Distribution of chemosynthetic biological communities in Monterey Bay, California

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ABSTRACT

We report the first quantitative evaluation of the distribution of seafloor chemosynthetic biological communities on a regional scale. The results are based on the analysis of video images and navigation from 792 benthic remotely operated vehicle dives conducted on the continental margin in Monterey Bay, California. These communities are common, occurring within 5% of the 25-m-square grid cells within which there have been bottom observations within 45 km of the bay's head and within 9% of the visited cells that are below 550 m water depth. Although it has been previously assumed that these communities are associated with fluid seepage from faults, they are not more common within known fault zones. Surprisingly, the communities in Monterey Bay occur preferentially on steep slopes, which are commonly sites of recent erosion.

Keywords: seeps, fluid flow, authigenic carbonate, faults, continental margins.

INTRODUCTION

Numerous seafloor sites have been discovered along continental margins where a supply of reduced chemical compounds, such as hydrogen sulfide or methane, supports chemosynthetic biological communities (CBCs), authigenic mineralization, and early diagenesis. CBCs depend on energy provided by microbial oxidation of these reduced compounds (Jannasch and Wirsen, 1979). The overall importance of the processes that occur at CBC sites is related to the proportion of seafloor affected and the mechanisms responsible for providing these compounds to the seafloor.

CBC occurrence is commonly used as an indicator of seafloor fluid venting. CBCs were first discovered around ridge-crest hydrothermal vents (Corliss et al., 1979). Originally it was presumed that these communities are extremely rare because vigorous hydrothermal springs are restricted to active submarine volcanic areas. However, discoveries of similar CBCs in a variety of other geologic settings have made it clear that CBCs may occur wherever adequate amounts of chemically reduced fluids make it to the seafloor before being oxidized (Hovland and Judd, 1988). CBC sites and authigenic carbonate deposits now have been encountered along all continental-margin segments where the seafloor has been visually imaged.

To determine the extent and distribution patterns of CBCs, large parts of the seafloor must be surveyed with techniques that allow CBCs to be detected. Sonar is the only remote-sensing tool that has been applied to this problem with any success (Carson et al., 1994). Because the organisms and authigenic mineralization associated with CBCs produce rough seafloor, these communities appear as areas of high reflectivity in sonar data. Unfortunately, sonar data cannot be used to independently map distributions of CBCs because other processes produce reflective seafloor. Thus, there is no individual remote-sensing technique that is adequate to map the distribution of CBCs and associated authigenic mineralization. Visual imaging is required to confidently identify CBC sites. Because only a tiny part of the seafloor has been observed, even in the best-studied areas, the extent of these communities is still unknown.

The Monterey Bay Aquarium Research Institute (MBARI) runs two remotely operated vehicles (ROVs) from Moss Landing harbor at the head of Monterey Canyon. These ROVs have conducted more than 2400 dives since 1989; the majority of dives are within Monterey Bay. MBARI's efforts make Monterey Bay's seafloor among the most observed anywhere.

Monterey Canyon is carved into the floor of Monterey Bay (Fig. 1). Various rock units crop out along the canyon's sides, including the Monterey Formation, which is known for its high organic carbon content (Pisciotto and Garrison, 1981). Thus, organic matter within the Monterey Formation has the potential to fuel microbial reactions that add methane and hydrogen sulfide to the pore waters in overlying sediments.

The Palo–Colorado–San Gregorio fault zone (Fig. 1), the westernmost active fault of the Pacific–North American plate boundary, extends underneath Monterey Bay (Greene, 1977). Another zone of faults with a northwest-southeast orientation, mapped from structural offsets seen in seismic reflection profiles, crosses the inner bay (Greene, 1977). Additional delineation of the active fault zone within the bay is provided by the pattern of earthquake epicenters (Fig. 1).

Initially ROV dive efforts in Monterey Bay were not directed at finding CBCs or to themes related to fluid seepage. However, early in the MBARI dive operations, CBCs were discovered on the flanks of Monterey Canyon (Barry et al., 1996). These communities are primarily characterized by living vesicomyid clams, but secondary amounts of bacterial mats and vestimentiferan worms also occur. Authigenic carbonates, which have stable isotope compositions indicating that they were produced from methane-derived carbon, are common on the floor of Monterey Bay (Stakes et al., 1999).

After initial discoveries, dives were specifically targeted to search for CBCs. The presence of CBCs was taken as an indicator of

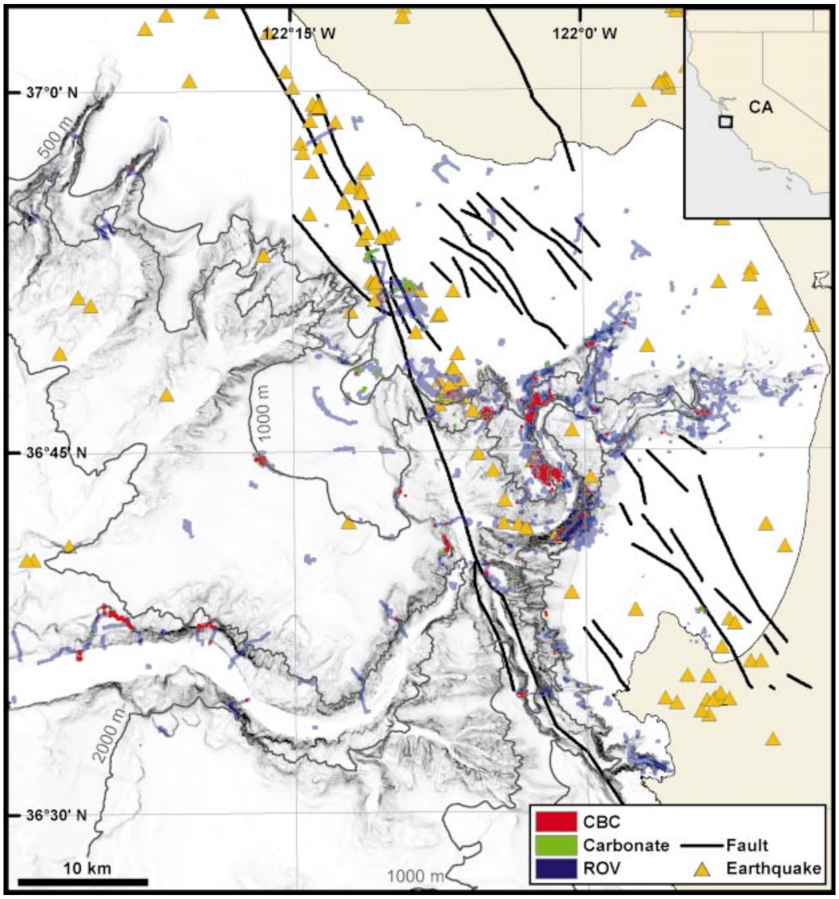

Figure 1. Locations of Monterey Bay Aquarium Research Institute's benthic remotely operated vehicle (ROV) dive tracks (blue) and sites where video annotations indicate occurrence of chemosynthetic biological communities (CBCs): seeps, vesicomyid clams, vestimentiferan worms, or bacterial mats (red), and authigenic carbonates (green) occur. Background is seafloor rugosity image based on multibeam bathymetry with 200 m, 1000 m, and 2000 m contours. Fault traces are from Greene (1977). Also shown are epicenters of earthquakes of magnitude 2 or higher since February 1967 (www.quake.geo.berkeley.edu). CA—California.

fluid flow within the seafloor of Monterey Bay (Orange et al., 1999). One strategy was to visit areas associated with faults, assuming that CBCs occur preferentially along active faults.

To understand the spatial distribution of CBCs and authigenic carbonates in Monterey Bay, we have systematically analyzed the archived MBARI ROV dive data. Here we consider how their distribution relates to local geologic controls.

METHODS

The R/V *Point Lobos* has operated as the support ship for the ROV *Ventana* for day operations in Monterey Bay since 1989, and the R/V *Western Flyer* has supported the ROV *Tiburon* since 1998. Both ROVs are equipped with multiple high-resolution video cameras. Continuous videotapes of one camera are routinely recorded during each dive, and >10,000 h of video footage are archived in the MBARI video library.

Videotapes collected during MBARI ROV dives are systematically viewed by professional, science-trained video archivists (Jacobsen Stout et al., 2001). Major features identified on the tapes are entered into the Video Annotation Reference System (VARS) database, which was designed to systematically record and quantify scientific observations made on all ROV dives. Keyword entries allow archivists to quickly annotate important observations (e.g., objects and organisms). To date, 8300 h of videotapes have been annotated. About half the dives had benthic objectives. A common time base was used to link the VARS database observations with the ROV navigation files.

We have focused on entries in the VARS database for seep, Vesicomyidae, bacterial mat, Vestimentifera, and carbonate. The term "seep" is defined in the video archivist instructions as an area where gray or black sediments, bacterial mats, and/or living chemosynthetic fauna are observed. Vesicomyid clams and vestimentiferan worms are easily identified, and bacterial mats appear as white or yellow seafloor coatings. Annotations for seep, Vesicomyidae, Vestimentifera, and bacterial mats are indicators of living CBCs. Because there are no carbonate-rock formations of a primary depositional origin underlying Monterey Bay, annotations for carbonates imply methane-derived authigenic carbonates that occur as nodules or crusts with distinctive irregular shapes.

MBARI ROV navigation data are derived from acoustic ultrashort-baseline (USBL) tracking systems, which measure range and bearing from the ship to the ROV. These data, combined with ROV depths derived from pressure sensors, allow the vehicle's position to be calculated with respect to the ship's position. R/V *Point Lobos* was navigated with a Mini-Ranger system and backed up with Loran-C in 1992–1995, prior to the availability of differential global positioning system (GPS) data. Since then, the navigation data of the R/V *Point Lobos* and all R/V *Western Flyer* data have been based on differential GPS. The real-time estimates of ROV latitude, longitude, and depth were logged at least every 5 s.

Raw USBL-based ROV navigation data often contain spurious fixes. This noise is dominated by errors in the USBL bearing. Jumps between individual fixes are often implausible because large speeds and accelerations for the ROV are implied. Data processing involved first interactively removing large spikes in the navigation and then solving for a plausibly smooth navigation track that minimizes acceleration and speed while fitting the original navigation data in a least-squares sense. This processing was performed by using Mbnavedit, an interactive tool included in the MB-System software package (Caress and Chayes, 1996; http://www.mbari.org/data/mbsystem/).

To determine where and how much of the Monterey Bay seafloor has been investigated by using ROVs, processed ROV navigation from on-bottom parts of benthic dives between 24 April 1989 and 20 June 2002 were converted to UTM coordinates and binned by using 25 m^2 grid cells. Simrad EM-300 30 kHz multibeam bathymetry data are available for water depths of >90 m throughout Monterey Bay from surveys conducted for MBARI during 1998 (Greene et al., 2002). Comparing water depths for the gridded ROV navigation with an equivalent 25 m^2 multibeam bathymetry grid cell identified on-bottom grid cells. ROV navigation grid cells were excluded wherever the ROV navigation depth differed by >20 m from the depth in the corresponding bathymetry grid cell. To further eliminate marginal data, grid cells that had less than four matches between ROV navigation and

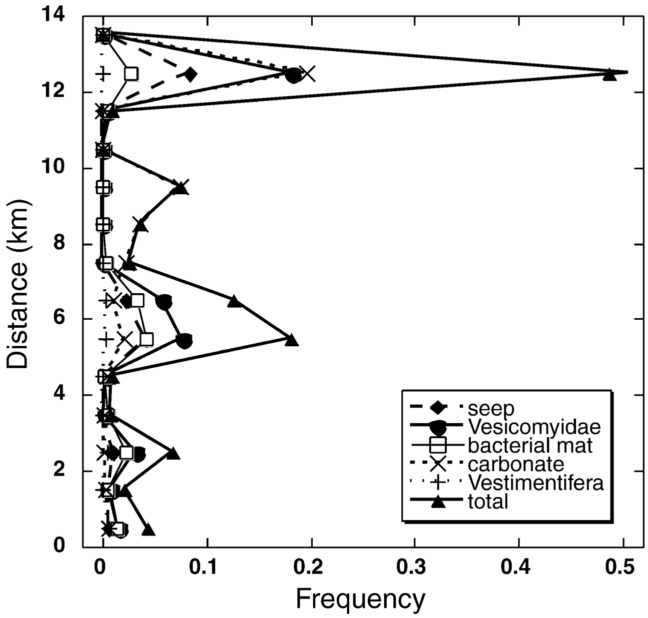

Figure 2. Plot showing frequency of chemosynthetic biologic communities, corrected for dive effort, with respect to distance to mapped faults (Fig. 1).

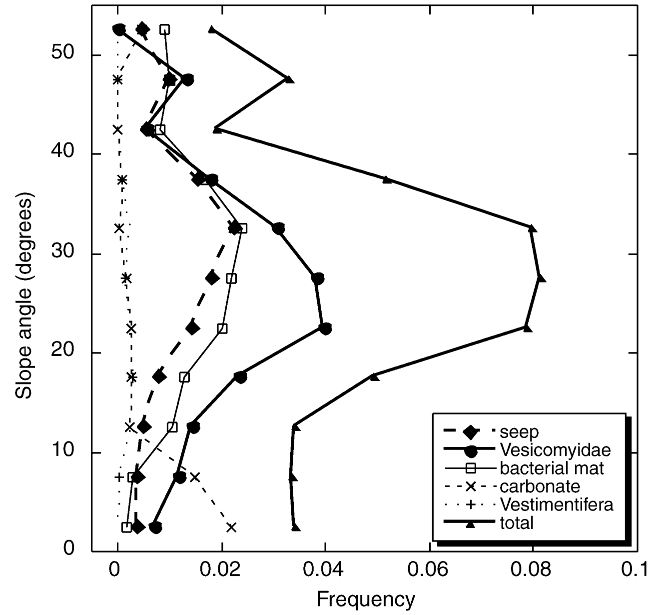

Figure 3. Plot showing frequency of chemosynthetic biologic communities, corrected for dive effort, with respect to equivalent angle of seafloor. Equivalent angle is measure of maximum seafloor slope calculated for each 25 m × 25 m cell, given depth of eight adjacent cells based on multibeam data.

the multibeam bathymetry were also eliminated from subsequent analysis. Dividing the number of observations of each phenomenon by the number of grid cells that were visited corrected for variations in dive effort.

RESULTS

The correlation of ROV depth and multibeam bathymetry shows that of the 3,087,376 grid cells within a 45 km radius of Moss Landing Harbor, 29,125 grid cells have been visited and observed by MBARI ROVs (Fig. 1). Thus, the seafloor has been visited within 0.9% of the grid cells in Monterey Bay that are within 45 km of Moss Landing Harbor. The VARS archive has a total of 10,850 navigation matches with sites having seep, Vesicomyidae, bacterial mat, Vestimentifera, or carbonate annotations. Of the visited 25 m^2 grid cells within 45 km of Moss Landing, 5% contain living CBCs.

Contingency table tests were conducted to determine whether the CBCs were randomly distributed with respect to water depth, distance from faults, distance from earthquakes, epicenters, and seafloor slope. The distributions used for comparison to the observed distributions were created by randomly assigning pixels that the ROV had visited as positive for CBC occurrence. The number of assigned pixels was equal to the number of measured CBC pixels. Each test was repeated 100 times to account for the variability in the random assignment. In all cases, the null hypothesis—that the random distribution and the measured distribution are the same—was rejected ($\alpha = 0.10$).

CBCs with living heterotrophic animals were encountered in 9% of the 25 m^2 grid cells that were visited below 550 m water depths. Although the distribution of dives shows that the greatest dive effort was focused in the depth range of 150–550 m, no living vesicomyid clam beds have been observed shallower than 550 m. The shallow bacterial mats found in <550 m of water appear to be associated with local and ephemeral organic carbon sources, in a similar fashion to the CBCs that occur on Monterey Fan associated with decomposing kelp falls (Embley et al., 1990). The occurrence of authigenic carbonates is not depth dependent because they occur on the shelf and at greater depth.

A plot showing the distance from the mapped faults and the occurrence frequency of CBCs and authigenic carbonates corrected for dive effort (Fig. 2) indicates that the occurrence of CBCs and authigenic carbonates is less frequent, rather than more frequent, near the mapped faults. The MBARI video database is clearly biased by the objectives of the scientists who conducted the dives. Many dives were located along the path of regional faults, in part to search for fluid seeps that might occur along those faults. Thus, the database is arguably biased toward searching within fault zones. However, this bias makes the lack of correlation of CBC occurrence with the faults zones more noteworthy.

Inspection of Figure 1 indicates that CBCs occur preferentially on the walls of Monterey Canyon where the seafloor slopes are high. The average slope of the seafloor in each 25 m^2 grid cell was compared with the occurrence frequency of CBCs. These data show that CBCs occur at much higher frequency on areas of steep slope than on areas with more gentle slope in Monterey Bay (Fig. 3).

Several biases exist that may overemphasize the frequency with which CBCs and authigenic carbonates are observed on relatively smooth seafloor. High-reflectivity areas on sonar maps were used to locate many of the dives that visited otherwise smooth seafloor. In flat terrain, CBCs make strong targets on the ROV scanning sonar. When ROVs transit flat seafloor, their course is commonly altered to investigate nearby sonar targets. Thus, CBCs within ~50 m of an ROV's planned path are likely to be observed. Conversely, because there are many sonar targets in rough terrain, the detection efficiency of CBCs is not substantially improved by the ROV's sonar. In addition, the technique of matching the ROV depth and multibeam bathymetry to determine when the ROV was on the bottom may unintentionally eliminate some data on steep seafloor. These biases may result in an underrepresentation of CBC occurrence on steep slopes of the canyon walls and in other areas of rough topography (Figs. 1 and 3).

DISCUSSION

Although a disproportionate percentage of the ROV dives occurred in the 150–550 m depth interval, no living heterotrophic CBCs were found in these water depths. Why living CBCs in Monterey Bay are restricted to water depths of >550 m is unclear.

Apparently, the distributions of authigenic carbonates and living CBCs are decoupled because authigenic carbonates remain common in <550 m of water. Although these authigenic carbonates contain methane-derived carbon (Stakes et al., 1999), they are not necessarily produced in the same environments that support seafloor CBCs. Methane-derived authigenic carbonates can be generated within the subsurface (Rodriguez et al., 2000), and once formed, they may be exhumed by erosion. Because they are more erosion resistant than the surrounding uncemented sediments, they will accumulate as a lag on the seafloor in areas of net erosion. Thus, unlike living CBCs, the occurrence of exposed authigenic carbonate does not require the continued presence of methane-bearing fluids and may not reflect modern conditions.

The occurrence of living CBCs in 9% of the visited grid cells below 550 m water depth indicates that these communities are common along the Monterey Bay continental margin. The existence of these organisms requires that hydrogen sulfide or methane be available in the immediate subsurface at these sites.

Previously published models of CBC distribution within Monterey Bay have assumed that CBCs occur along fluid-flow conduits associated with faults that bring methane or hydrogen sulfide to the seafloor (Orange et al., 1999). Although fluid flow along faults conduits may support some CBCs, the distribution of CBCs in Monterey Bay does not mimic the independently mapped fault distribution (Figs. 1 and 2).

The occurrence of CBCs in Monterey Bay shows a preferential association with steep slopes and slide scars (Figs. 1 and 3). Presumably these areas have undergone recent erosion, and a causal relationship may exist between steep slopes and CBCs.

Because continental-margin sediments are frequently organic rich, series of biogeochemical reactions occur with increasing depth into the seafloor that involve the progressive reduction of oxygen, nitrate, iron, manganese, and sulfate in the pore waters and the accumulation of methane below the depth of sulfate depletion (Claypool and Kaplan, 1974). One consequence of the rapid removal of the upper sediment veneer by erosion (especially by slope-failure events) is that methane-rich, sulfate-free sediments are exposed on the newly formed seafloor. Methane within the exposed sediments will be oxidized aerobically where it is in contact with oxygenated seawater and anaerobically where it is exposed to oxygen-depleted sulfate-bearing seawater (Reeburgh, 1976). Anaerobic oxidation of methane produces hydrogen sulfide, a necessary chemical substrate for most chemosynthetic communities.

We propose that the CBCs exploit the methane and hydrogen sulfide that are exposed on the seafloor by erosion. Communities of anaerobic, methane-oxidizing Archaea will flourish in the subsurface under areas of recent erosion as sulfate from the overlying seawater diffuses into methane-bearing sediment. The hydrogen sulfide produced by anaerobic oxidation of methane will diffuse up toward the seafloor to support chemoautotrophic bacterial mats, vesicomyid clams, and vestimentiferan worms.

CONCLUSIONS

Extensive ROV operations and 8300 h of annotated videotape make the seafloor of Monterey Bay, California, among the most observed continental margins in the world. These data show that living CBCs are common, occurring in ~9% of the 25 m^2 grid cells that are associated with bottom observations in Monterey Bay below 550 m water depth. If this association is applicable to other continental-margin areas, the area associated with living CBCs and exposed to the related rapid diagenesis may be much greater than previously assumed. The distribution of CBCs in Monterey Bay does not support the hypothesis that they are primarily associated with tectonically driven flows through regional faults. Living CBCs are most common on steep slopes where recent seafloor erosion is likely to have occurred. Recent erosion may sharpen the geochemical gradients sufficiently to expose methane near enough to the seafloor to support the CBCs.

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