Exploration of the Deep Gulf of Mexico Slope Using *DSV Alvin*: Site Selection and Geologic Character

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ABSTRACT

The Gulf of Mexico is well known for its hydrocarbon seeps, associated chemosynthetic communities, and gas hydrates. However, most direct observations and samplings of seep sites have been concentrated above water depths of approximately 3000 ft (1000 m) because of the scarcity of deep diving manned submersibles. In the summer of 2006, Minerals Management Service (MMS) and National Oceanic and Atmospheric Administration (NOAA) supported 24 days of *DSV Alvin* dives on the deep continental slope. Site selection for these dives was accomplished through surface reflectivity analysis of the MMS slope-wide 3D seismic database followed by a photo reconnaissance cruise. From 80 potential sites, 20 were studied by photo reconnaissance from which 10 sites were selected for *Alvin* dives. Four sites, found in Atwater Valley Lease Area, Block 340 (AT 340), Green Canyon Lease Area, Block 852 (GC 852), Alaminos Canyon Lease Area, Block 601 (AC 601), and Alaminos Canyon Lease Area, Block 818 (AC 818) had impressive and diverse chemosynthetic communities as well as well-defined fluid-gas expulsion geology. In addition to chemosynthetic communities, GC 852 had abundant hard and soft corals seated on substrates of exposed authigenic carbonate boulders. During the two dives at this site the water depths (WD) were ~ 4760 ft (1450 m), and the currents were estimated to be 1-1.5 kts (~50-80 cm/s). At AC 601 (WD ~ 7675 ft (2340 m)), a brine lake that was 13 ft (4 m) deep and 590 ft (180 m) wide with a salinity of ~ 90‰ (parts per thousand) was investigated and sampled. White "flocs" floating in the brine and concentrated at the "shoreline" were found to be barite. No visible animal life was observed in the brine, but moribund fauna were found both in the lake and at the shoreline. Isolated living communities of mussels and urchins were found on the lake margins. Geochemically, the concentration of methane in the water column above the

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lake exceeded all their *Alvin* dive sites by one order of magnitude. Methane was supersaturated all the way to the surface, suggesting the site could be a source of methane to the atmosphere.

INTRODUCTION

Hydrocarbon seepage in the Gulf of Mexico is a historical fact that is documented by the earliest explorers to the region as tar on beaches and slicks on the sea surface. Oil slicks miles long have been reported by ships transiting the Gulf. These numerous and ever present oil slicks can now be tracked by satellite (MacDonald et al., 1993). The visible expressions of hydrocarbons at the surface are reminders of a geologic framework with numerous "leak points" in a deep water province known the world over for its oil and gas production. These points of hydrocarbon seepage and sometimes more rapid venting are the locations of remarkable impacts on both surficial geology and biology. Early studies of these sites, primarily from the upper continental slope (Kennicutt et al., 1985; Brooks et al., 1986; Childress et al., 1986; Roberts and Aharon, 1994; Sassen et al., 1994; and many others), documented: gas-charged sediments; hardgrounds and carbonate mounds; mud volcanoes and mud flows; brine flows and lakes; gas hydrates; and unusual chemosynthetic communities that flourish on hydrocarbons and the products derived from them. These chemoautotrophic communities from the Gulf of Mexico upper continental slope are the best known in today's oceans with respect to their community structure, functional biology, and life histories. This knowledge was primarily gained through Chemo I and II which were two large MMS (Minerals Management Service) sponsored studies of chemosynthetic communities and their geologic settings. However, most of the research has been concentrated on the upper continental slope in water depths shallower than 3280 ft (1000 m). The reason for this depth limitation is that acquiring the use of deeper diving manned submersibles essential for critical observations, placement of in situ experiments, and sampling, is a highly competitive process within the scientific community for use of the nation's only deep-diving submersible, *DSV Alvin*.

In the summer of 2006, the MMS and NOAA (National Oceanic and Atmospheric Administration) sponsored 25 days of *DSV Alvin* dives on the middle to lower continental slope of the northern Gulf of Mexico. This project, Chemo III, represented the first concentrated effort by the scientific community to study the surficial geology, geochemistry, and biology of hydrocarbon seep and vent sites in the deep slope settings of the Gulf of Mexico.

DIVE SITE SELECTION

Success in finding chemosynthetic communities and deep coral sites can be attributed to a two stage data collection program initiated prior to the *Alvin* dives. In October 2005, project personnel in conjunction with MMS geoscientists reviewed extensive volumes of 3D seismic data using surface reflectivity, strength, phase, and pattern as inputs to interpreting seafloor geology and to some extent biology using the methods described in Roberts et al. (2006). In addition, fluid-gas migration pathways from the deep surface were identified in seismic profiles. The "plumbing" beneath deep marine hydrocarbon seeps is reflected in both the biologic and geologic seafloor responses (Hornbach et al., 2007). The entire continental slope of the northern Gulf from DeSoto Canyon on the east to the Texas shelf on the west has been shot with 3D seismic with some areas containing multiple generations of overlapping surveys. These data sets are housed at MMS and used for source evaluation critical to the leasing process for oil and gas exploration and production. Because MMS is a sponsor of this project, these data were made available for site selection. By January 2006, 80 sites of potential chemosynthetic community occurrence were selected to address both potential depth dependant and geographic dependant variations in the fauna. These sites were further prioritized to 20 candidates by March 2006. Nineteen of the sites were imaged during March 11-25, 2006 with a drift camera system comprised of a digital camera, conductivity temperature depth recorder (CTD), and ultra-short baseline transceiver (USBL) navigation pinger. Based on both characteristics of the geophysical data and bottom photography, 10 locations were selected as *Alvin* dive sites for the May-June cruise (Fig. 1). Consistent with project objectives, the final dive plan represented sites from a wide range of water depth and geographic locations

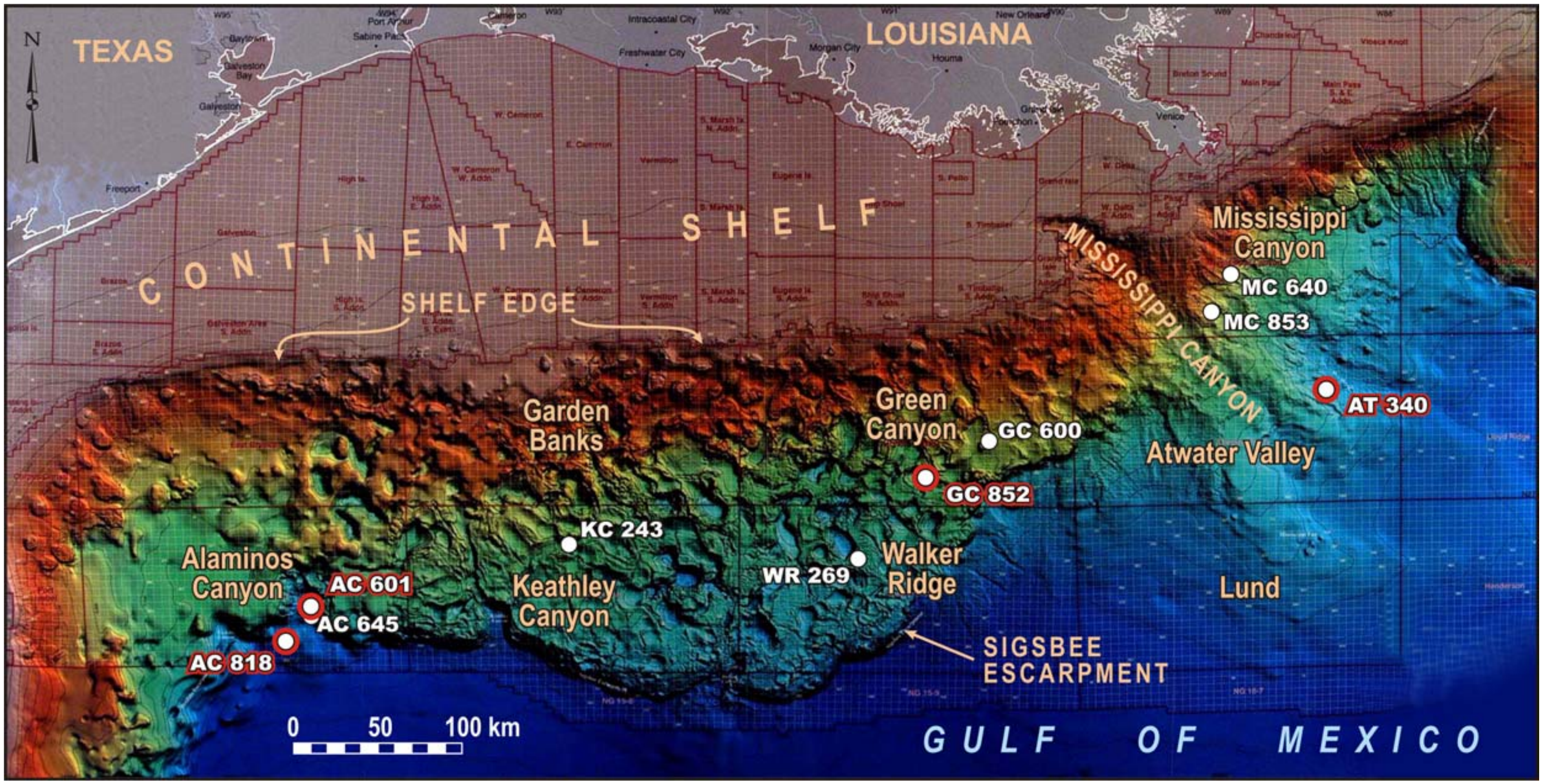

Figure 1. A shaded multibeam bathymetry image of the northern Gulf of Mexico continental slope illustrating the locations of 2006 *Alvin* dive sites.

The *RV Atlantis II* with *Alvin* and a full complement of researchers left Key West, Florida, on the morning of May 1, 2006, for a 26 day cruise across the Gulf arriving in Galveston on June 2, 2006. At each of the ten dive sites, surface reflectivity maps and photographs taken during the drift camera cruise were used for dive planning. As a product of our dive site prioritization process, all sites visited had chemosynthetic communities.

The 2006 *Alvin* cruise was the initial installment of a four year study funded by MMS and NOAA's Ocean Exploration Program. Twenty-four *Alvin* dives were made at the 10 different sites (Fig. 1); however, Atwater Valley Lease Area, Block 340 [(AT 340) N 27° 38.8'; W 88° 21.9'], Green Canyon Lease Area, Block 852 [(GC 852) N 27° 06.3'; W 91° 09.9'], Alaminos Canyon Lease Area, Block 601 [(AC 601) N 26° 23.5'; W 94° 30.9'], and Alaminos Canyon Lease Area, Block 818 [(AC 818) N 26° 10.7'; W 94° 37.3'] were the key sampling sites. These sites generally had the most flourishing and diverse communities as well as the most interesting seafloor geology. Multiple dives focused intense biological and geological/geochemical sampling at these sites.

KEY DIVE SITE CHARACTERISTICS

Atwater Valley Block 340 (AT 340)

The AT 340 dive site is geologically characterized as a bathymetric high along the eastern extension of the Mississippi Canyon where it transitions from a canyon to a submarine fan. The site consists of three mounded areas on top of the overall bathymetric high (Fig. 2). Geophysical data indicate that the feature is supported by salt in the shallow subsurface. Seismic profiles identify a clear vertical migration pathway for the flux of fluids and gases to the modern sea floor. This pathway is defined by acoustic blanking of the seismic records, suggesting both reflection of acoustic energy by hard bottom conditions at the surface and perhaps gas in the subsurface along the migration route. The surface reflectivity maps, created by analyzing the first return from the seafloor from 3D seismic data, indicate high reflectivity in the areas localized around the mounded features.

Five dives were made on the AT 340 feature. Three dives concentrated on the local mounded area in the southeast quadrant. On the 3D seismic surface reflectivity maps, this area displayed a complex pattern of high to moderate reflectivity. Observations from *Alvin* confirmed extensive hard bottom conditions that resulted from authigenic precipitation of massive carbonates, a by-product of microbial utilization of seeping hydrocarbons. Inspection of these carbonates revealed that they contained abundant mussel shells. In addition, carbonate precipitation had occurred around the bases of tubeworm bushes. Scattered among the authigenic carbonate blocks and pavements were living mussel beds and tubeworm colonies. One site represents an elongate (~ 246 ft (75 m) long) and densely packed bed of living mussels which formed in a joint or separation in the underlying authigenic carbonate pavement. Figure 3A illustrates this area of carbonate hardgrounds and densely packed mussels, *Bathymodiolus brooksi* and *B. heckerae* (smaller, brown species). Between the blocks of carbonates, clumps of tubeworms, and beds of mussels, were patches of sediment colonized by heart urchins, a few soft corals, and other sparsely distributed organisms. Of the abundant tubeworms, *Escarpia laminate* were the dominant species, but *Lamellibrachia* sp. was also abundant (Fig. 3B).

Green Canyon Block 852 (GC 852)

This site lies on the southern part of a steep-sided, N-S trending and elongated mound rising from water depths of 4600-4900 ft (1400-1500 m) (Fig. 4). This feature occurs at the southeast edge of a well-defined intraslope basin. The overall mounded area is approximately 1.5 mi (2 km) long with the highest elevation at the southern end. The area of primary interest is characterized by a localized mound that rises more than 65 ft (20 m) above the rest of the overall feature. The 3D seismic surface reflectivity data from this area indicate that the entire crest at the ridge-like feature exhibits a high amplitude response relative to the surrounding sea floor, suggesting the presence of hard bottom conditions. Scattered highly reflective targets are concentrated in the vicinity of the southern mound. Profiles of the southern end of the elongated ridge indicate acoustically turbid migration pathways to the modern sea floor. These "wipeout zones" are interpreted as routes for upward transport of fluids and gases from the deep subsurface. Submersible operations confirmed the indicators of hydrocarbon seepage in this area.

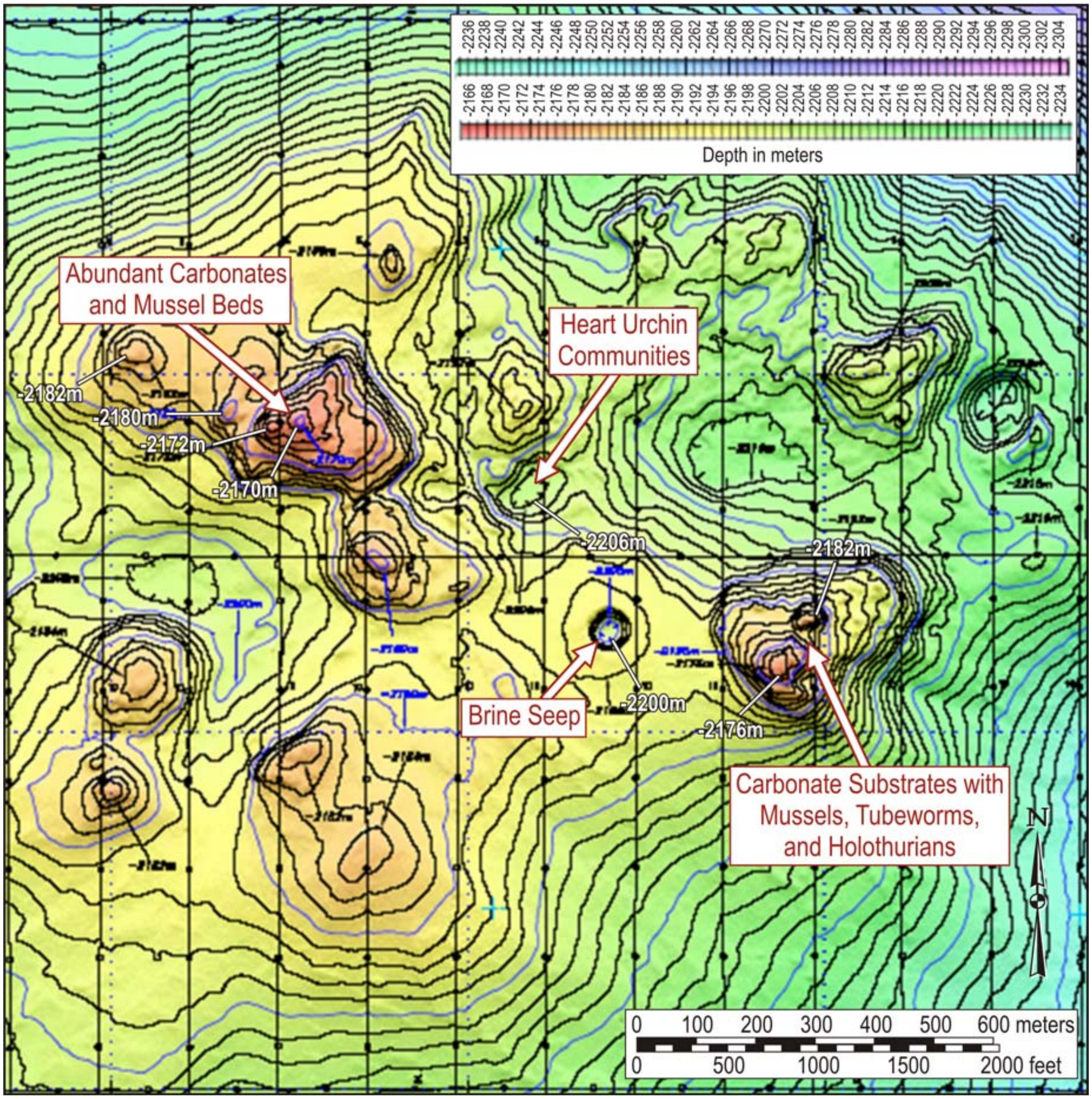

Figure 2. A detailed multibeam bathymetry image acquired by the C-Surveyor II AUV over the AT340 site. Note the numerous local mounded features (expulsion sites) on top of an overall bathymetric high.

The crest of the feature had extensive carbonates that appeared to have been scoured by currents which removed sediments and exposed large carbonate blocks. At the tops of the blocks were numerous types of corals (Fig. 5). Observed at this site were: Gorgonians, antipatharians, bamboo coral, scleractinians, numerous individuals of globose hexactinilid sponges, a few anemones, and a yellow zoanthid that was encrusting dead bamboo corals. Numerous plumate polychates and hydroids were observed among the carbonates. The hard coral, *Solenosmilia variablis*, was collected and *Madrepora oculata* was photographed. A potential identification of *Lophelia pertusa* was also made from the photographic record, but this could not be confirmed since there were no specimens of this species collected.

Also observed on top of the mound were scattered tubeworms, smaller carbonates and an area of active oil seepage. On the flanks of the mound were two areas of active seepage and outcropping authigenic carbonates.

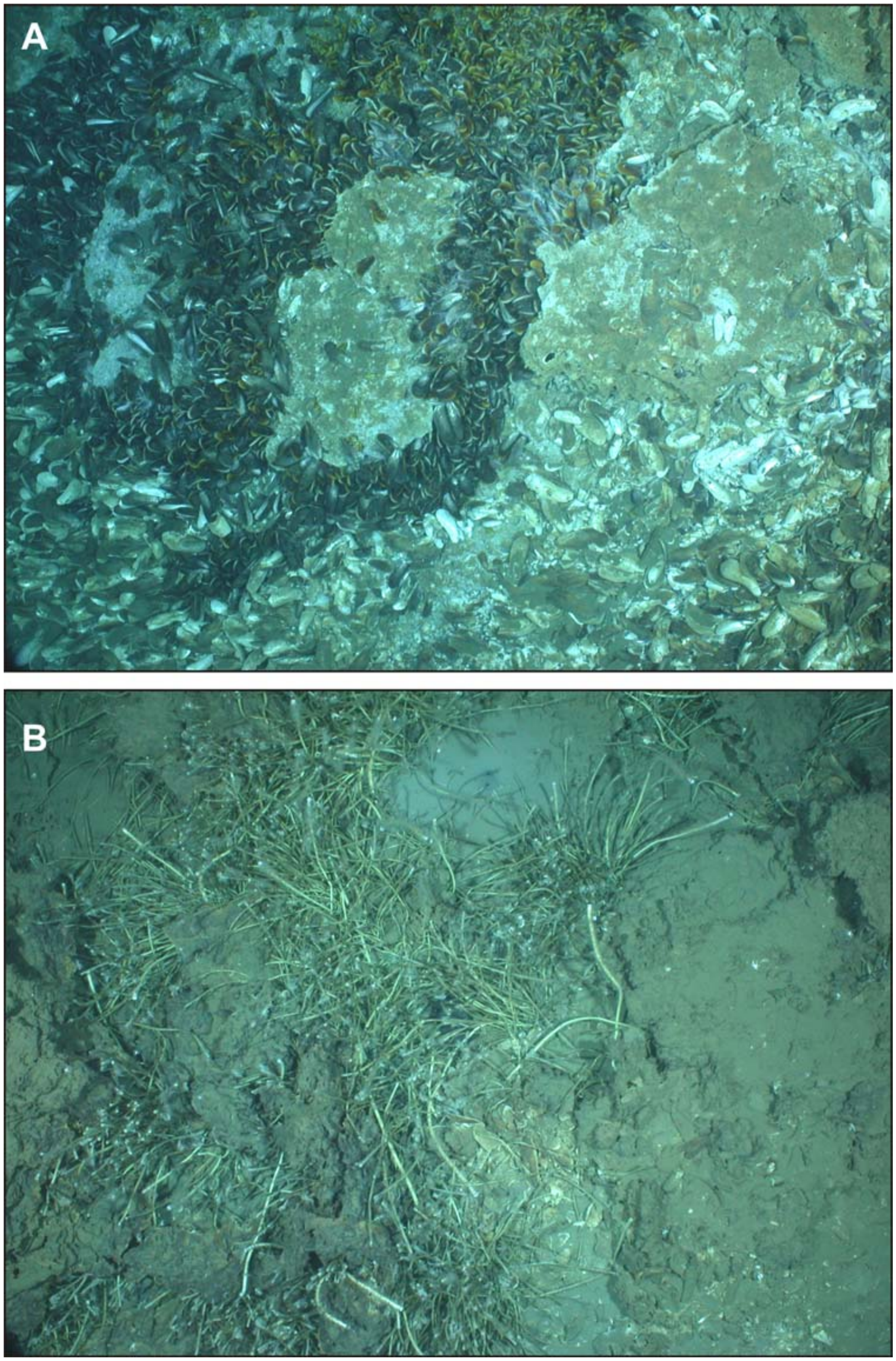

Figure 3. Photographs acquired during an *Alvin* dive to AT 340 illustrating: (A) densely populated mussel beds occupying cracks in an authigenic carbonate pavement, and (B) tubeworm colonies among carbonate boulders and hardgrounds.

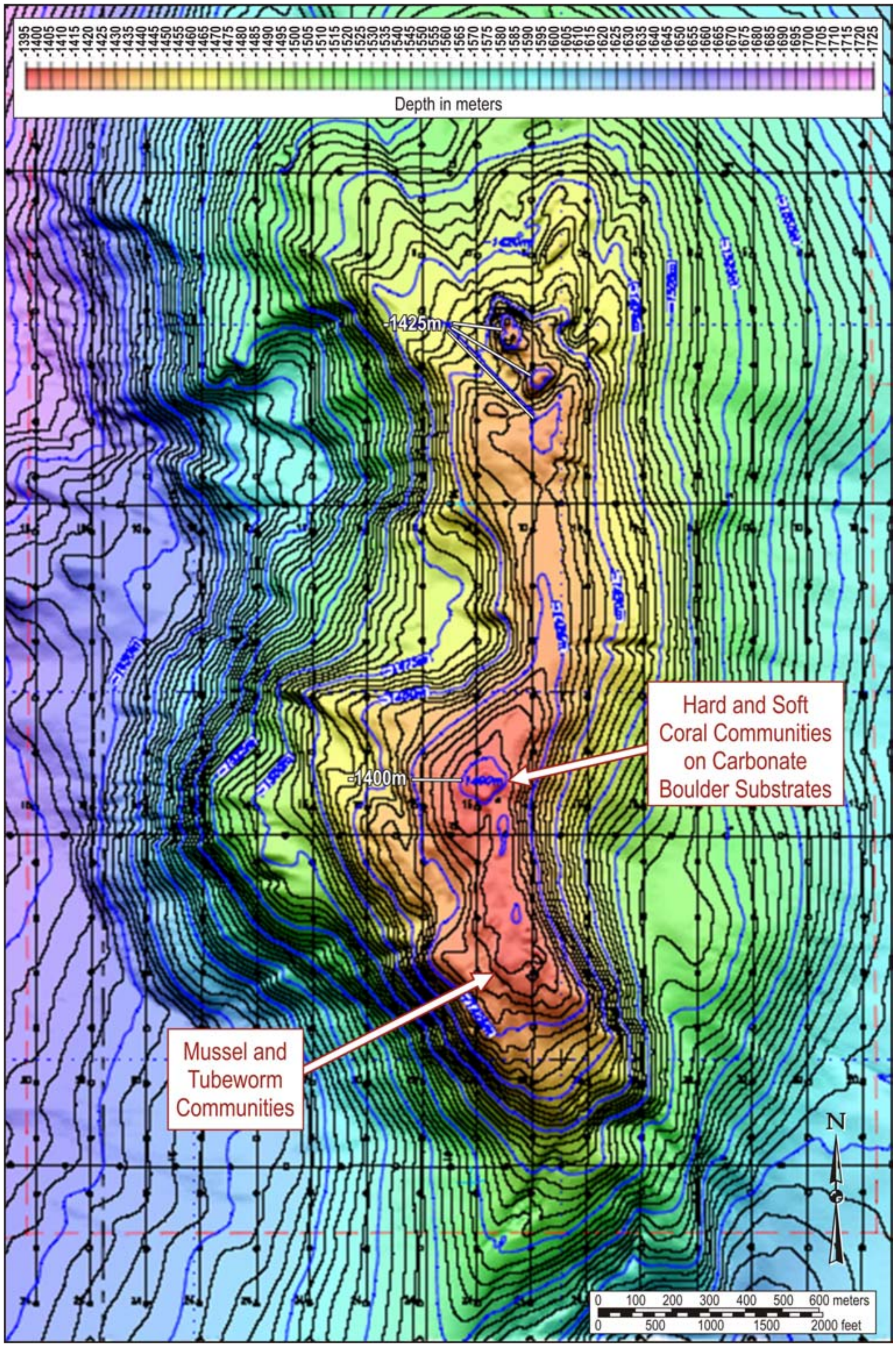

Figure 4. A detailed multibeam bathymetry image acquired by the *C-Surveyor II AUV* over GC 852. This N-S trending mound had active oil and gas expulsion and abundant carbonates with associated chemosynthetic communities as well as deep water corals.

Figure 5. Large blocks of authigenic carbonate at GC 852 on which both hard (left colonies) and soft (right colony) corals have attached. A strong current was encountered at this site.

One rock outcrop area was approximately 260 ft (80 m) to the northeast of the corals and consisted of low-lying cracked carbonate blocks, occasional methane bubble streams, and oily sediments. Aggregations of both species of tubeworms, *E. laminata* and *Lamellibrachia* sp., were collected from this site. Small mussel beds comprised of *B. brooksi* and *B. childressi* were nested in the carbonates. The most common associated fauna were a shrimp, *Alvinocaris muricola*, and a brittle star *Ophioctenella acies*. A second area of active seepage was found approximately 1316 ft (400 m) to the south of the corals near the top of a ridge. The substrate in this area consisted of numerous small to medium-sized carbonate slabs, boulders and areas of carbonate rubble.

The same species noted above were present in the second area. The tubeworms were present as scattered individuals, small aggregations associated with carbonates and mussels present in beds among the carbonates, and as small groups apparently nestled in the sediment, as described for AT 340 site. Vesicomyid clams were also present in this area although none were collected.

Oil slicks were visible on the sea surface during much of the time *RV Atlantis* occupied this site. Streams of bubbles, possibly lined with oil, were observed escaping through beds of mussels at several positions on the bottom. Gas hydrate was inferred from hard layers encountered while collecting push cores and was photographed in an exposed patch at one site.

Walker Ridge Block 269 (WR 269)

The WR 269 dive site is illustrated here as opposed to our key sampling site at AC 818 due to the narrowness of site AC 818 and its only slight bathymetric expression resulting from its occurrence along a fault. The Walker Ridge site occurs at the northern edge of a suprasalt basin on the lower continental slope, approximately

10 lease blocks away from the Sigsbee Escarpment. The site consists of a series of mound-like areas that extend to the east into WR 270. These mounded features are on a ridge that separates two very distinct sedimentary basins floored by salt or salt welds. Previous studies using high quality 3D seismic data indicate the presence of a well-defined bottom simulating reflector (BSR) that cuts across stratigraphic reflectors of the basin fill to the south of the area of interest (McConnell and Kendall, 2003). This feature, which is interpreted to be the base of the gas hydrate stability zone, appears to have free gas trapped beneath it. The mounds on the modern sea floor are updip of the interpreted gas hydrates and associated free gas. It appears that gas is bypassing the gas hydrate stability zone along permeable beds which are upturned along the basin margin. One of the topographic buildups is the focal point of our investigation (Fig. 6). The buildups are interpreted as being several large mounds constructed through the extrusion of fluidized sediment along with other products such as hydrocarbons (Fig. 6). Surface reflectivity maps of the area derived from 3D seismic data suggest the location of several active vents, which are seen as circular low amplitude zones, and associated flows that have localized areas of high reflectivity. The areas of high reflectivity are interpreted as regions of local seafloor lithification and perhaps fields of clam shells.

The particular area selected for investigation was characterized by rather subtle topography except for a localized mound that rises some 100 ft (30 m) above the surrounding sea floor (Fig. 6). The area was selected on the basis of its characteristics on geophysical records. The mound-like feature was interpreted as a sediment extrusion site and the surrounding areas as overlapping mud flows. The surface reflectivity maps suggested that there were some highly reflective zones that surrounded and were located to the west of this central vent feature. These highly reflective zones are often lithified seafloor areas or fields of mussel or clam shells, which turned out to be the case at the top of the mounded area. Authigenic carbonate slabs, mussel beds (*Bathymodiolus* sp.), and tubeworms were found at the apex of the mound in a slow hydrocarbon seep environment. Pogonophoran communities with holothurians and crustaceans were observed and sampled on the mound flank. The low amplitude response observed on the surface reflectivity maps of the vent area suggested the presence of gas and soft bottom conditions. Small islands of slightly increased reflectivity in the vent area suggested variable bottom conditions and a reasonable probability of finding tubeworms, mussels, and carbonate rocks. This proved to be the case. The lobe-like areas to the west of the vent site were interpreted as being old flow deposits. One of the areas was circular and possibly represented an old venting site (Fig. 6). If hydrocarbons were still being migrated to the sea floor in this area, it could support a sizeable area of chemosynthetic communities. Unfortunately, we were not able to test our interpretations of the areas west of the main venting site because our dive was cut short due to weather.

Alaminos Canyon Block 601 (AC 601)

Alaminos Canyon is a reentrant into the Sigsbee Escarpment at the base of the continental slope south of the Lousiana/Texas border. From the edge of the Sigsbee Escarpment, the Alaminos Canyon extends landward a distance equivalent to 6-7 lease blocks. Our dive sites in AC 601 were located in approximately the middle of the canyon and toward the eastern side. Geologically, the sites were located on the top of a breached anticline that generally trends E-W. The fractures and faults that breach the crestal area provide the migration pathways for transporting fluids and gases to the modern sea floor. The AC 601 block is situated directly over the anticline crest and consequently, there are a number of well-defined expulsion features in this block. The locations of these features are easily identified on 3D seismic surface reflectivity maps. On subsurface profiles, clear migration pathways to the sea floor can be identified. There are 4 major reflectivity targets and a number of smaller targets in AC 601. The anomaly of interest for this project is in the northwest corner of the block (Fig. 6). It was mapped with deep-tow side-scan sonar and subbottom data in the 1990s. From analysis of these data, the feature in the northwest quadrant of the block was interpreted as a mounded fluid and gas expulsion feature with some evidence of mudflow activity radiating from the crestal area of the mound. More recent analysis with 3D seismic data indicates high reflectivity targets associated with the mound top and a low amplitude zone to the north of the mound. The high amplitude targets at the crest and on the upper flanks of the mound suggest it is an old feature due to lithification of the sea floor which usually indicates inactivity of fluidized sediment venting. In 2005, a MMS-sponsored remotely operated vehicle (ROV) survey confirmed the presence of localized carbonate substrates and chemosynthetic communities at this site. This survey also found that the low amplitude zone to the north of the mound represented a sizeable brine lake.

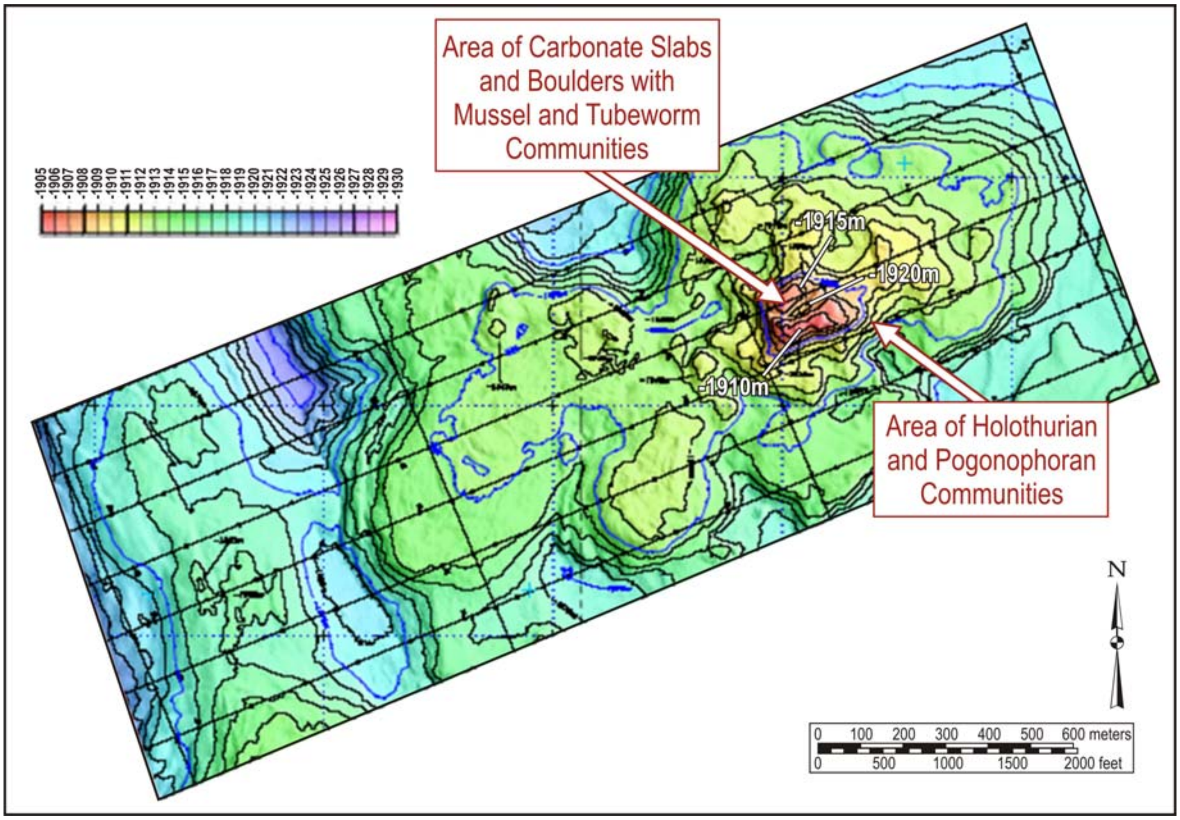

Figure 6. A detailed multibeam bathymetry map acquired by the *C-Surveyor II AUV* over a selected area of WR 269. Active chemosynthetic communities were found to be associated with the well defined mound at the eastern end of the map.

The lake was surveyed by *Alvin* and was found to be about 13 ft (4 m) deep and approximately 590 ft (180 m) in diameter. Analysis of the brine found that it was nearly 3 times that of normal sea water (~ 90 ‰ salinity). The "shoreline" of the brine lake and the lake bottom were white. Analysis of this material (x-ray diffraction and scanning electron microscopy) as well as "flocs" floating in the brine determined that it was barite. No living organisms were found in the lake or in the cores acquired from the lake bottom. However, fish, holothurians, and an octopus were found in a moribund state either in the brine or at the shoreline. Bathymodiolid mussel beds and fields of heart urchins were scattered around the lake perimeter. Methane concentrations in the sediments and in the water column above the lake were higher by an order of magnitude than any other site measured on the *Alvin* cruise. In the water column methane was supersaturated throughout the 7544 ft (2300 m) to the sea surface suggesting that this site may be providing methane to the atmosphere (Roberts et al., in press).

SUMMARY

The 24 *Alvin* dives made between May 7 and June 6, 2006, successfully demonstrated the occurrence of fluid and gas expulsion sites on the lower continental slope. Responses to the expulsion process in both surficial geology and occurrence of chemosynthetic communities are similar to those observed and studied on the upper slope. From a pool of 80 potential dive sites identified by careful analysis of 3D seismic, 19 were prioritized for drift-camera imaging conducted during a special cruise prior to the *Alvin* dives. The final 10 sites were distributed from the eastern Gulf (N 27º 38.8'; W 88º 21.7') to the western Gulf (N 26º 11.0'; W 94º 37.4'). They spanned water depths from 3523 ft (1074 m) to 9100 ft (2775 m). At all sites evidence of seepage or venting of hydrocarbons was observed, and chemosynthetic communities occurred at each site but with considerable variability in species composition and abundance.

Geologically, 9 of the 10 dive sites represented bathymetric highs formed partially through the extrusion of fluidized sediment in combination with the production of authigenic carbonate, a by-product of microbial utilization of hydrocarbons in the surface and near-surface sediments. Some sites were supported by salt in the shallow subsurface. Additionally, the vertical accretion of successive communities of symbiont-containing species that secrete calcium carbonate shells (mussels and clams) add to seafloor topography as Mg-rich carbonates cement shells into substantial pavements and blocks. The AC 818 site was the only site that did not fit this description. Hydrocarbon seepage at this site occurs along a well-defined linear fault. Although chemosynthetic communities and associated thin pavements of authigenic carbonate occur along this trend, the seepage zone is narrow and vertical buildups are small and limited to very local areas. The multibeam bathymetric maps of AT 340, GC 852, WR 269, and AC 601 all indicate substantial mound-like structures. These are the areas where the 3D seismic surface amplitude maps indicated the highest levels of reflectivity. The high reflectivity corresponded to a hard bottom which was composed of various types of carbonate lithification (nodules in sediment, slabs, and boulders) as well as associated chemosynthetic communities. In many cases, both surface reflectivity maps from 3D seismic and data from side-scan sonar swaths/mosaics defined fluid flow pathways originating from the mound-like bathymetric highs. These features suggest episodic expulsion from vents that extrude fluidized sediment as well as hydrocarbons and brines. Some small-scale mud flows were observed at several dive sites, but no active large-scale flows were found. Frequently, the expulsion centers (usually at the mound tops) have low reflectivity on 3D seismic surface amplitude data and occasionally display a phase reversal suggesting gas-charged surficial sediments that have not been lithified or do not contain abundant shells.

Other areas of low reflectivity were found as circular bathymetric lows, as shown on the multibeam bathymetry maps of AT 340 (Fig. 2) and AC 601 (Fig. 7). The AC 601 site is of particular interest because it is a well-defined brine lake with a salinity of about 90 ‰. The chloride-to-sodium ratio of the brine is approximately 1, suggesting that the brine was derived from dissolution of halite. Although surrounded by a carbonate supported ridge along the southern margin of the lake, “flocs” in the brine and precipitates on the lake bottom and concentrated at the shoreline are composed of barite (Roberts et al., in press). No living macrofauna were found in the lake or in lake-bottom sediments.

Our knowledge of the geology of hydrocarbon sites as well as the depth range and geographic distribution of key chemosynthetic community species advanced significantly from our 2006 *Alvin* dive program. Two groups of symbiont-containing species that are the foundations of the Gulf’s chemosynthetic communities, the bathymodiolid mussels and vestimentiferan tubeworms, undergo a species-level change with depth. This change appears to occur between about 3500 ft (1065 m) and 5000 ft (1525 m). The reasons for this shift are still unknown and under investigation. Answering this and other questions about the change in biology with increasing water depth and the inescapable links with the fluid and gas expulsion process are goals of the Chemo III program.

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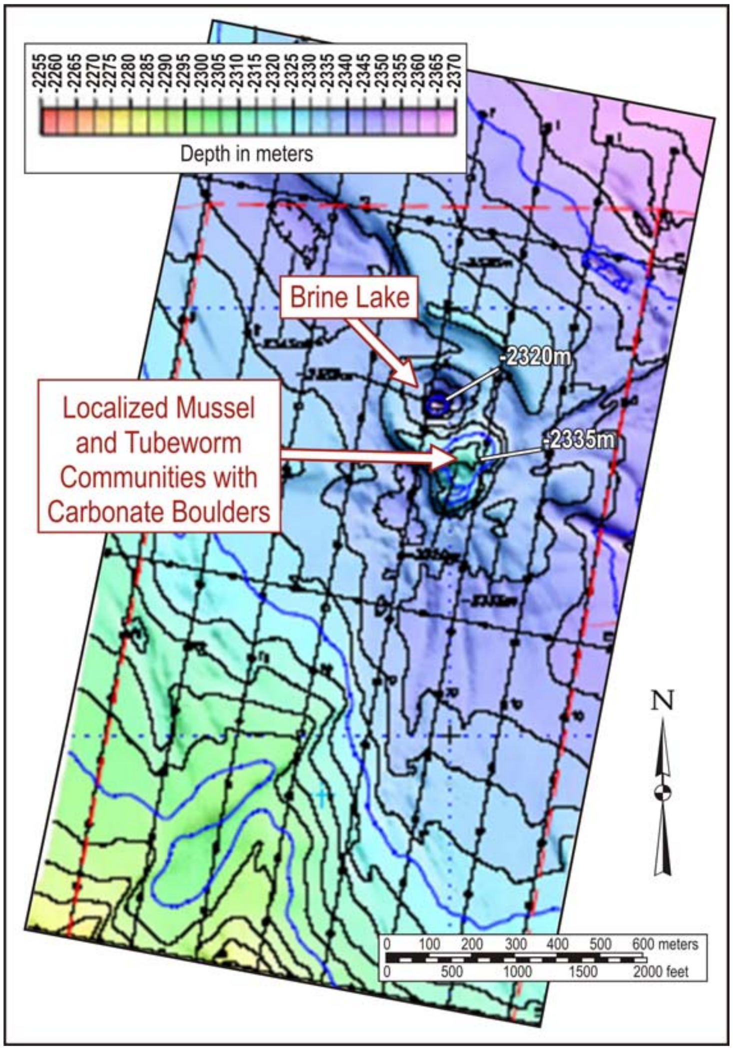

Figure 7. A detailed multibeam bathymetry map acquired by the *C-Surveyor II AUV* over a selected area of AC 601. Note the circular feature north of a mounded area. The circular feature is a brine lake.

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