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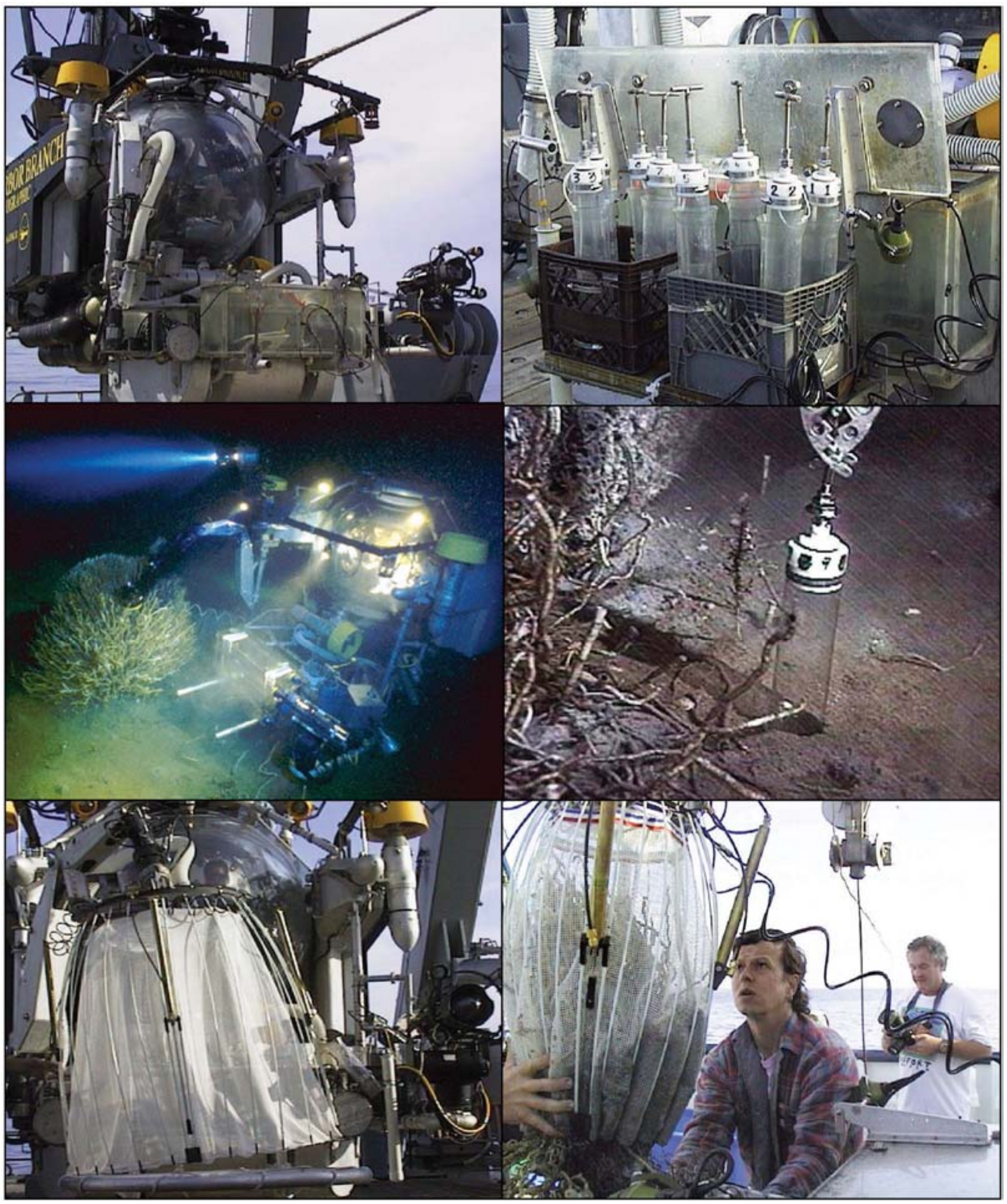
MMS 2002-035

Stability and Change in Gulf of Mexico Chemosynthetic Communities

Volume I: Executive Summary



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U.S. Department of the Interior
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Stability and Change in Gulf of Mexico Chemosynthetic Communities

Volume I: Executive Summary

Editor

Ian R. MacDonald

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COVER ART

Submersible sampling operations with submarine Johnson *Sea Link*.

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1.0 Executive Summary

1.1 Introduction

A multidisciplinary team of marine scientists has completed a program entitled Stability and Change in Gulf of Mexico Chemosynthetic Communities. The program was carried out under contract with the Department of Interior, Minerals Management Service, with technical supervision of the Gulf of Mexico Outer Continental Shelf Regional Office, New Orleans, Louisiana. The fundamental concern of the program was the effect that development of offshore energy reserves might have upon dense assemblages of deep-sea organisms, particularly chemosynthetic tubeworms, mussels, and clams, as well as fish and crustaceans, that live in association with them. Hydrocarbons from commercial oil and gas reserves escape into the sea bottom at natural seeps found commonly across the Gulf of Mexico's northern continental slope. Chemosynthetic animals utilize chemical energy from hydrocarbons to maintain colonies that have unusually high biomass compared with the sea bottom elsewhere. Chemosynthetic communities at hydrocarbon seeps were discovered in 1984 and have been previously investigated in studies funded by MMS. However, more knowledge was needed about the life history and ecology of chemosynthetic communities in the Gulf of Mexico. The program has produced a substantial body of findings, which include numerous peer-reviewed publications and student theses in addition to the results detailed in the final report. Given the pace of publication, it is likely that this productivity will continue for some time to come.

The program obtained results from an extensive program of field collections and laboratory analyses. Under the direction of the Geochemical and Environmental Research Group of Texas A&M University, sixteen investigators, associates, and students from seven separate institutions collaborated to formulate and carry out the work. During the course of two ambitious field seasons, program investigators collected samples from over fifty stations, which were distributed among four principal sampling sites with use of the submarine Johnson SEA-LINK. Extensive additional collections were made with use of the R/V GYRE and the US Navy Submarine NR-1. The primary geochemical samples included more than fifty sediment cores, which were extensively sub-sampled by sediment depth. Extensive collections of chemosynthetic and heterotrophic animals were obtained for investigations to determine, among other objectives, growth rates, health, genetic diversity, and food-web structure. A regional context for the targeted sampling was established through geophysical survey, sediment coring, and layered comparisons between community and regional-scale data with use of geographic information system (GIS) tools. Valuable time-series records of current, water temperature, and fluid discharge properties of the seep environment were obtained from targeted deployments of *in-situ* instruments and moorings. Satellite remote sensing records were obtained through cooperation with industry to examine large-scale variation in seepage rates.

Throughout the program, the investigators benefited from cooperative arrangements with other agencies and interests, including notably the NOAA National Undersea Research Center at the University of North Carolina, Wilmington, the Naval Research Laboratory Washington, DC laboratory, and the US Navy SUBLANT group, all of whom assisted with obtaining ship and submarine time over and above what would have been possible under the contract.

1.2 Objectives and Basic Study Design

The request for proposal that initiated this program specified the following objectives for study (taken *verbatim* from solicitation number 3813):

Objective One. Review biotic and abiotic features of existing conceptual models of chemosynthetic communities which explain observed patterns of distribution and abundance, in order to develop an effective, refined plan for continued research.

Objective Two. Further evaluate the physical-chemical factors (e.g., depth, temperature, water chemistry, sediment types, and dissolved gasses) which influence, limit, enhance, or control the distribution, abundance, and growth of chemosynthetic communities.

Objective Three. Further investigate the sources (e.g., deep versus shallow or petrogenic versus biogenic) of any necessary dissolved gasses and the likelihood that petroleum production may ultimately deprive the animals of an energy source.

Objective Four. Further determine if chemosynthetic communities are robust or fragile, and whether they are essentially permanent or ephemeral; characterize age, growth rate, turnover rates, reproduction and recruitment, and patterns of senescence and death in the dominant chemosynthetic animals; further examine recovery rates of communities damaged by physical disturbance.

Objective Five. Further determine the reliability of methods for detecting chemosynthetic communities using remote acoustic and/or geophysical devices, imaging instrumentation, hydrocarbon measurements, and/or other available technologies.

To address objective one, a thorough review of published literature and reports was completed. Two principal conclusions were reached. First, it was evident that the chemosynthetic fauna from Gulf of Mexico hydrocarbon seeps (tubeworms and mussels) were taxonomically and functionally similar what is found at hydrothermal vents at mid-ocean ridges, but included important differences. They are all dependent on symbiosis with bacteria that can utilize chemical energy. Tubeworms in both settings use hydrogen sulfide (H_2S) to nourish their symbionts. Seep mussels have symbionts that can oxidize methane (CH_4) from natural gas, while vent mussels rely only on H_2S. However, communities at hydrothermal vents are attached a rocky substratum; they obtain needed H_2S directly from vent fluids and are frequently disturbed by volcanic eruptions and other catastrophic events. Vent communities are often separated from each other by hundreds of miles of inhospitable habitat. Seep communities thrive on soft marine sediments where elemental cycling by microbial and chemical processes strongly influence the environment. Importantly, the H_2S is produced by microbial consumption of seep organics—i.e. oil and gas. Many seeps appear to be stable features, in which colonies can persist for decades or longer without major natural disruptions. Seep also appears to be much more numerous and wide-spread than vents within comparable seafloor areas. This means that there is more opportunity for interaction between neighboring seeps (e.g. exchange of recruits) and a greater scope for non-seep fauna to utilize the productivity of seep animals as a food supply. It was concluded that new conceptual models of colonization, persistence, and interaction would have to be developed to describe seep chemosynthetic communities.

The second finding of the review and study design process was that two styles of seepage have been described at Gulf of Mexico hydrocarbon seeps and contribute to habitant formation. In *sediment diffusion* habitats, mussels, clams, and tubeworms utilize reduced compounds – CH_4 and H_2S – by extending body parts into the sediment or by bathing their brachia (gills or plumes) in the steep gradients immediately above the sediment/water interface. *Brine pooling* habitats are found where concentrated brines are associated with petroleum migration and seepage. Because brines are much denser than sea water, brine discharge can form distinct pools on the seafloor. The brines contain high concentrations of CH_4, which support dense mussel beds. Much of the community-level diversity in cold seep communities can be explained by examining the environmental consequences of these two styles of seepage.

Spatial scale is an important factor in characterization and management of seep communities. Both habitat types occur in areas that are no more than a few hundred meters across. Within these habitats, the environmental gradients can be very high, leading to a heterogeneous patchwork of animal colonies. To meet the ambitious requirements of the request for proposal, a program of careful sampling in individual chemosynthetic communities was combined with observations at the regional level. All activities were conducted in on the continental slope south of Louisiana and Texas. Community level sampling was primarily carried out with use of the research submersible Johnson SEA LINK (JSL), deployed from a surface ship R/V EDWIN LINK. Regional sampling utilized the US Navy research submarine NR-1 and the R/V GYRE.

1.3 Study Sites

Most of the community-level sampling was carried out within four discrete sites. However, because the area of the Gulf of Mexico slope occupied by known chemosynthetic communities spans a depth range from about 500 to 2500 m, the geophysical survey was carried out within shallow- and deep-water areas. These two mega-sites were designated as survey sites for the development and testing of criteria to improve the prediction of the presence of chemosynthetic communities based on geophysical or other remote sensing data (Figure 1). Four principal community-level sites were designated for the intensive collection of samples and deployment of experiments and instrumentation (Table 1). Two of the sites were in brine-pooling settings; two others were sediment-diffusion settings. The sites differ principally in that two sites contain significant amounts of liquid hydrocarbons in the sediments and are dominated by tubeworms (GC185 and GC234) and two sites are brine seeps and are dominated by mussels (GC233 and GB425). These sites have been the subjects of historical studies, which in most cases provided ancillary geographic data. Because the sites contain the major faunal groups found in chemosynthetic communities (tubeworms and mussels) and cover a range of environmental conditions, hypotheses concerning abiotic controls on community ecology could be tested. Within each site, a series of sampling stations was established. The stations were chosen on the basis of the dominant chemosynthetic fauna found in the immediate vicinity, e.g. adult tubeworms, mussels, etc. Each station was marked so that it could be re-sampled. (Figure 1) shows the regional mega-sites and sampling sites. Table 1 details the attributes of the study sites and list the sampling stations.

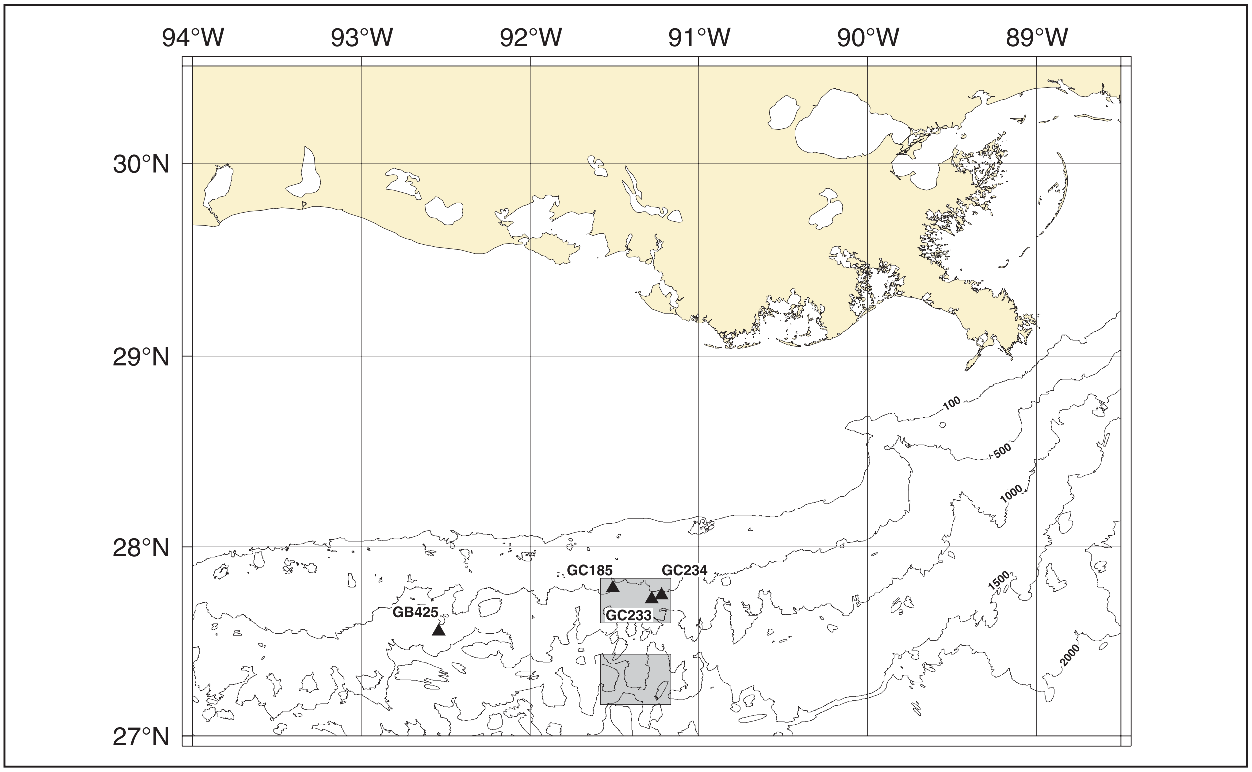

Figure 1.1 Northern Gulf of Mexico showing study site locations for submersible operations (triangles) and mega-site areas for geophysical survey (shaded rectangles). Depth contours in meters.

1.4 Sampling Methods

A 24-day cruise on board the R/V EDWIN LINK, acting as tender ship for the submersible Johnson SEA-LINK II, was completed during 8 to 13 July 1997. This cruise (JSL97) comprised a major portion of the field effort for Year 1 of the program. The goals for this cruise were to complete an extensive series of sample collections, to release marked animals for growth studies, to deploy in-situ monitoring instruments, and to map the study sites for future effort. Data produced by this effort was crucial to the success of the program. Despite a very ambitious cruise plan, all goals were achieved thanks to the dedicated efforts of the cruise participants. A total of 52 stations were occupied at four separate sites. A complete list of stations is provided in (Table 1).

A 15-day cruise on board the R/V EDWIN LINK, tender ship for the submersible Johnson SEA-LINK I was completed during 4 to 18 July 1998. This cruise (JSL98) completed the sampling effort begun in the previous year. Most of the stations sampled in the JSL97 cruise were re-sampled. Sampling efficiency was improved on the basis of experience gained during the previous year so that more samples were collected in a shorter cruise.

A highly integrated program of sample collection and site description was conducted during the two submersible cruises. All collections and stations were carefully documented with video and still photography and an exhaustive and carefully controlled list of collection, stations, and observations was made to ensure accurate sample identification and tracking. Principal sampling methods included sediment collection, water and gas collection, animal collections and manipulations, and photographic documentation. Methods are described in detail in the technical report volume and are only briefly summarized here. Sediment sampling was accomplished using inert plastic tubes, 7.5 cm in diameter and 30 cm in length. The tubes, called push cores, were pressed into the soft sediment using specially designed handles that could be manipulated with the submersible's mechanical arm. Sediment sections were processed for geochemical analysis using methods to squeeze out pore fluids under carefully controlled conditions. Other sediment samples were frozen or preserved in analysis of the solid component, volatile gasses, or liquid hydrocarbon components. Push cores were taken in replicate at all stations unless the substrata were too rocky or too liquid for effective collection.

Animal samples were collected using a variety of quantitative methods. Mussels were scooped from pre-measured frames into seal, separated containers. Tubeworms were collected with use of large, inverted net-bags that were placed over tubeworm clusters and cinched at the bottom with a hydraulic mechanism. Tubeworms and mussels were both marked for recapture in controlled studies of growth rate. Mussels were collected, measured, and marked with numbered tags prior to release. Tubeworms were marked in place using a device that stained the ends of their tubes with a vital dye.

Auxiliary sampling methods included coring devices (box cores) lowered from surface ships, temperature and salinity measurements made from instruments attached to the submersible and lowered from surface ships. Several in situ measurement instruments were deployed and recovered using the submersible.

Table 1.1 Stations Sampled According to the Experimental Design Criteria.

Site	Habitat	Level within habitat	Stations
GC185 (Bush Hill) Oily diffusion Station prefix = BH	Tubeworm	Adult	AT1, AT2, AT3, AT4, AT5
		Senescent	ST1, ST2
		Juvenile	JT1, JT2, JT4, JT5, JT6
	Mussel		M1, M2, M3, M4, M5
	Bacterial Mat	White Mat	B1
		Pigmented Mat	B2
	Reference	Unoccupied	boxcore from ship
GC234 Oily diffusion Station prefix = GC	Tubeworm	Adult	AT1, AT2, AT3, AT4
		Senescent	ST1, ST2
		Juvenile	JT1, JT2, JT4, JT5
	Mussel		M1, M2
	Bacterial Mat		B
GC233 (Brine Pool) Brine dissolution Station prefix = BP	Tubeworm	Adult	AT1
	Mussel	Inner edge	M1, M4, M7
		Outer edge	M2, M3, M5
GB425 Brine dissolution Station prefix = GB	Mussel		M1, M2

2.0 Major Findings

2.1 Physical Oceanography

Although the circulation of the overlying waters has been fairly well studied (Nowlin *et al.* 1998), surprisingly little is known about the oceanic environment of the sea floor on the continental slope of the Gulf of Mexico. Knowledge of the deep currents, temperature, and salinity is important in understanding how the environment affects the ecosystems found in the study region. Ocean currents give clues to the dispersal pathways taken by larvae of chemosynthetic species. Ocean temperatures can affect the reproductive cycling of organisms present. Ocean temperature also affects the stability of gas hydrate deposits. To learn more about the physical environment at the study sites, we made physical measurements as part of the two submersible cruises carried out during this program on the R/V EDWIN LINK. A current meter mooring was deployed in GC185 during the August 1997 cruise and recovered about nine months later on the May 1998 cruise. The mooring had two current meters, one 10 m above the bottom (530 m) and one approximately 200 m above the bottom (250 m). During these two cruises, measurements with a recording conductivity, temperature, and depth instrument (CTD) were made from the support ship, R/V EDWIN LINK, as well as from the SEA-LINK itself.

This examination of the oceanic environment at chemosynthetic communities, although limited in scope, found that current speed and direction and water temperatures varied dynamically. The annual range in bottom water temperature equaled or exceeded 3°C in all measurement intervals (Figure 2). A strong diurnal periodicity in water temperature and current speed is clearly demonstrated in the long-term temperature records that were collected and analyzed. Currents speeds were significantly greater at the top meter and predominant current directions were different (Table 2). This periodic fluctuation is undoubtedly a predictable feature of sea floor habitats in the depth range of the study sites (500-600 m). Also evident from the temperature records are regular, but non-periodic episodes of temperature variations that tend to recur on a monthly or sub-monthly basis. These episodes result are evident as gradual fluctuations of the temperature baseline over a range of 2 to 3°C. Coupling between Loop Current eddies and transient deep-water currents are indicated, but the data are not extensive enough to define the mechanisms.

Because chemosynthetic organisms are quite temperature-sensitive [Fisher, 1990 #100], the range and consistency of diurnal and longer-term temperature variations constitutes an environmental signal. This is noteworthy because the deep sea, which is devoid of sunlight, is often described as being temporally constant and unchanging. Moreover, because slight temperature increases can have an immediate and significant effect on the rates of venting from gas hydrate deposits [MacDonald, 1994 #187], a rise in temperature can influence the availability of nutrients in methanotrophic organisms such as seep mussels. Findings to date clearly indicate that events driven by Loop Current can have biological and possibly geochemical significance on the outer continental slope of the Gulf of Mexico. However, the observations we obtained have been quite limited geographically and in terms of water depth. Future work should prioritize obtaining temperature time-series from deeper sites to determine whether the diurnal periodicity and longer term fluctuation continues to be present as one moves further offshore.

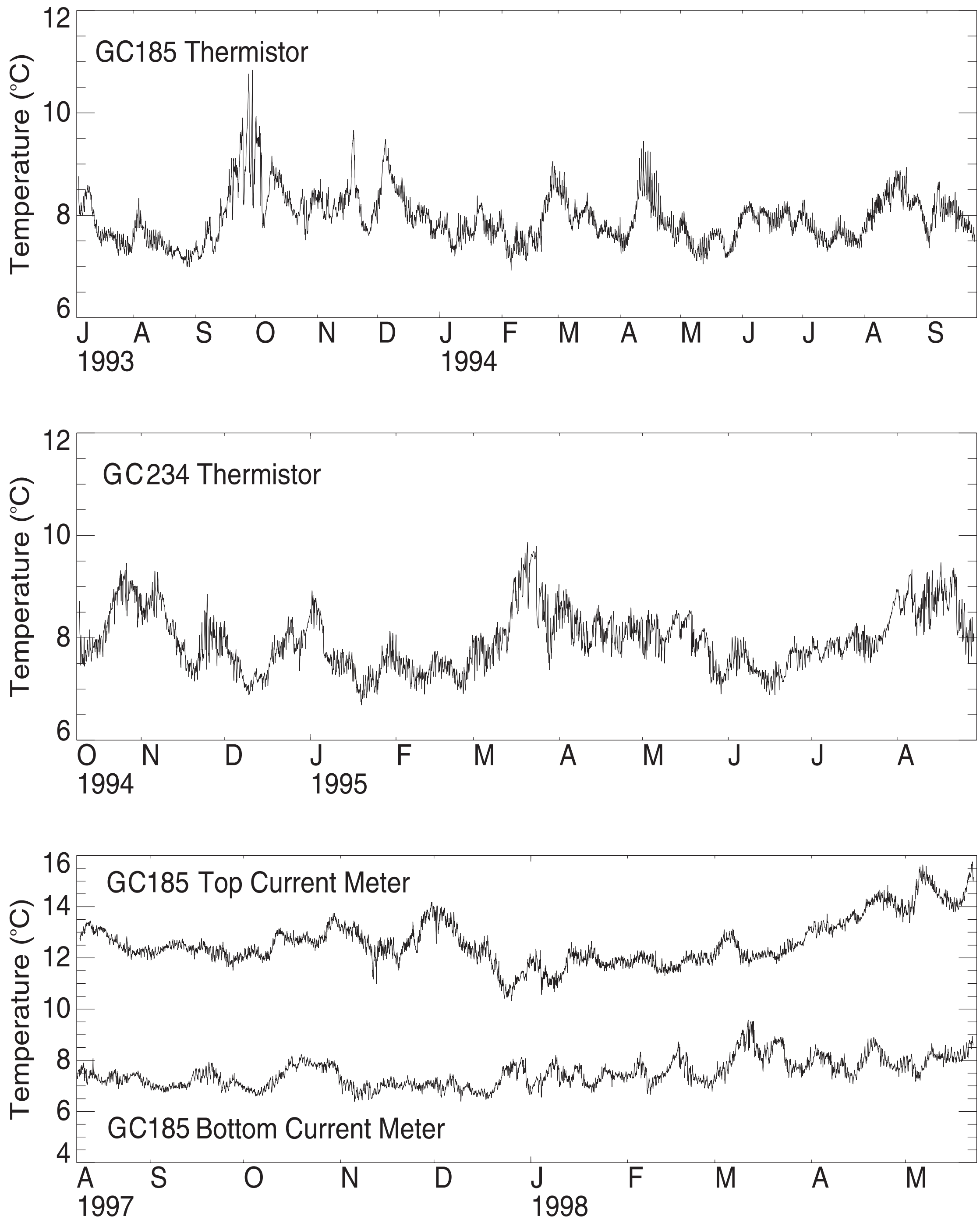

Figure 2.1 Time series of temperatures recorded by thermistors at GC185 and GB425. Time series of temperature collected at GC185 at the top and bottom current meter.

Table 2.1 The frequency, in percent of time, that currents had a particulate range of speed and direction for the top and bottom meters. Rows with less than 0.5% have been deleted. The column at the left summarizes the speed ranges for all directions. The row at the bottom summarizes the percent of time for octant of direction for all speeds.

CHEMO Top Current Meter

Speed (cm/sec)	N	NE	E	SE	S	SW	W	NW	Total
< 2	7.48	0.17	0.35	0.06	0.15	0.25	0.41	0.41	9.28
2 - 10	5.01	4.87	5.29	3.52	3.84	3.79	11.03	8.05	45.40
10 - 20	1.48	2.47	5.20	2.92	1.16	2.46	10.74	3.57	30.00
20 - 30	0.26	0.71	3.44	0.57	0.03	0.45	3.91	0.25	9.62
30 - 40	0.00	0.33	2.89	0.01	0.01	0.17	1.05	0.01	4.47
> 40	0.00	0.01	1.15	0.01	0.01	0.01	0.01	0.01	1.21
Total	14.23	8.56	18.32	7.09	5.20	7.13	27.15	12.30	

CHEMO Bottom Current Meter

Speed (cm/sec)	N	NE	E	SE	S	SW	W	NW	Total
< 2	24.32	1.70	3.28	2.00	1.12	0.68	3.19	1.68	37.97
2 - 10	8.60	6.16	7.87	10.90	6.03	3.06	5.60	8.70	56.92
10 - 20	1.02	0.57	0.77	0.75	0.01	0.09	0.12	1.65	4.98
Total	33.94	8.44	11.93	13.66	7.17	3.84	8.92	12.04	

Geophysical Signatures of Chemosynthetic Communities

Although continental slope and rise of the northern Gulf of Mexico technically fits into the category of "passive margin," (i.e., it contains no plate boundary) in actuality it is very active because of the tectonic deformations of a massive layer of salt that underlies marine sediments. The marked irregularity of the slope is caused by rising salt diapirs or massifs and by basins resulting from salt withdrawal by (Bryant *et al.* 1990; 1991; Bouma and Bryant 1994). Gulf of Mexico chemosynthetic sites are found in water depths from several hundred meters to more than two thousand meters, seemingly wherever there are hydrocarbon seeps on the continental slope. However, much of the knowledge of chemosynthetic ecosystems in the Gulf of Mexico comes from a small number of sites, most found by chance. A fundamental unanswered question is whether lush chemosynthetic sites are rare and fragile or ubiquitous and robust. Although chemosynthetic organisms cover only a tiny fraction of the seafloor, they have the potential to cause the offshore energy industry to spend large sums of money to make sure that drilling rigs, pipelines, and other production equipment do not blunder into community sites and cause harm. Geophysical techniques can detect hydrocarbon seeps because the seeps change the physical properties of surface and near-surface sediments (Roberts *et al.* 1990). The task of remotely locating chemosynthetic organism sites is one of defining the small percentage of the seafloor affected by seepage and then checking within that area for chemosynthetic habitation.

Active seeps are often visible owing to their release of oil and gas in the water. Slicks on the water surface can be imaged from space (and presumably lower altitudes), using photography or synthetic aperture radar (SAR), because oil reduces the roughness of the sea surface and cause it to appear bright: patches of floating oil are called "slicks".(MacDonald *et al.* 1993; 1996). More often, seeps are recognized by their effects on the physiography of the seafloor and acoustic characteristics of near-surface sediments. Seeps give rise to several distinct signatures on high-frequency echo-sounder profiles and seismic reflection profiles. In echo-sounder records, seeps cause acoustic "wipeout," which is the absence of subsurface reflectors. The effects of seepage are often noted on seismic reflection data, in particular the 2D and 3D multi-channel seismics often used for hydrocarbon exploration by the energy industry. Side-scan sonars also have the ability to show differences in surface sediment properties and thus may be useful in imaging seeps.

The rationale of the study was to collect a high-resolution geophysical data set in these known seep areas and compare it with other geophysical and geologic data. This program was designed to focus on a few data types in limited areas. Two areas were chosen to be representative of the upper and lower slope morphologic regions. The areas were surveyed using long-range side-scan sonar. Figure 3 shows the side scan mosaic from the shallow mega-site. The side-scan images provided a data set that could be compared to pre-existing geophysical and submersible data. Piston cores, collected with a surface ship, as well as deep geophysical data and observations with submarine NR-1 were obtained from selected targets in the sonar images.

Probably the most significant result from this study relative to the geophysical characterization of seeps is an increased awareness of their complexity in geophysical data. Generally, there is a tight link between faults, seeps, and chemosynthetic communities. In side-scan sonar data, seep related faults show high acoustic backscatter. Cores from the affected areas do not always show the same geologic characteristics, but are typically altered from normal hemipelagic property in a number of ways. Many of the cores exhibited carbonate nodules or layers, suggesting that much of the acoustic scattering in seep affected areas may result from authigenic carbonate material. Another potential disturbance is the formation of gas hydrate, which was recovered in several cores from GC185 and GC234 sites. Strong reflections might be caused by carbonate crusts and gas hydrate bodies. A feature of special importance to seep geology is the subcircular mud mound. The side-scan sonar mosaics imaged many subcircular, sonar-bright patches. In general, there were three different signatures: (1) uniformly high-backscatter (Figure 6.26), (2) a high-backscatter center with a halo of lesser backscatter intensity ("bulls eye", Figure 6.26), and (3) high-backscatter with a central spot having little or no backscatter ("dead eye", Figure 4). Some of the uniformly high backscatter patches were mud mounds, although none that we visited with submarine NR-1 was obviously active. A few subcircular sonar-bright patches were merely areas of the seafloor that appear to have had moderate seepage sometime in the past, but not enough to build a mound or support chemosynthetic communities. At several bulls eye sites, the near-bottom chirp sonar records from submarine NR-1 imply that the central high-reflectivity zones are hard-bottoms, which we interpret as either carbonate or gas hydrate layers. The surrounding haloes seem to be wipeout areas (either attenuation or turbidity) caused by lesser seep-related disturbances to the sediments

Knowledge about the geologic controls of chemosynthetic communities still has several significant gaps. Most research to date has focused on a small number of sites, so conclusions about chemosynthetic community occurrences, even on the upper slope, is limited by the generality of those sites. Increasing the number of seep sites investigated should be a high priority. This should include investigations into the number within a given area, so that we have better knowledge about the density of sites. It should also include an effort to obtain a broader picture of chemosynthetic sites in different structural settings. To date, most investigations have been on the Louisiana upper slope. The morphology of the lower slope is different from the upper slope, suggesting that controls on seeps may be different. In addition, the style of faulting changes from west to east across the continental slope and this may change the controls on seep occurrence. Because a large amount of geophysical data already exists for the Gulf of Mexico, collected by the energy industry, it would be prudent to consider obtaining geophysical data on seeps from a variety of settings and using computer GIS and database technology for assimilation and study.

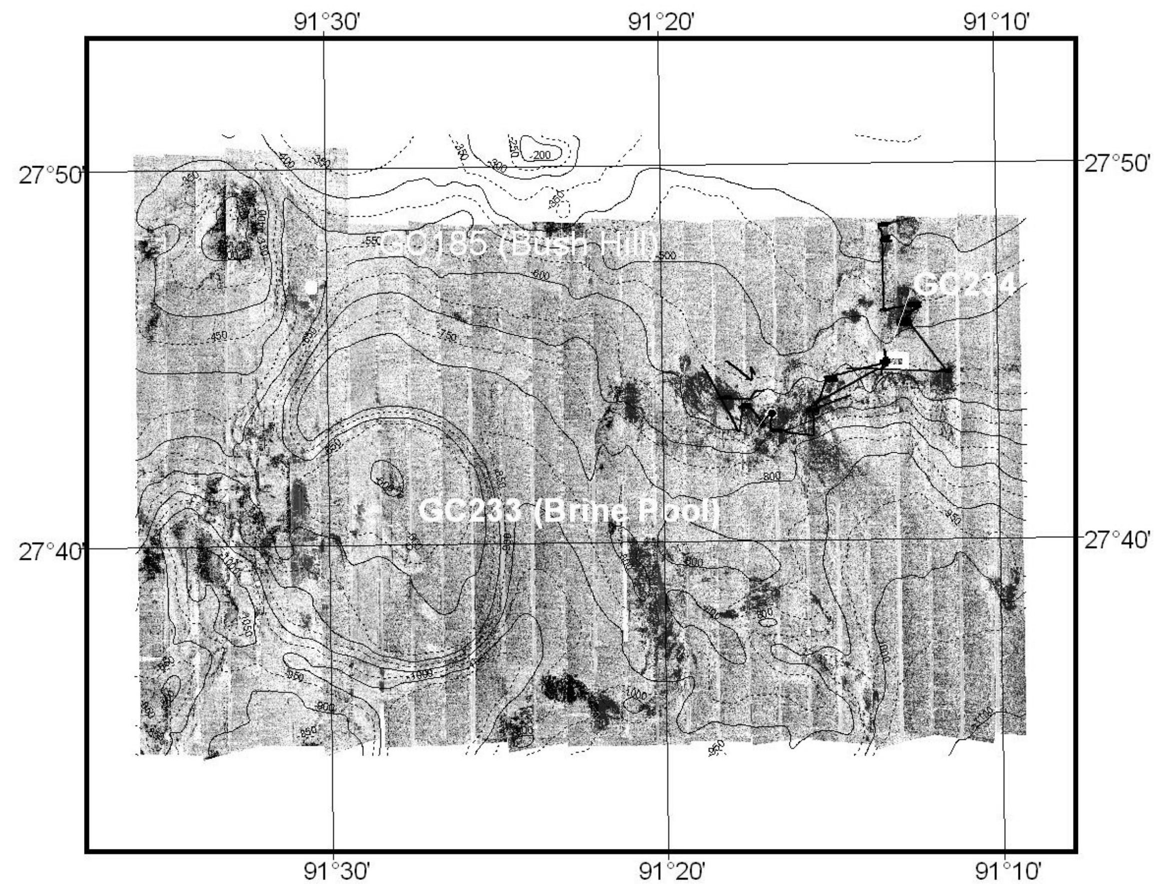

Figure 3. Side-scan sonar mosaic of the shallow mega site with locations of three of the community study sites. Overlay shows tracks of the 1998 submarine NR-1 dives. Thin dark lines are 50-m bathymetry contours.

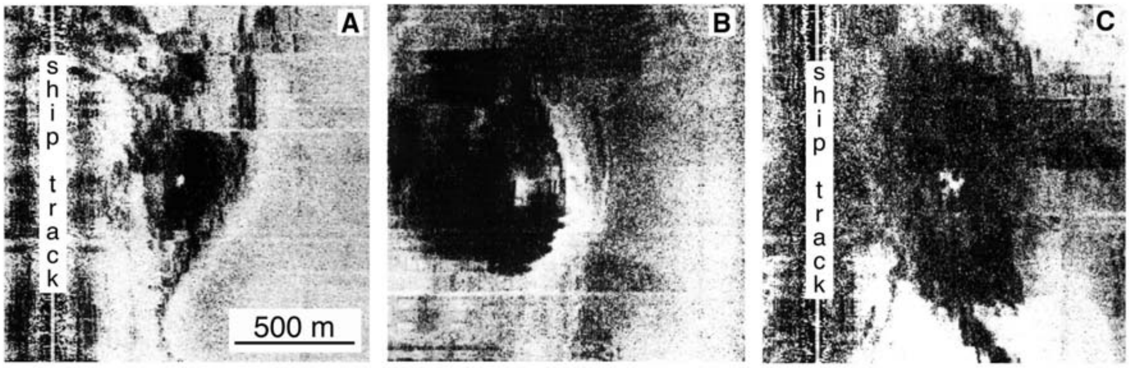

Figure 4. Side-scan sonar image of different mound backscatter characteristics. This record shows several subcircular high backscatter patche A., a large bulls eye mound, B. and another mound that has a dead spot (which shows better on another overlapping swath). C. The dead eye mound is where chemosynthetic organisms were found during NR-1 dives at a previously unknown seep. This record is from Green Canyon lease block 191.

Geologic Controls on Chemosynthetic Communities

Questions about the distribution and persistence of chemosynthetic communities in the northern Gulf of Mexico have to be posed in terms of scale. Over distances that span the Western and Central Lease areas, occurrences of chemosynthetic communities are determined by the presence of hydrocarbon reservoirs. At an intermediate scale, a major management concern remains the so-called lush chemosynthetic community and there are a number of questions that managers must consider: What constitutes a lush chemosynthetic community? How large an area does it cover? What densities of chemosynthetic species and what sorts of normal variation do such communities experience over a multi-year timeframe? The program study sites (Figure 1, Table 1) were chosen because they typify lush communities. Quantifying the dimensions, densities and faunal composition of these sites provides a baseline against which communities newly discovered can be compared. Mapping the fine-scale limitations posed by seep geology at each site creates a template that can be used to refine the search for lush communities in future surveys. Case studies of evidence for variability or persistence are used to identify general tendencies or processes that are relevant to management timeframes. Available data included surveys conducted during the present program and data gathered during previous efforts and reanalyzed with use of updated techniques. Clearly, having a small number of sampling sites limits the generality of these results. However, the four sites represent two pairs of communities supported by distinct styles of seepage: sediment diffusion versus focused flow and the pooling of hypersaline fluids. Summary descriptions for each site are as follows.

The GC185 site is also called Bush Hill. It is a sediment-diffusion type community and is probably the type-example for lush chemosynthetic communities [MacDonald, 1989 #132]. It occupies a broad, low mound, roughly hemispherical in cross-section, the rocky western margin of which aligns with high angle faulting. The biological community is concentrated in a relatively small portion of the mound, in a 40-m wide band that is offset, but largely parallel with, the axis of the fault. Gas hydrate outcrops on the eastern-most margin of this band, furthest from the fault, and appears to be a plug that waxes and wanes at the orifice of an active gas vent. The outcropping deposits of gas hydrate are dynamic structures in terms of their size, but occur persistently at predictable locations. Shallow deposits of gas hydrate extend from the community to locations well away from the principal axis of biological activity. Although these characteristics result from mapping a single site, which had been previously defined as a sediment diffusion site, comparison of similar attributes at the program's second sediment diffusion site, GC234, provide a means for evaluating their generality.

The GC234 site is the locality where the first documented collections of sediments containing thermogenic hydrocarbons were made in the Gulf of Mexico (Anderson *et al.* 1983). The geology of the region has been described by Behrens (1988) and Reilly *et al.* (1996). The extensive chemosynthetic community is situated on a slump block within a half-graben. Steep escarpments rise above the community on three sides, with extensive lithification on the western slope, and the bottom slopes away to the south.

Visual observations from the SEA-LINK cruises at GC234 conclusively link several of the mounds with shallow deposits of gas hydrate. Notably, the HYD1 station, when first observed in the 1997 cruise, was a prominent outcrop of gas hydrate that exposed a broad expanse of gas hydrate on its downslope margin (Figure 5) The polychaete *Hesiocaeca methanicola* (Desbruyeres and Toulmond 1998) was first observed on the exposed portion of this gas hydrate outcropping (Fisher *et al.* 2000). From these results, it is evident that gas hydrate forms in the upper few meters of the sediment column and produces broad mounds that breach the seafloor on the margin of steeper slopes (MacDonald *et al.* 1994). This exposes patches of gas hydrate, which subsequently dissolves so that the localized relief gradually deflates. A cycle of exposure, dissolution, re-growth and re-exposure repeats at fixed localities within individual mounds.

Figure 5. Exposed gas hydrate at the HYD1 station in GC234 site, 1997. This is the location where the ice worm (*Hesiocaeca methanicola*) was first collected. This deposit disappeared between the 1997 and 1998 SEA-LINK cruises. Note the band of sediment sandwiched between two layers of hydrate.

The clustering of chemosynthetic animals within the site is apparent from characteristics observed at the sampling stations during SEA-LINK dives (Figure 6). As was the case at the GC185 site, sampling stations defined by juvenile, adult, and senescent tubeworms were readily located, as were stations defined by mussels and bacterial mats. Though tubeworm colonies were abundant in the immediate vicinity of the sampling stations, there were large areas that were unoccupied by tubeworms and other chemosynthetic animals. As was also seen at the GC185 site, the association between tubeworm aggregations and gas hydrate at the site was consistent, but not deterministic. Dense aggregations of tubeworms extended beyond the limits of the hydrate mounds (e.g., Station AT1, Figure 6).

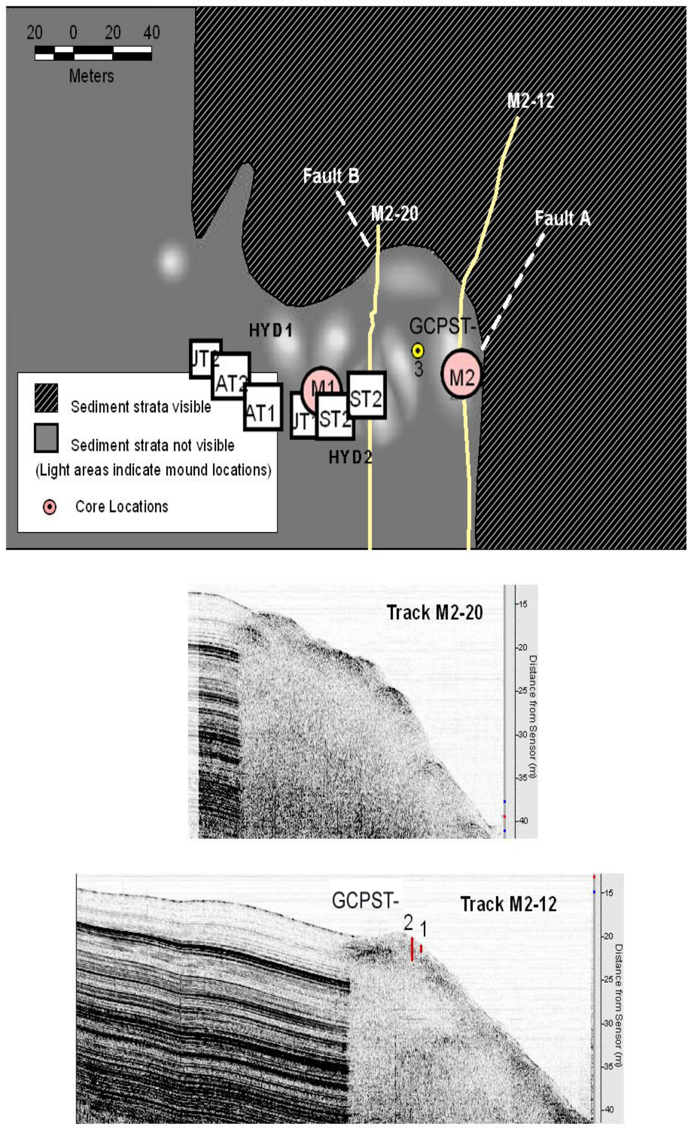

Figure 6. Results of X-Star subbottom profile survey. (A) North-south tracklines overlaid on sediment style showing location of hydrate mounds, faults, and sampling station locations. (B) X-Star subbottom profiles showing abrupt transition between stratified and un-stratified sediments, faults, mounds and piston core locations.

It is evident from the results at GC234 that sharp discontinuities in seepage are prevalent within the study area. A probable cause of these discontinuities is ongoing fracturing of the sediment column during the movement of the slump block and the expansion of the graben found at the site. The effect upon community development is to generate a patchwork of animal clusters distributed across a wide area. Although the underlying cause of this heterogeneous distribution is differential seepage along fault margins, the patterns are obscured by the happenstance of settlement history and minor disturbances. This confused pattern contrasts sharply with the orderly gradients found at brine pooling habitats.

The brine-filled pockmark and mussel bed at the GC233 site is a notable example of a chemosynthetic community supported by focused flow and methane dissolved in pooled hypersaline fluid (MacDonald *et al.* 1990b). This pool is situated on a low mound, which is elevated 6 to 8 m above the surrounding seafloor and has a basal diameter of approximately 100 m (Figure 7). The fluid filling the pool has a salinity of 130 practical seawater units and is supersaturated in biogenic methane. The seep mussel community as this site has developed in the present day to a continuous band that completely surrounds the pool on the level margins of the crater. The persistence of these animals is strong evidence for conditions that have favored chemosynthetic animals over an extended time. The probable age of the larger seep mussels in this population exceeds 100 y (Nix *et al.* 1995). Stability of the level of brine filling the pool is essential because the brine is anoxic in addition to being hypersaline. Therefore, it would be fatal for mussels to be submerged in the brine. Examination of the inner edges of the pool, however, reveals that the mussel hold their siphons less than half their body lengths (about 4 cm) above the brine. The outer edges are less than 15 cm higher than the inner edges. Because mussels are sessile and bound in place by the byssal threads of their neighbors, even the slightest increase in the brine level would produce widespread stress or mortality. Subbottom profile data collected by NR-1 show a mound formed by repeated eruptions of fluidized mud through two distinct vents. The two piston cores that were taken from the pool edges provided strong evidence for continual chemosynthetic communities at the site. Core RN8-1 was collected at the outer edge of the mound. Mudstones and stiff clay in the upper sections are consistent with the strong reflector seen in the upper portion of the subbottom record. A lucinid shell recovered from 1 m subbottom indicates circumstances favorable to chemosynthetic animals in this stratum. Notably, at 3.7 m subbottom a seep mussel shell indicates presence of a mussel colony at a position about 80 m, laterally, from present mussel colonies. Core RN8-2 was recovered immediately south of the pool and mussel bed. Fragments of lucinid shell and mud stones at 0.5, 2, and 4 m subbottom are consistent with the depths of the upper layers in the subbottom profile. This site and its strikingly dense population represent an equilibrium state between the violent forces of formation and continual processes (e.g., dissolution of the brine) that are eroding the present conditions. Perception of stability in the face of potentially destabilizing forces is intuitively clear. However, not all brine pools are similarly stable, as findings from the fourth study site, GB425 illustrate.

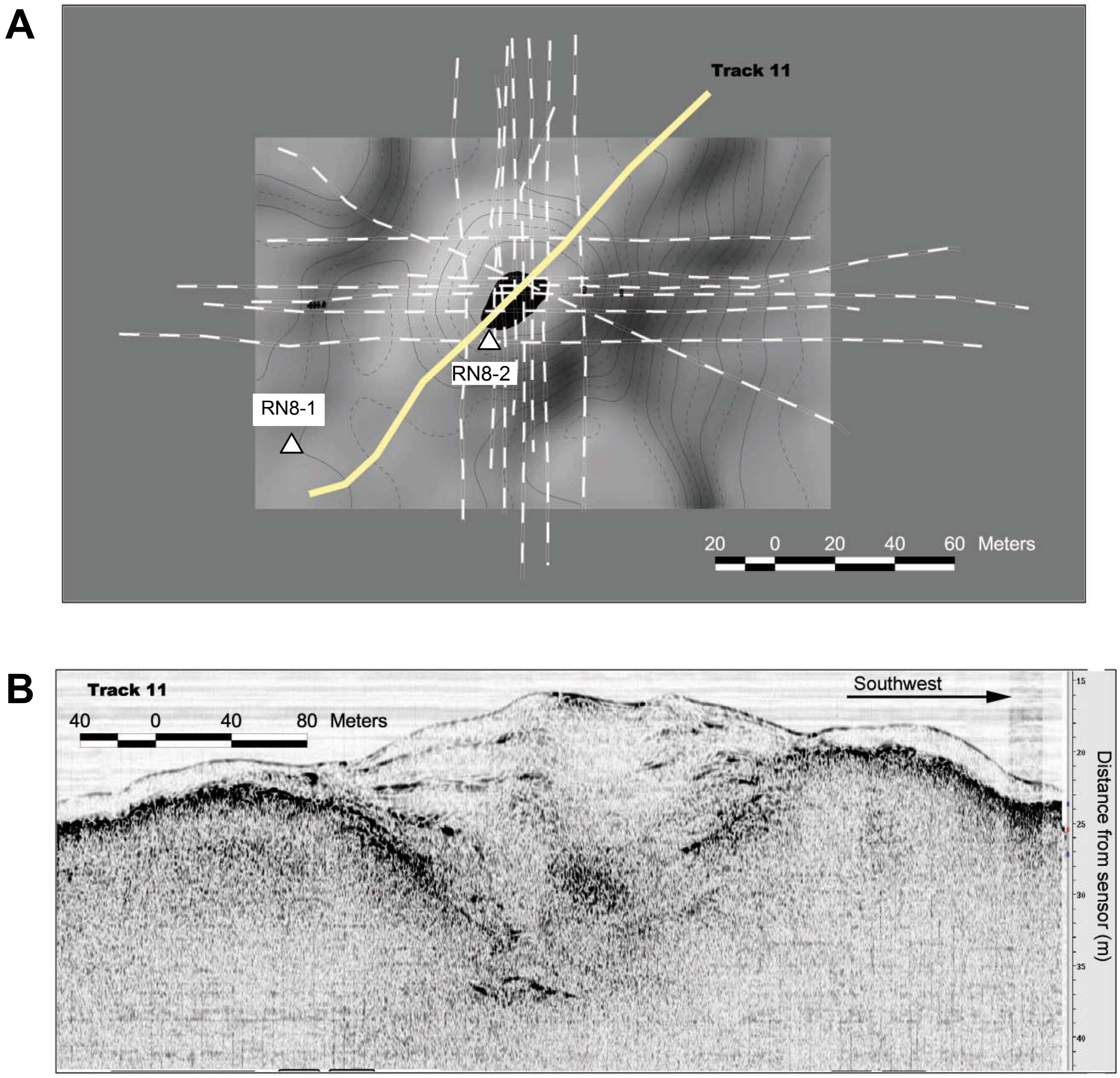

Figure 7. Subbottom profile survey of GC233 brine pool. (A) Plan of site showing trackline and piston core locations. (B) Example subbottom record from Track 11 taken along southwest to northeast track. Water depth of submarine was held constant (within < 1 m) along trackline, so bottom profile is accurate. Note horizontal banding marking sea floors buried by successive eruptions of the pool.

The GB425 site is a ~1-km wide plateau located at the edge of an intraslope basin that contains economically significant hydrocarbons in the Auger, Cardamom, and Macaroni fields and is bordered to the west by tabular salt bodies (McGee *et al.* 1993). Sediment cores from this zone have recovered high-molecular weight hydrocarbon and thermogenic gas hydrate. Fluids migrating up these faults disturb surface sediments due to the formation of carbonate nodules, oil and gas pockets, and biogenic debris. A lake of fluidized mud and brine is situated on the southeast edge of the plateau (Figure 8)

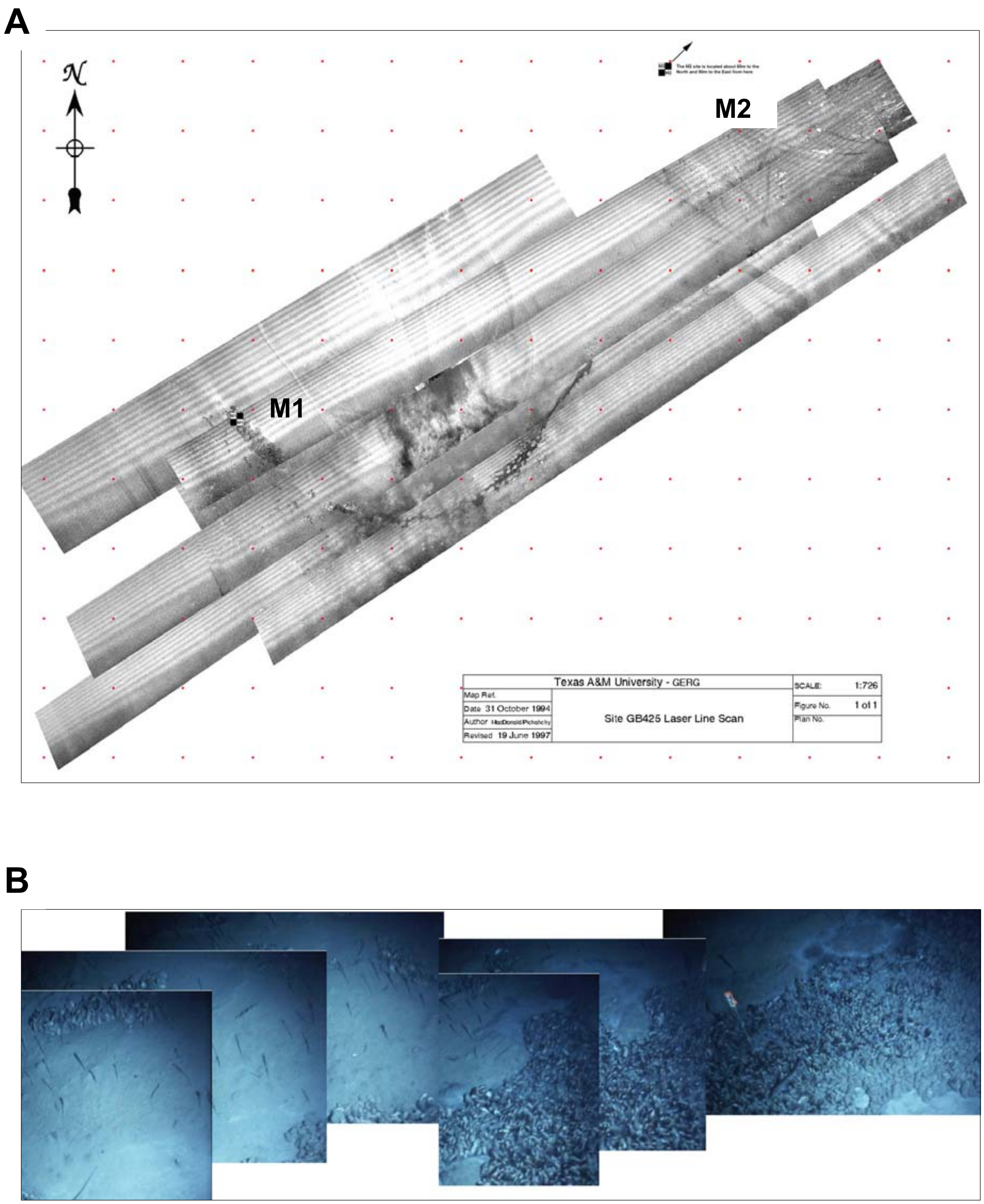

Figure 8. Mud-filled crater at GB425. (A) Laser line-scan mosaic of GB425 brine pool, showing location of M1 sampling station (grid points are at 10 m centers). M1 station is located approximately 150 m to the northeast. Mussel beds are restricted to southwestern (upslope) end of pool. (B) Photomosaic of M1 station looking south. Note marker float.

The mud lake at GB425 was sampled with use of the SEA-LINK on 29 July 1997 and 11 July 1998. On the first visit a thermistor was suspended below a float anchored on a short tether. It recorded a reading every 20 min. The anchor was attached to a 75 by 75 cm plate to prevent it from sinking in the soft mud of the crater bottom. Samples of brine and mud were collected with use of a chamber that the SEA-LINK positioned below the fluid-seawater interface and sealed for recovery. The brine had a salinity of 133 practical salinity units. The fluid degassed violently when the collection chamber was opened on the surface, indicating that methane gasses in the fluid were super-saturated with respect to sea level temperature and pressure.

Changes in the fluid properties of the mud lake over a one-year period indicated episodic activity related to fluid discharge. The geologic evidence of mud slides and the formation of large flat-topped structure points to ongoing and massive fluid expulsion. Episodic events are difficult to capture with sampling cruises of a few days separated by months or years. To provide independent data on fluid discharge at GB425 and from the region as a whole, available satellite synthetic aperture radar (SAR) data were reviewed in collaboration with scientists from Unocal Corporation. Satellite SAR readily detects layers of floating oil that form over active seeps. It provides a means to survey the numbers of hydrocarbon seeps across oil-producing regions and to estimate the rates at which seeps are flowing. Comparison of SAR images collected in the Gulf of Mexico indicates large differences in the amount of oil seepage over short time lags. These changes are too great to be attributed to ambient sea surface conditions.

Available time-series data from the 1997 through 1998 periods at GB425 comprised six SAR images and the records from the thermistor (Figure 9). Three of the SAR images were collected in May and June 1997, prior to deployment of the thermistor; three were concurrent with the deployment. The area of oil slicks overlying the fault zone repeatedly underwent order of magnitude changes between the May 1997 and the February 1998 observations (Figure 7.20B). During the 349-day thermistor deployment, fluid temperatures varied between 6.1° and 48.3°C with a mean of 26.1°C and standard deviation of 9.07. one can speculate that pulsed flows result when ongoing filling of hydrocarbon traps in western Auger Basin induces the failure of the permeable seals in the fault zone, injecting gas, oil, brine, and mud into surface strata and the ocean. Previous remote sensing surveys have depended on repeated detection of floating oil to confirm flowing seeps (Kornacki *et al.* 1994, MacDonald *et al.* 1993, MacDonald *et al.* 1996, Mitchell *et al.* 1999). This criterion would have overlooked seeps like the one described here. These results suggest that the time-dependence of seepage rates should be considered when evaluating the relative stability of seepage and seep dependent communities.

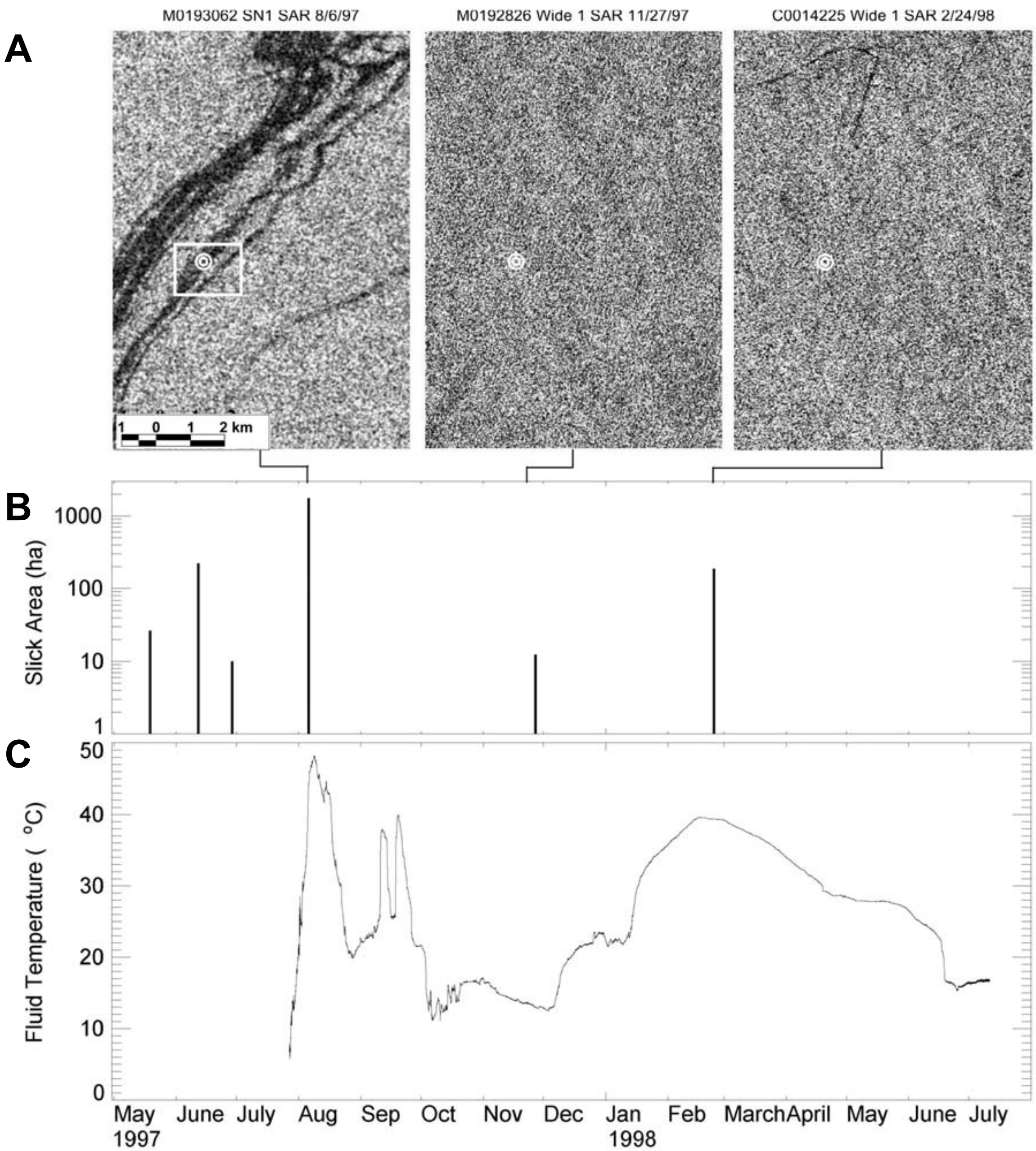

Figure 9. Comparison of temperature time series to abundance of floating oil above site. (A) Three sub-scenes of SAR data are reproduced to show, from left to right, large-, small-, and medium-size oil slicks. (B) Time series of slick areas (in hectares) imaged by available SAR. Slick areas were compiled for an 18.7 by 13.1 km region overlying the Auger Basin fault zone (Figure 7.19). (C) Temperature time series from fluid in diatreme recorded between 27 July 1997 and 11 July 1998.

Ecology of Seep Fauna

The Gulf of Mexico seep communities exist as a direct consequence of the biological oxidation of the energy-rich pore fluids seeping from the sea floor and the concomitant production of biomass. The organisms responsible for this production are chemoautotrophic and methanotrophic bacteria. These bacteria exist as free-living cells throughout the seep environment and also occur as thick mats on the sediment or other surfaces. Chemoautotrophic sulfide-oxidizing bacteria also occur as symbionts in several different invertebrates, most notably vestimentiferan tubeworms (Figure 10A) and several species of mussels and clams. The seep mussel (*Bathymodiolus childressi* see Figure 10B), which is the dominant mussel species at these sites, harbors symbiotic methanotrophic bacteria. In each of these cases, the symbiotic bacteria provide the overwhelming bulk of the host's nutritional needs, making the animals themselves chemoautotrophic in a sense.

Three overlapping types of communities are present in the primary sites that were a focus for this study. Bacterial mat communities are apparent both separated from and immediately adjacent to aggregations of other types of seep fauna. These mats can be quite extensive in both size of individual mats and abundance of mats at a site. Because the mats produce organic biomass and oxidize potentially toxic substrates, they are potentially important primary producers and detoxifiers for the seep ecosystem. Tubeworms and mussels, because of their autotrophic lifestyle, gregarious settlement behavior, and relatively large size, function as "ecosystem engineers." As such, they create substantial areas of habitat for numerous other species of endemic and non-endemic animals. Tubeworm and mussel communities can be relatively small or can completely cover areas up to thousands of square meters. Each can occur where the other is absent, or they can co-occur, each literally growing on one another.

One of the long-term goals of the Minerals Management Service's programs to study seep communities has been to develop an understanding and appreciation of these relatively poorly known and recently discovered communities. The hope is to provide the knowledge base for well-informed management decisions. Over the past fifteen years, many other projects have also contributed to the database on these and related communities. However, only recently has there been available sufficient information to put together a cohesive picture of the biology and ecology of the seep animals. The present study specifically built on what was known about the physiology, genetics, and ecology of the three key faunal groups (bacteria, tubeworms and mussels) to build and test working models of the animal's life histories and the communities they form. In some cases, studies were designed to address very fundamental physiological or genetic questions important to understanding the animals. In other cases, studies were designed to test system-level concepts arising from developing models of community succession, larval dispersal, or niche differentiation.

To the greatest extent possible, experimental design included integrated sampling between the different components of the overall project. For example, before a mussel bed was sampled, water samples were taken from beneath and over the mussels for chemical analysis. The bed was then sampled in a quantitative approach that allowed the biomass and size of all inhabitants to be determined and the biomass of the entire bed to be calculated from photographs or mosaics. Each collection was further sub-sampled for all appropriate components (i.e., condition analyses, PAH tissue load determination, histopathology, population genetics, stable isotope food-web studies,

Figure 10. Chemosynthetic fauna from the Gulf of Mexico. A. Tubeworms surround a mound of gas hydrate. Surface of mound is covered with bacterial mats. The mound is about 1 m wide. B. Seep mussels at gas seep. Note associated crustaceans and gastropods. The mussels are 8 to 10 cm long.

and in some cases growth or transplant studies). This greatly enriched the interpretation and future usefulness of each individual study and is also an ecologically sound approach to obtaining the maximum amount of knowledge with minimal impact on the populations.

Over the course of the program, numerous discoveries were made that fundamentally changed the views of the animals and the working models of these communities. Many of the studies remain ongoing because early results led to new directions and/or development of new techniques. Finally, as discovery usually does, the results of these studies spawned new and important questions that were not anticipated when the program was initiated.

The key discovery that the tubeworms are extremely long-lived, in fact, the longest lived animals known to exist on the planet. (Figure 11) shows the age estimates for tube worm whose growth was monitored during the program. It indicates a maximum ages in excess of 200 years. This is in direct contrast to the hydrothermal vent tubeworms, which are a very fast-growing, opportunistic species. Because the tubeworms produce the framework for a complex ecosystem, the seep tubeworms are much more analogous to trees in the sense of being long-lived and ecosystem-structuring. As a result, activities that damage well-established communities may have an impact that would last for centuries. In fact, consideration of their long life in light of the non-persistent size distributions in the aggregations suggests that old communities might never recover from serious damage because the time window for vestimentiferan recruitment to the site would have passed.

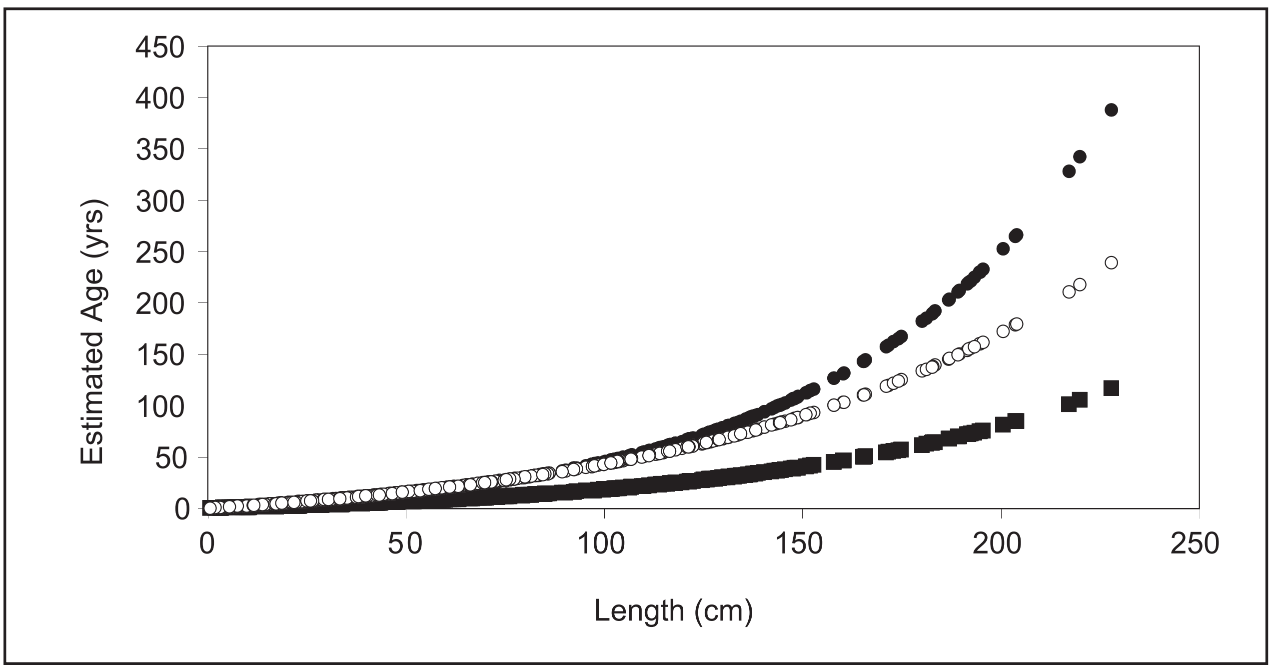

Figure 11. Individual ages predicted from tube length using the negative exponential model. The 1998 data set (solid circles) and the 1995-1998 data set (open circles) predict the average expected age of an individual. The upper bound of the 1998 data set (closed squares) predicts the minimum theoretical age of an individual constantly growing at the maximum growth rate of the species throughout its life.

A second discovery is that at least one of these species can acquire sulfide from buried sources and therefore may not require surface expression of seepage (into the water column). This may explain how the tubeworms live for centuries and also why the diversity of non-endemic fauna in these communities is much higher than at hydrothermal vents. It also suggests that the sulfide supporting these communities must be present at depths considerably greater than the depths of sulfide generation from seawater sulfate reduction. Thus, hydrocarbon seepage alone (with attendant production of sulfide in very shallow sediments) may not be sufficient for maintenance of large and long-lived tubeworm colonies. Therefore, the source of sulfide necessary to support these communities may be more patchily distributed than hydrocarbon seepage in general.

Another completely unexpected finding was that the mussel beds in some areas of the Gulf of Mexico were so severely infected with parasites that mussels in these areas are effectively sterile and therefore cannot contribute to larval pool of the *Bathymodiolus childressi* in the Gulf of Mexico. (Figure 12) shows the histology of parasite infections in seep mussels from the study sites.

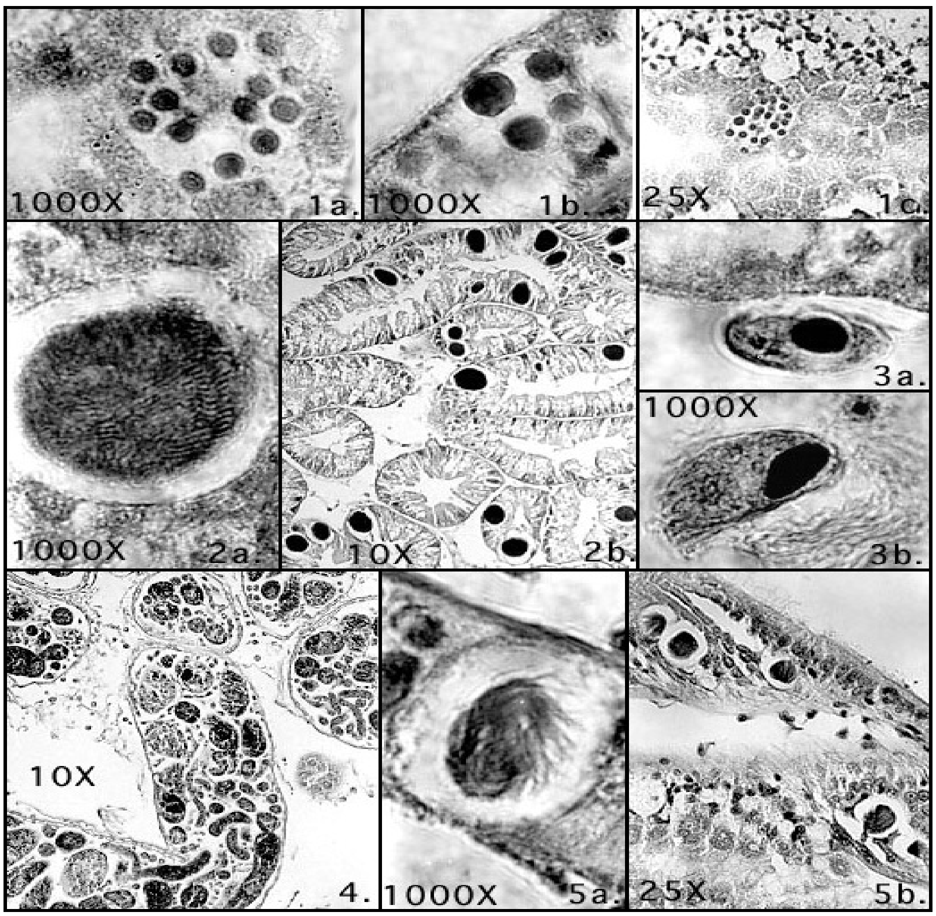

Figure 12. Parasite infections of seep mussels from study sites. Plate 1. Gill rosettes -- 1a, b: 1000x; 1c: 25x. Plate 2. Rickettsial-like bodies in the digestive tubules and diverticula -- 2a, b: 1000x. Plate 3. Gill ciliates between the demibranches -- 3a, b: 1000x. Plate 4. *Bucephalus* in the gonad -- 10x. Plate 5. Rickettsial-like bodies in the gill -- 5a: 1000x; 5b: 25x.

By comparison, mussel populations at other sites were quite healthy. Thus, some populations may be key to the maintenance of the Gulf-wide meta-population, while other sites are inconsequential. Differential growth was evident in direct measurements of mussel growth made using mark and recapture methods. The results show significantly different rates of growth among populations from individual sites (Figure 13)

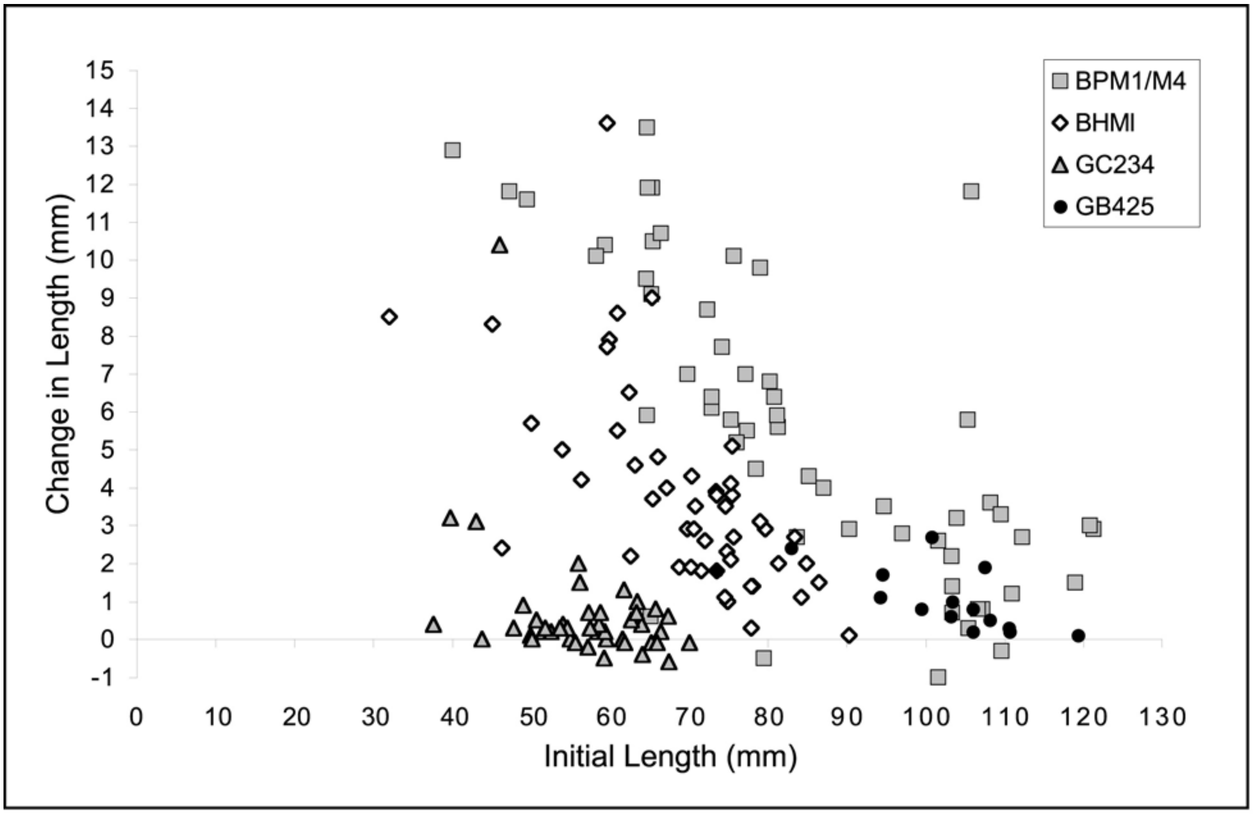

Figure 13. Growth of mussels between 1997 and 1998 field seasons at the GC233 and at MMS study stations BHM1, GCM1, and GBM1.

Results from stable isotope studies show that seep primary production not only supports a higher diversity of animals that are seep endemics or colonists than previously demonstrated, but also that significant amounts of seep primary production are being transferred into the surrounding deep-sea benthos. Of the eight species of larger mobile predators captured and analyzed for this study, individuals of six contained a significant amount of seep carbon and nitrogen in their tissues, indicating continued consumption of seep animals or bacteria over a significant period of time. Thus the seeps are not small islands of productivity inhabited by unique animals to be managed in isolation, but rather they are affecting and being affected by the surrounding deep-sea fauna.

Related to this finding is the discovery that significant numbers of the mat forming bacteria are present in situations when the mats are not visually apparent, and the strong implication that most of the fauna found among the tubeworms are not deriving their nutrition from tubeworm primary production. This finding, which is detailed in Section 8.2, suggests that primary production from free-living seep microbes may be much more important to the communities than usually recognized and underlies how little we know about the microbial ecology of these systems.

The molecular genetics studies indicate that over the areas sampled for this study, the tubeworm and mussel populations are exchanging larvae between sites and therefore can be managed as single, large, meta-populations. Genetic diversity is not at risk through anthropogenic activities in this region. Another key finding is that the symbionts of four Gulf of Mexico tubeworm species are not specific to the host species, but rather to the geographic region where they are found. This strongly supports the hypotheses that the symbionts are not transmitted directly (rather they must be acquired de-novo each generation) and that niche-differentiation between species at a site is not a function of symbiont differences, and further suggests site-specific differences in the bacterial populations at different sites. All of this information contributes to our working models of these species.

Based on our current level of understanding of the biology of the key ecosystem engineers and of the community ecology of the seep ecosystem, we have refined our working model of these communities. It is important to note that in the regions of the Gulf of Mexico where the seep communities occur the larval population is well mixed, and based on other studies, we know that the larvae of key species spend weeks or more in the water column. Thus, colonization and evolution of a new site will follow the same general pattern as colonization and evolution of patches of organisms within an established site, although the increased abundance of mobile consumers at established sites will likely influence the process through biological interactions.

Biogeochemistry of Chemosynthetic Communities

Upper Jurassic-sourced oil is found in anomalous amounts in sediments at or near four of our chemosynthetic community sites (GC185, GC234, GC233, GB425). The mean of 108 measurements of oil concentration performed on the four study sites is about 11,778 ppm by sediment weight. The range between individual measurements is large, however, from 6 ppm to 46,834 ppm. This wide range is expected in sediments of hydrocarbon seeps and even within single piston cores of seep sediments. Although oil is normally absent or present in low abundance in most Gulf slope sediments (<10 ppm), three of the study sites are clearly anomalous in terms of oil concentration. Differences in concentration of oil between three sites (GC185, GC234, GB425) are not thought to be meaningful. In contrast, the data do not demonstrate that crude oil is as widely distributed in sediments adjacent to the GC233 brine pool site. This, however, could be an artifact of sampling.

Hydrocarbon gas is concluded to be more effective than oil at driving biogeochemical processes at all of our study sites (GC185, GC234, GC233, GB425). The biogeochemistry of hydrocarbon seeps is fundamentally related to the concentration, fluxes, sources, and sinks of dissolved gases. Gases, such as methane and other hydrocarbon components, which migrate from depth or are supplied by disassociating methane hydrate located close to the sediment-water interface, may represent a major source of reduced carbon in these environments. Carbon dioxide (CO_2) and hydrogen sulfide (H_2S) play critical roles as metabolic products of microbial sulfate reduction and exert a major influence on critical environmental variables such as pH and oxidation-reduction potential (*p*e/Eh). The reoxidation of reduced sulfur also plays a critical role as an energy source for benthic organisms.

Classification of the sampling stations

20 Years of Service to America

MMS

Minerals Management Service

1982-2002

The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Minerals Revenue Management** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.