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Alvin Explores the Deep Northern Gulf of Mexico Slope

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Many of the world's productive deepwater hydrocarbon basins experience significant and ongoing vertical migration of fluids and gases to the modern seafloor. These products, which are composed of hydrocarbon gases, crude oil, formation fluids, and fluidized sediment, dramatically change the geologic character of the ocean floor, and they create sites where chemosynthetic communities supported by sulfide and hydrocarbons flourish.

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Unique fauna inhabit these sites, and the chemosynthetic primary production results in communities with biomass much greater than that of the surrounding seafloor.

The northern Gulf of Mexico continental slope is well known for hydrocarbon seeps and fluid-gas expulsion geology. Following the 1984 discovery of chemosynthetic communities in the Gulf [*Kennicutt et al.*, 1985], the majority of studies there have focused on the upper continental slope, at depths reaching 1 kilometer below the sea surface. With respect to community structure, basic biology, and life histories of the dominant fauna, the Gulf's upper slope hydrocarbon seep communities are the most intensely studied and best understood of any cold seep communities.

Prior to the summer of 2006, however, few hydrocarbon seep sites in water depths greater than 1 kilometer had been visited and sampled. Differences in geologic setting and species composition of seep communities on the deep slope pose important scientific questions concerning cross-slope and along-slope biological variability and geological controls.

A 7 May to 2 June 2006 research cruise using the manned submersible *Alvin* explored the northern Gulf of Mexico's deep continental slope (water depths below 1 kilometer). The primary cruise objective was to determine the cross-slope and along-slope variations in chemosynthetic communities and their geologic settings.

The Recent Cruise

The cruise was jointly funded by the U.S. Minerals Management Service (MMS) and the NOAA Office of Ocean Exploration. MMS has responsibility for protecting chemosynthetic communities and deepwater corals, while NOAA is interested in the unexplored deeper parts of the slope and relationships between biology and surficial geology/geochemistry.

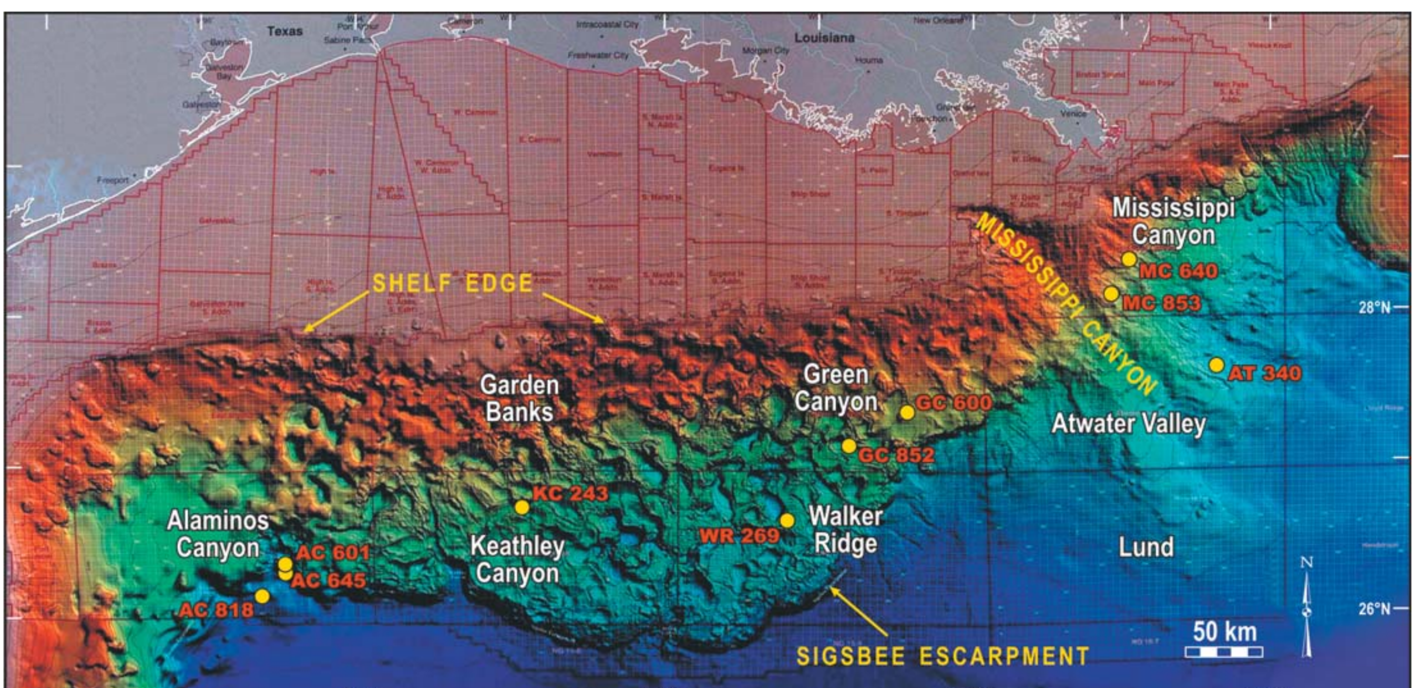

Fig. 1. A multibeam bathymetric image of the northern Gulf of Mexico continental slope on which the 10 Alvin *dive sites are plotted. Lease areas established by the U.S. Minerals Management Service for managing oil and gas activities are superimposed on the image.*

A total of 24 *Alvin* dives were made at 10 sites (Figure 1), and chemosynthetic communities were found at all of the sites along with hydrocarbon seepage, carbonates, and occasional brine seeps. Four sites had especially diverse and densely populated seep communities and topographically complex seafloor geology, and they were the focus of multiple dives: Atwater Valley Block 340 (AT 340, 2200 meters), Green Canyon Block 852 (GC 852, 1410 meters), Alaminos Canyon Block 601 (AC 601, 2340 meters), and Alaminos Canyon Block 818 (AC 818, 2740 meters). These site locations can be found in Figure 1.

Finding chemosynthetic communities and deep coral sites was the result of a two-stage data collection program initiated by the authors in conjunction with MMS geoscientists prior to the *Alvin* dives. In October 2005, three-dimensional seismic data were analyzed at the MMS office in New Orleans, La., to help predict seafloor conditions. Eighty potential chemosynthetic community sites were identified, and 19 were prioritized (between October 2005 and February 2006) then imaged with a digital drift camera between 11 and 25 March 2006. From these, the 10 *Alvin* dive sites were selected, with the final dive plan representing sites from a wide range of water depths (1070–2775 meters) and geographic locations (see Figure 1).

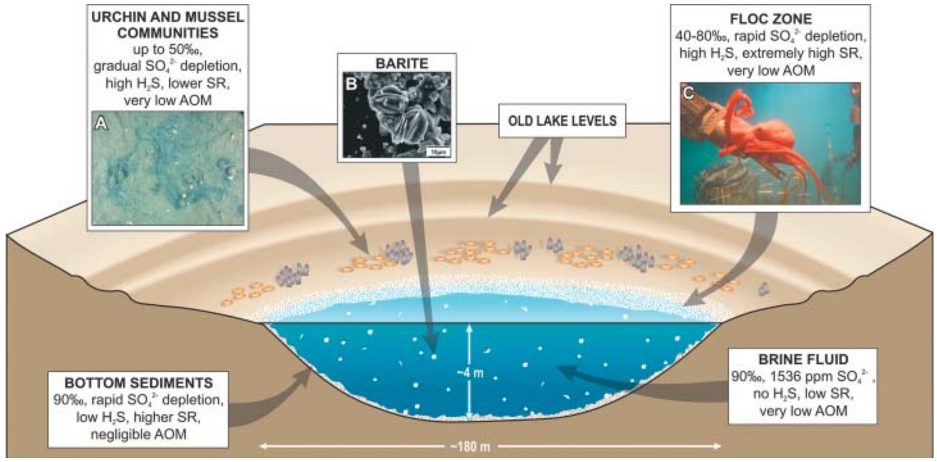

Fig. 2. Diagram of the brine lake found in Alaminos Canyon Block 601 at a depth of 2334 meters, illustrating geochemical conditions and primary lake margin communities. Photographs represent heart urchins in reducing sediment (A), scanning electron microscope photograph of barite 'flocs' in brine (B), and a new species of octopus (Benthoctopus sp.) found in a moribund state at the lake edge (C; photo by Bruce Strickrott).

Deep-Slope Hydrocarbon Seep Biological Communities

Gulf of Mexico hydrocarbon seep communities share broad similarities but differ in many details over their depth ranges of about 500–3300 meters. At all depths, species with chemoautotrophic bacterial symbionts persist at different stages in a geological progression from fluid-prone to mineral-prone habitats [*Bergquist et al.*, 2003]. This progression results in different combinations of vestimentiferan tube worm, mussel, and bacterial mat dominance, and occasional areas with abundant vesicomyid clams and pogonophoran tube worms.

Bathymodiolid mussels were sampled from every site visited. Four different species of mussels were collected, one of which appears to be a new species to science, based on our preliminary molecular analyses. *Bathymodiolus childressi*, abundant on the upper slope, was collected as deep as 1450 meters and has been previously collected from Alaminos Canyon Block 645 (AC 645) at 2220-meter depth [*Cordes et al.*, 2007]. *Bathymodiolus heckerae* was never found shallower than 2200 meters and also did not co-occur with *Bathymodiolus childressi*. *Bathymodiolus brooksi* has the widest depth range of any of these mussels and is the most common mussel between 1040 and 3300 meters.

Vestimentiferan tube worms (siboglinid polychaetes) were visually confirmed at every site except one, Mississippi Canyon Block 640 (MC 640), and the tube worms were collected from seven sites. *Escarpia laminata* dominated the sites in water depths below 1400 meters while a new, undescribed species of *Lamellibrachia* often was abundant at intermediate depths between 1100 and 2300 meters. A single individual of another undescribed *Lamellibrachia* species was identified from collections at GC 852 in our preliminary molecular survey; however, no morphological variation between the *Lamellibrachia* species was noted at the time. None of the three other vestimentiferan species found at shallower sites on the upper slope was seen or collected at these deeper sites.

The communities closely associated with lower slope mussel beds and tube worm aggregations also were quite different from upper slope communities. Species of decapod shrimp (*Alvinocaris* species) and galatheid crabs (*Munidopsis* species) found on the lower slope were different from those on the upper slope. *Alvinocaris muricola* was the dominant species in the lower slope seep communities, composing over 50% of the biomass in sampled communities. Higher phylogenetic-level changes were seen among the dominant seep-associated primary consumers. In this category, gastropod mollusks were dominant above 900 meters [*Bergquist et al.*, 2003; *Cordes et al.*, 2005]; echinoderms predominated below 1400 meters, notably, the brittle star, *Ophioctenella acies*, the sea cucumber, *Chirodota heheva*, and heart urchins. The cause for this phylum-level shift from Mollusca to Echinodermata remains elusive, but it mirrors a similar shift in the nonseep fauna with water depth [*Carney,* 2005].

Meiofauna (animals passing a 1-millimeter sieve but retained on a 32-micrometer sieve) were sampled from all dive sites. Nematoda and Copepoda were the most common taxa, but Tanaidacea, Isopoda, and Ostracoda also were present. Among the numerous undescribed species was one of the largest free-living members of the phylum Nematoda ever collected.

In addition to chemoautotrophy-based hydrocarbon seep communities, another focus of the *Alvin* cruise was deepwater corals. Gorgonians were present at most sites, and several large colonies of bamboo corals (Family Isididae) were observed at AC 645. At GC 852, an extensive coral community that included at least two species of scleractinian corals along with several species of octocorals was observed on a mound of carbonate boulders (water depth, 1392–1500 meters) located in a current estimated to have a speed of 50–70 centimeters per second. A specimen of the hard coral *Enallopsammia rostrata* was collected from a depth of 1397 meters, and another scleractinian coral, *Madrepora oculata*, was photographed at the same location and water depth but was not sampled. Both of these cosmopolitan species were found close to their depth limits (1646 meters for *E. rostrata* and 1500 meters for *M. oculata* [*Cairns et al.,* 1993]).

Deep-Slope Hydrocarbon Seep Biogeochemistry

Cores (to 30 centimeters long) collected on 14 of the 24 dives revealed extremely high spatial variability in sediment chemistry at every site. Nonetheless, general trends emerged. All sediments were extremely sulfidic (up to 825 parts per million (ppm)), and in many cases the methane concentrations also were high (up to 120 ppm methane). Brine advection through the sediment was apparent at several sites, as evidenced by pore water salinities that exceeded 3.5 times the salinity of seawater. There were substantial variations in the rates of microbial sulfate reduction and anaerobic oxidation of methane within and among the sites. At nonseep control sites, rates of microbial activity were very low, from 100 to 1000 times less than the rates observed at seep sites. In samples influenced by brine seepage, sulfate was rapidly depleted and sulfate reduction rates 100 or more times the rates observed at control sites were observed in the surficial, sulfate-rich sediments. Unlike other seeps where rates of the anaerobic oxidation and sulfate reduction rates are comparable to one another, rates of the anaerobic oxidation of methane at Gulf of Mexico seeps were generally were lower than sulfate reduction rates by a factor of 10 or more.

Brine Lake

Two dives explored a brine lake in AC 601 at a depth of 2334 meters The lake (shown in Figure 2) was approximately 4 meters deep and approximately 180 meters wide. The brine lake was about 2 times seawater salinity and presented a clear interface between the brine and the overlying seawater. White 'flocs' in the brine that were concentrated at the 'shoreline' were found to be barite. The lake brine contained about half as much sulfate as normal seawater (1536 ppm sulfate versus 2688 ppm sulfate in seawater), but pore water from lake bottom cores was sulfate-free and the chloride-to-sodium ratio was approximately one, suggesting that the brine derived from NaCl mineral (halite) dissolution.

No animal life was visible in the brine or in cores from the lake bottom. Dead pelagic sea cucumbers and fish were observed in the lake, and a moribund new species of octopus was collected from the shoreline (Figure 2). Bathymodiolid mussels and heart urchins were patchily distributed on the shoreline within 10 meters of the lake edge. Lake bottom and lake edge sediments were supersaturated with methane relative to that expected at in situ pressure, temperature, and salinity.

Microbial activity and sediment geochemistry were examined at several sites to evaluate differences between distinct regions of the brine lake. Control cores, collected away from the lake, contained very little methane (<0.1 ppm) and exhibited low rates of both sulfate reduction and anaerobic oxidation of methane. Rates of sulfate reduction in shoreline sediments were the highest measured during the cruise (1000 times control rates); however, rates of anaerobic oxidation of methane were low (10 times control rates). Sulfate reduction and anaerobic oxidation of methane in the brine lake fluid, lake bottom sediments, and sediments collected from nearby heart urchin beds exhibited lower rates of sulfate reduction (50 times control rates) and anaerobic oxidation of methane (5 times control rates). Methane concentrations in the water column above the lake exceeded those of all other sites by an order of magnitude. Methane was supersaturated with respect to equilibrium with the atmosphere throughout the 2300-meter water column, suggesting that the site is a possible methane source to the atmosphere. The brine lake is a complex, spatially variable environment that is characterized by large variations in microbial activity and geochemistry.

Results of this cruise confirm the widespread existence of hydrocarbon seep habitats and their chemosynthetic communities on the middle and lower parts of the continental slope. The cross-slope and along-slope variability in the geology and geochemistry of these deepwater seeps supports a surprisingly high density of biological communities. Clearly, hydrocarbon seepage sustains life to the deepest parts of the Gulf and highly productive chemosynthetic communities are not limited to water depths shallower than 1000 meters.

Acknowledgments

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References

Bergquist, D. C., J. Andras, T. McNelis, S. Howlett, M. J. van Horn, and C. R. Fisher (2003), Succession in upper Louisiana slope cold seep vestimentiferan aggregations: The importance of spatial variability, *Mar. Ecol., 24*, 31–44.

Cairns, S. D., D. M. Opresko, T. S. Holmes, and W. W. Schroeder (1993), New record of deep-water Cnidaria (Scleractinia & Antipatharia) from the Gulf of Mexico, *Northeast Gulf Science, 13*, 1–11.

Carney, R. S. (2005), Zonation of deep biota on continental margins, *Oceanogr. Mar. Biol. Annu. Rev., 43*, 211–278.

Cordes, E. E., S. Hourdez, B. L. Predmore, M. L. Redding, and C. R. Fisher (2005), Succession of hydrocarbon seep communities associated with the long-lived foundation species *Lamellibrachia luymesi, Mar. Ecol. Prog. Ser., 305*, 17–29.

Cordes, E. E., S. L. Carney, S. Hourdez, R. Carney, J. M. Brooks, and C. R. Fisher (2007), Cold seeps of the deep Gulf of Mexico (1900 to 3300 m): Community structure and biogeographic comparisons to Atlantic Equatorial Belt seep communities, *Deep Sea Res., Part I, 54*, 637–653.

Kennicutt, M. C., II, J. M. Brooks, R. R. Bidigare, R. R. Fay, T. L. Wade, and T. J. MacDonald (1985), Vent-type taxa in a hydrocarbon seep region of the Louisiana slope, *Nature, 317*, 351–353.

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