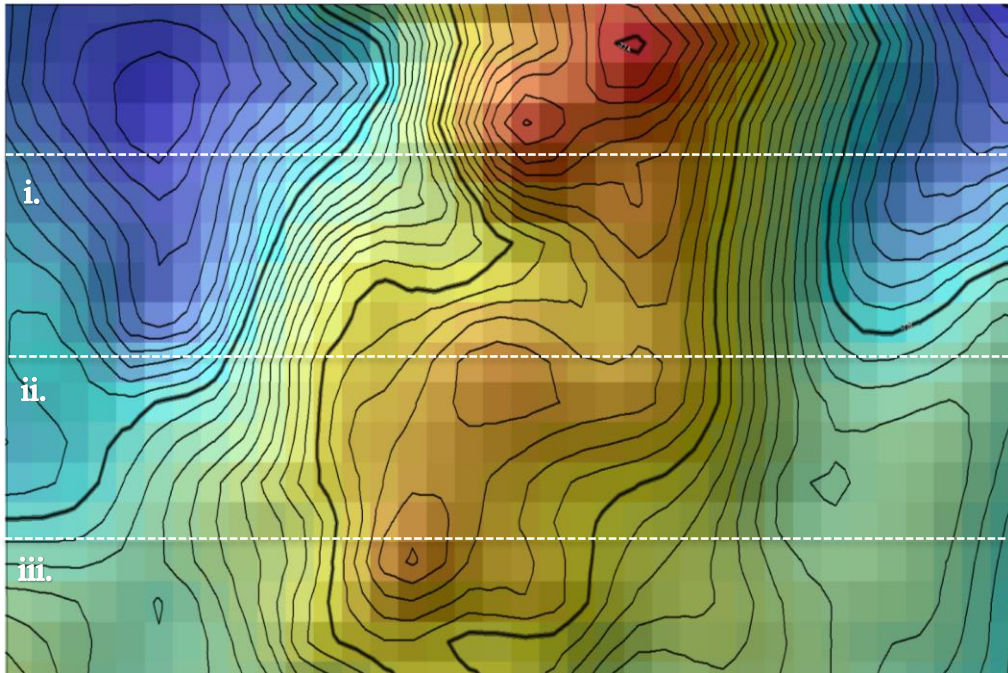


Figure 8. Bathymetry of Einstein's Grotto (0.1 m depth contours) collected by the AUV *Sentry* in 2010. Dashed lines correspond to vertical profiles in Figure 9.

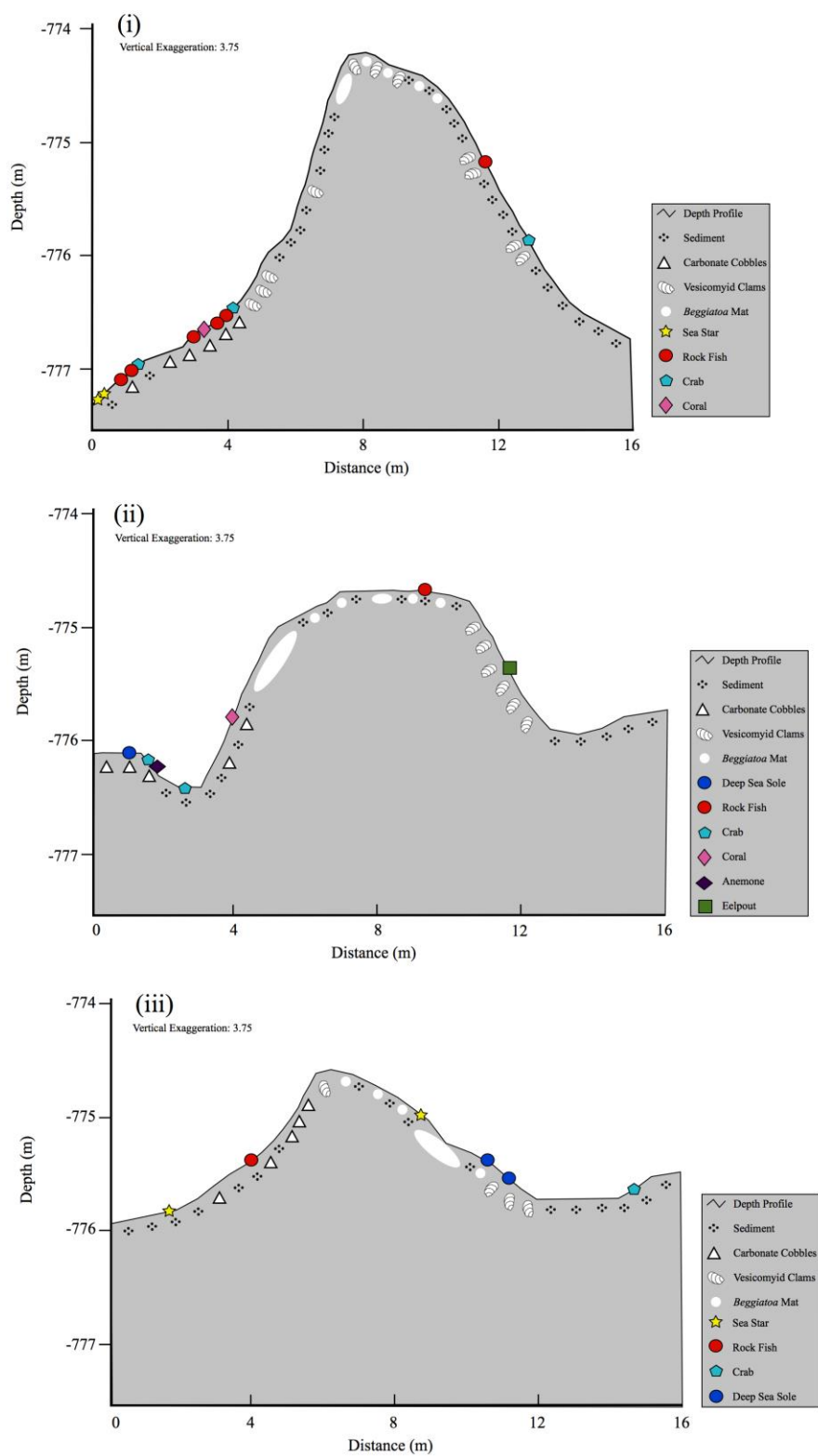


Figure 9. Vertical profiles of Einstein's Grotto with morphotype distribution and substrate types marked.

Discussion

Southern Hydrate Ridge has recently received considerable attention, in part because of the completion of the OOI Cable Array. Over the next two decades the site will be continuously monitored with a wide array of instruments aimed at understanding the evolution of this site, the linkage among seismic activity and fluid flow, and quantification of methane flux from the seafloor. This study provides the first baseline for the macrofaunal benthic community, location of individual seep sites, and underlying geology.

Previous studies at SHR have showed a relationship between seeps and distribution of *Beggiatoa* bacterial mats and vesicomid clams as well as the infauna distributions (Sahling et al., 2002; Sommer et al., 2002). This study supports that finding in the vagrant macrofauna. At Einstein's Grotto, the non-specialized vagrant species are in greater abundance above non-bacterial mat substrates surrounding the seep. This distribution may reflect an avoidance by most animals of the low-oxygen, high-sulfur conditions that characterize the mat environments (Torres et al. 2002, Tryon et al. 2002). Carney (1994) observed a "hit and run" feeding behavior by crabs into and out of the bacterial mat at seeps in the Gulf of Mexico. They suggested mobile species utilized the bacterial mats for food, but not for living habitat. This may explain why the more mobile morphotypes occur at nearly equal densities inside and outside of the bacterial mat at Einstein's Grotto. Their mobility allows them to exploit the resource despite the adverse environmental conditions.

A new finding from this study is the relationship between macrofaunal distributions and carbonate outcrops and cobbles. There appears to be an affinity for all macrofaunal types for carbonate deposits (pebbles, cobbles, and boulders) compared to sandy sediments on the outskirts of the seep. This relationship is understandable for the sessile anemones and soft corals, which require hard stable substrates for colonization (Mercier et al. 2016). Some of the mobile

morphotypes at Einstein's Grotto, such as rockfish and sea stars, have been found to demonstrate a preference for rocky habitat in other locations (Carlson and Straty 1981). However, the temporally limited nature of the dataset in this study limits our ability to interpret the exact nature of this relationship. A possible alternative to substrate preference for mobile groups is that the observed distributions are due to avoidance of low-oxygen, high-sulfur water transported by currents from the seep.

Conclusion

This baseline study provides the first quantification of bacterial mat and animal distributions at SHR, and the relationship of these biological communities to the underlying geology. At Einstein's Grotto macrofauna were observed in higher densities outside of the regions characterized by *Beggiatoa* bacterial mats and demonstrate a preference for carbonate deposits. Preliminary observations of organism distributions at the seven other sites at SHR are consistent with what was reported here for Einstein's Grotto, and concur with interpretations from other published literature (Carney, 1994; Rybakova et al., 2013; Wagner et al., 2013). However, further processing and analysis using the same methods as those employed for Einstein's Grotto are necessary to confirm these observations. Data from such analysis may also provide insights into what is driving some of the variations documented between sites in this study, such as why the RSND and Rudder sites have such low organism density in comparison to the others (Figure 5).

Furthermore, the 2011 data, while the first to provide insight into the benthic community at SHR at large, is only a snapshot in time. As part of the construction of the OOI Cable Array, SHR and Einstein's Grotto in particular have been visited almost yearly since 2010. However, further faunal counts have not been undertaken. Dramatic changes in geologic features (Figure 10) and *Beggiatoa* mat distributions have been observed, sometimes over the course of only a

few days. We conclude that time series data is critical at this site to fully understand how these seafloor changes, along with other physical processes such as current variations, influence different components of the benthic community. A time series at this location could also provide insights into the environmental impacts of permanent scientific installations on the seafloor. These impacts are important to understand as cabled monitoring systems become prevalent in ocean sciences, as well as in the gas, oil, and mining industries.

Because SHR hosts a unique system in the OOI Cable Array, the opportunities available for time series data reach beyond simple return visits with ROVs and AUVs. Although these vehicles can provide year-to-year data, they are limited by the expensive nature of shipboard operations

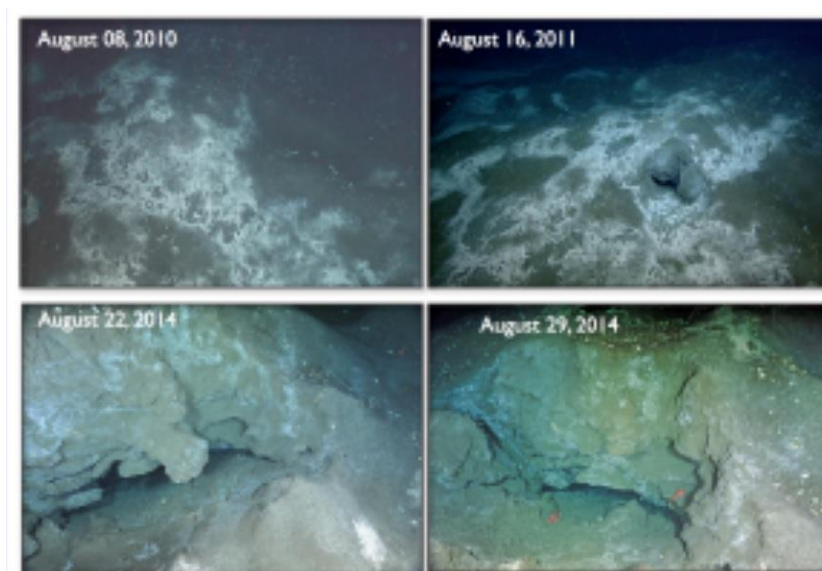


Figure 10. The development of a chasm at Einstein's Grotto over four years. Images were taken of the same location in 2010, 2011, and a week apart in 2014.

and the local weather window for fieldwork. A vehicle stationed at SHR as part of the Cable Array could circumvent these limitations. An example of such a system at another methane hydrate seep, Barkley Canyon, is the Wally Deep Sea Crawler. The crawler carries a suite of instruments and follows a reproducible path through the environment to allow real-time monitoring and investigation of the benthic ecology (Purser et al. 2013). Another approach that could be used for this research is docked AUVs. Originally developed for the same monitoring tasks as the crawlers, the AUVs aren't tied to a set track. This allows greater maneuverability and

flexibility in missions (Pontbriand et al. 2015), which could be critical in locations like methane seeps that can have such dramatic changes in short periods of time.

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