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Habitat formation at Gulf of Mexico hydrocarbon seeps

Ian R. MACDONALD
Texas A & M University, 727 Graham Rd, College Station, TX 77845 USA
Fax: (1) 409-862 1347 - e-mail: ian@gerg.tamu.edu

Introduction

The Gulf of Mexico hydrocarbon seeps are a major example of diversity and productivity supported by chemoautotrophic symbioses (Fisher, 1990; MacDonald et al., 1989). Seep localities in water depths of 500 to 750 m often contain communities in which Vestimentifera (*Lamellibrachia* c.f. *barhami* Webb, 1969, *Escarpia* sp.), seep mytilids (Seep Mytilid Ia, a provisional taxonomic designation), and Vesicomyidae (*Calyptogena ponderosa* (Boss, 1968) and *Vesicomya cordata* Boss, 1968) dominate the biomass. However, the communities include abundant fishes, crustaceans, and molluscs that are commonly found elsewhere on the slope. The chemosynthetic species have strong taxonomic and functional similarity to counterparts at hydrothermal vents of the eastern Pacific Ocean. Despite their similarities, seep and vent chemosynthetic species occupy very different habitats. Outlining robust differences between the two habitats is helpful for understanding the points of divergence between these fauna.

Dependence upon seeping hydrocarbons places Gulf of Mexico chemosynthetic fauna squarely in the one deep-sea locality most likely to be affected by human activities. Expansion of the offshore energy industry has experienced several episodes in the past twenty years. All of these have increased activities at ever greater depths. The amount of seafloor influenced by seepage is quite small compared to the extent of the subbottom hydrocarbon system and industry engineers generally strive to avoid the unstable substrate at seeps (Reilly et al., 1996). Nonetheless, the Minerals Management Service, which regulates offshore drilling and production, has stipulated limits to activities that might impact seep communities (MacDonald et al., 1995). Current interest lies in improving the capacity to predict where seep communities will occur and in understanding processes that contribute to either stability or change in this environment so that anthropogenic changes could be distinguished from natural processes. It is therefore important to identify processes that cause major variation in composition among seep communities.

I. Differences between vent and seep chemosynthetic habitats

One major difference between vent and seep habitats is that the oxic-anoxic interface is relatively turbulent at vents and relatively laminar at seeps. A principal cause for this difference is the sedimentary overburden found at seeps. At a typical hydrothermal vent, reduced chemical compounds alternate with sea water in the effluent plume that either discharges vigorously from a vent orifice or courses through a basement of fractured rock. Vent chemosynthetic fauna occupies the “flickering” zone affected by hydrothermal effluent (Hessler & Kaharl, 1995). At Gulf hydrocarbon seeps, oil and gas migrate to the seafloor from deep (3000-5000 m subbottom) reservoirs that are broadly distributed across the continental slope. Migration conduits are fault networks generated by tectonic deformation of a Jurassic Age salt unit (Williams & Lerche, 1987). Near the seafloor, a layer of unconsolidated hemipelagic sediment several hundred meters thick diffuses and retains oil and gas over areas considerably larger than the fault axis (Reilly et al., 1996).

Another distinction between seeps and vents is the source of chemosynthetic substrates. Reduced sulphur compounds are produced at vents as a direct result of high temperature reactions between basalt and seawater (Hannington et al., 1995). At hydrocarbon seeps, chemosynthetic substrates are generated as by-products of microbial consumption of hydrocarbons in the upper few meters of the sediment column. H_2S is both produced and consumed by biotic and abiotic processes in hydrocarbon seep communities at much higher rates than in normal sediments. Biogenic reaction products are responsible for formation of iron sulphide minerals and in some cases massive deposits of carbonate minerals at seep sites (Sassen et al., 1991). Vestimentiferan colonies at seeps can extend for tens of meters with densities of 1000 or more animals per sq. m. This biomass appears entirely to be supported by sulphate reduction of hydrocarbons in the upper sediment layer (MacDonald et al., 1995). Seep mytilids have methanotrophic symbionts that can satisfy their carbon and energy requirements from hydrocarbon gas (Fisher, 1990). Thermogenic gas is commonly utilized by seep mytilids (Brooks et al., 1987), which removes an immediate dependence on microbial activity. However, many significant mussel communities are known in which $\delta^{13}C$ ratios of -60 per mil or less in mussel tissue demonstrate dependence on methane of biogenic origin (MacDonald et al., 1990b). So, the interaction of free-living bacteria can be important for these species as well.

Adaptation to a sedimentary benthos causes a number of differences in how colonies of chemosynthetic fauna aggregate. Whereas vent Vestimentifera are superficially attached to rocky surface, seep Vestimentifera "root" themselves as much a meter or more into the surface sediments (MacDonald et al., 1989). Vesicomyidae at vents form largely static lines along local faults and fissures where their feet can access subsurface fluids. At seeps, they plow furrows across 100 m expanses of oil-rich sediment (Rosman et al., 1987). Under certain circumstances, vent mytilids may compete directly with Vestimentifera for effluent (Hessler & Kaharl, 1995). At seeps, the dependence upon methane by seep mytilids largely precludes competition between the two groups. Seep mytilids aggregate around active gas vents (MacDonald et al., 1989), but they can also occupy diffusion gradients generated by brine (MacDonald et al., 1990b) or gas hydrate (MacDonald et al., 1994).

It is common in hydrocarbon seeps to recover sediment samples which vigorously discharge gas when brought to the surface, drip with oil, and smell powerfully of H_2S (personal observation). These are the components presumed to support chemosynthetic fauna; yet the locations where these samples were collected seem to be quite unoccupied by vestimentiferans, mytilids, or vesicomyids-even *Beggiatoa* are largely absent. This observation points to a final difference between vent and seep habitats. At vents, formation and destruction of settlement surfaces available to chemosynthetic fauna is rapid and unstable because the driving, sub-seafloor processes, are dynamic and because the precipitate structures (chimneys, etc.) are physically fragile. Consequently, vent fauna is capable of rapid settlement and growth (Lutz et al., 1994). Seep chemosynthetic fauna responds more slowly to the availability of chemosynthetic substrata. Seep Vestimentifera probably have life-spans of several hundred years; they live in "the slow lane" (Fisher et al., 1997). Seep mytilids are also comparatively slow-growing and long-lived (Nix et al., 1995). At hydrocarbon seeps, habitats come about after protracted physical and biogeochemical transformations in a sedimentary regime.

II. Habitat-shaping processes at hydrocarbon seeps

Results obtained by compiling submersible surveys of seeps in the northern Gulf of Mexico (MacDonald et al., 1990a), detailed studies of known seep communities (MacDonald et al., 1995), and geophysical data (Roberts & Carney, 1997) suggest that the evident variety in seep communities is determined by the processes that move and retain seep fluids through the upper sediment column. Two forcing processes are responsible for much of the evident variety within the seep environment: these are sediment diffusion and brine pooling. Sections below present composite sketches of these habitat types based on material from references given above and on unpublished observations. Cartoons of the habitats are shown in Figures 1 and 2.

In a sediment diffusion habitat (Figure 1), gaseous and liquid hydrocarbons (C_1 to C_{15}+) permeate the unconsolidated sediments in the upper 1 to 50 m of the sediment column. Gases in solution - methane and H_2S - diffuse from pore fluids into the water column. Gaseous hydrocarbons move with low resistance up fault planes and may bubble off into the water column. Liquid hydrocarbons occur as lugs, vugs, and veins through the sediment mass.

A number of processes work in concert to create lateral barriers to seepage in the upper sediments. Under appropriate conditions of low temperature (< 7.5°C) and high pressure (> 50 bar), lenses of gas hydrate will form where methane and higher hydrocarbons are trapped to create a gas-water interface. Each lens is relatively impermeable to gas and deflects subsequent seepage to its edges. Hydrate lenses may coalesce as extensive layers. Where such layers intersect slopes, hydrate can breach the seafloor and spall off in free-floating pieces. Above and around the hydrate layers, hydrocarbon oxidation by free-living bacteria produces copious sulphate reduction and precipitation of authigenic carbonates.

Methane diffusing through or bubbling past hydrate layers supports dense beds of Seep Mytilids. Carbonates offer a settlement substratum for vestimentiferans. These barriers to seepage consume or divert much but not all of the seeping hydrocarbons. Local blow-outs occur where accumulated pressures are relieved catastrophically. Blow-outs are evidenced as upturned slabs of carbonate-sometimes with vestimentiferans still growing imbedded in the rock matrix-or as pockmarks and slope failures. Over geologic time the entire seep complex may develop as a series of mounds or a graben along the primary fault that supplies source hydrocarbons from depth.

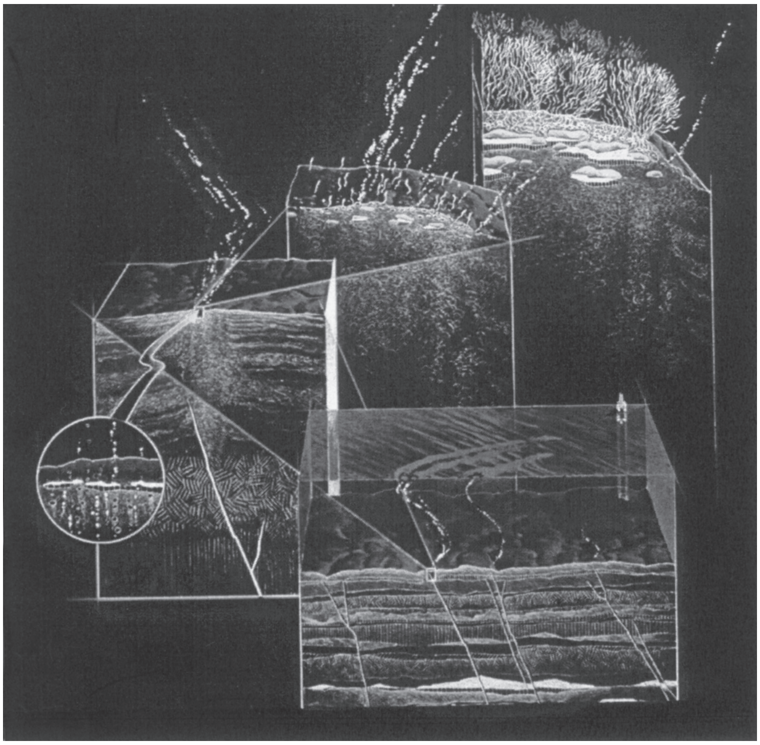

Figure 1. Cartoon of the chemosynthetic community formation in a sediment diffusion style hydrocarbon seep. Gas and oil migrate along fault planes that penetrate reservoirs (lower), then diffuse through unconsolidated sediments approaching the seafloor (middle left). Formation of gas hydrate, layers of biota, and authigenic carbonate entrap hydrocarbons in uppermost sediment (middle right). Painting by Bruce Moser.

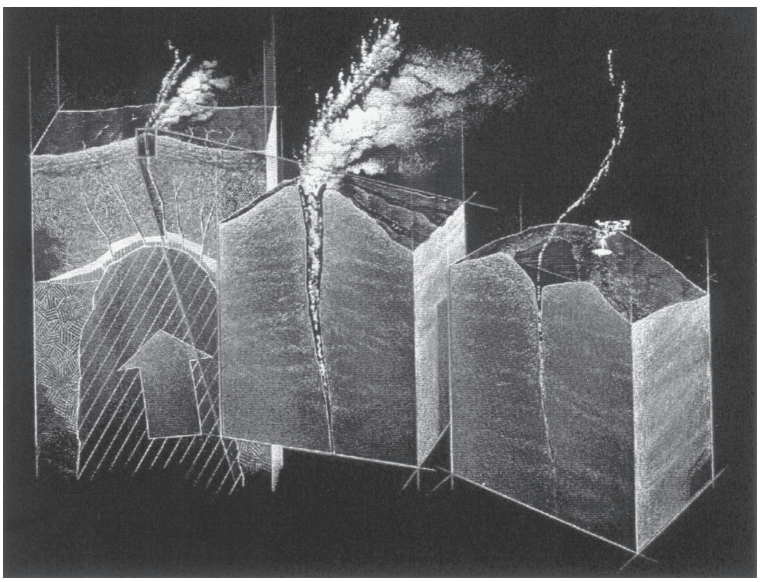

Figure 2. Cartoon of the chemosynthetic community formation in a brine pooling style hydrocarbon seep. Salt diapir pressurizes a shallow reservoir of methane (left). Subsequent release of gas excavates a surface crater and diatreme (middle). High concentrations of methane are available to seep mytilids around edges of brine pool formed by dissolution of salt (right). Painting by Bruce Moser. Figure 1 and Figure 2 are reprinted with permission from National Geographic Magazine (I.R. MacDonald and C.R. Fisher, National Geographic 1996, 4: 86-97).

Strong brines are often associated with petroleum formations and natural seepage. In a brine pooling habitat (Figure 2), brine density tends to retain it as a distinct fluid in depressions on the seafloor. Seafloor brines often take the form of rivulets extending for short distances along slopes. Brine and gas flows occur when deep fluid layers become over-pressured due to accumulation of overlying sediment. When pressure release is violent, fluid flow will excavate a crater and may continue as successive sheet flows of mud and debris; eventually constructing a mound. Oil drops may flux vigorously from the centre of the pool. Some of the more active oil seeps visible in satellite imagery have been found to have brine or mud pools at their source. Brine or fluidized mud will fill the quiescent crater. Heat flux from depth is greatly increased, and the brine surface may represent a temperature anomaly of 10 to 15°C above ambient seawater. Gas bubbles escaping through the fluid will waft clouds of fine sediment into the water column, continuing the mound building process. The brine is saturated with methane, but high temperatures and high chlorinity preclude hydrate formation. Seep mytilids can establish very dense colonies along the edges of brine pools, but require relatively stable settlement substrata. Inundation by brine or mud is fatal to mussel colonies, so the existence of a mussel bed along a pool edge indicates recent relative stability of the pool. Sheet flows of mud create thin, organic-rich layers on the surrounding slopes. Such layers are the natural habitat of vesicomyid and lucinid clams. Frequently the slopes of brine or mud pools accumulate extensive areas occupied by living bivalves or shell litter.

These habitats have been presented as separate processes. In actuality, the sediment diffusion and brine pooling events can occur in close proximity to one another. Also, the processes can produce similar forms at large and small scales. For example, one can find brine pools from 1 m to 100 m in diameter that have quite similar morphology and that are utilized by seep mytilids in much the same way.

A major limitations to understanding the Gulf of Mexico seep system in detail is that most of the known examples have been explored by submarines that are limited to operating depths of < 1 000 m. As depth increases on the slope the depth of the sediment overburden decreases. The stability horizon for gas hydrate formation is projected downward into the sediment. These factors alone could have a profound effect upon the form and fate of seep communities in deeper water. Satellite evidence for seeps and preliminary findings at 2500 m in Alaminos Canyon (MacDonald et al., 1995) suggest that seep fauna will be found throughout the northern Gulf of Mexico. It is likely, therefore, that the additional models will be required, as future work provides further examples of hydrocarbon seep communities.

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