STRUCTURE OF A CARBONATE/HYDRATE MOUND IN THE NORTHERN GULF OF MEXICO

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ABSTRACT

A one-kilometer-diameter carbonate/hydrate mound in Mississippi Canyon Block 118 has been chosen to be the site of a multi-sensor, multi-discipline sea-floor observatory. Several surveys have been carried out in preparation for installing the observatory. The resulting data set permits discussing the mound's structure in some detail. Samples from the water column and intact hydrate outcrops show gas associated with the mound to be thermogenic. Lithologic and bio-geochemical studies have been done on sediment samples from gravity and box cores. Pore-fluid analyses carried out on these cores reveal that microbial sulfate reduction, anaerobic methane oxidation, and methanogenesis are important processes in the upper sediment. These microbial processes control the diffusive flux of methane into the overlying water column. The activity of microbes is also focused within patches near active vents. This is primarily dependent upon an active flux of hydrocarbon-rich fluids. The geochemical evidence suggests that the fluid flux waxes and wanes over time and that the microbial activity is sensitive to such change. Swath bathymetry by AUV combined with sea-floor video provides sub-meter resolution of features on the surface of the mound. Seismic reflection profiling with source-signature processing resolves layer thicknesses within the upper 200-300m of sediment to about a meter. Exploration-scale 3-D seismic imaging shows that a network of faults connects the mound to a salt diapir a few hundred meters below. Analyses of gases from fluid vents and hydrate outcrops imply that the faults act as migration conduits for hydrocarbons from a deep, hot reservoir. Source-signature-processed seismic traces provide normal-incidence reflection coefficients at 30,000 locations over the mound. Picking reflection horizons at each location allows a 3-D model of the mound's interior to be constructed. This model provides a basis for understanding the movement of fluids within the mound.

Keywords: carbonate/hydrate mound, seismic structures, gas migration, seafloor observatory

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INTRODUCTION

A carbonate/hydrate mound approximately a kilometer in diameter occurs in the south-central portion of Mississippi Canyon lease block 118 (MC118), the location of which is shown in figure 1.

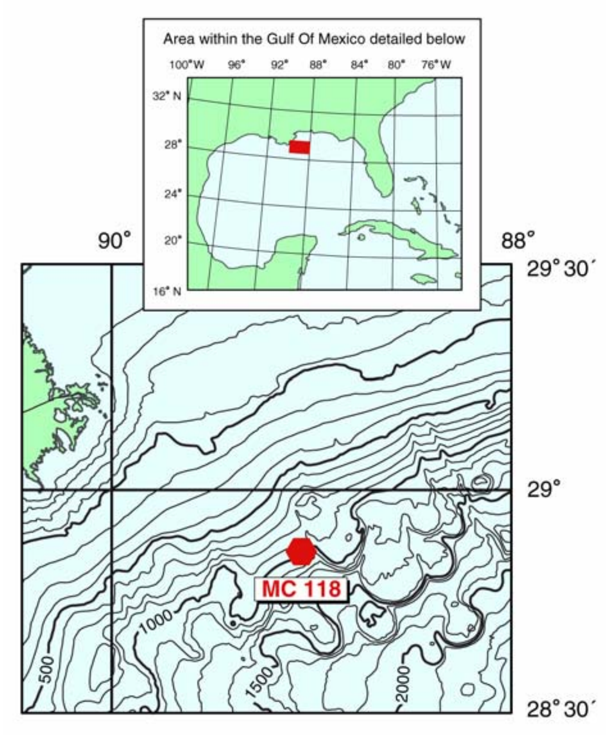


Figure 1 Location of Mississippi Canyon Block 118 (MC118)

This mound has been chosen by the Gulf of Mexico Hydrates Research Consortium to be the site of a multi-sensor, multi-discipline sea-floor observatory. The observatory (figure 2) includes seismo-acoustic, geochemical and micro-biologic sensors which will monitor ambient seismo-acoustic noise, fluid venting and environmental conditions for a period of five-to-ten years.

It is expected that such monitoring will lead to an understanding of how fluids migrate and effect the formation of hydrates within the mound. Seismo-acoustic monitoring will be based on methods of seismic interferometry [1] that use ambient noise correlations to measure travel times between hydrophones. The hydrophones will be distributed both vertically and horizontally. Since distances between hydrophones will be known, changes in travel times can be stated as changes in speeds of propagation that result from physical changes within the material comprising the mound. Since gas migration is likely to be the most changeable aspect of that material, it is expected that the travel-time changes will be related to movement of gas and will correlate with changes in vent-gas volume (observed acoustically) and/or changes in gas chemistry (observed by an in situ spectrometer). Corroborating evidence will be provided by observations of nearby microbial communities.

Several surveys have been carried out in preparation for installing the observatory. The resulting data set permits a preliminary discussion of the structure of the mound. Such discussion is crucial to proper deployment of the various sensors before monitoring commences.

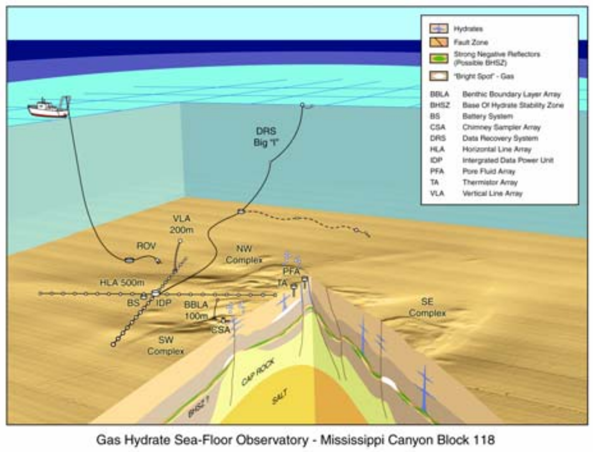


Figure 2 Illustration of sea-floor observatory components.

SURFACE MORPHOLOGY

The surface of the mound has been imaged by multi-beam bathymetric sonar from an autonomous underwater vehicle (AUV) 40m above the sea floor as well as by cameras at or a few meters above the sea floor deployed from drifting surface vessels or tethered submersibles. Also, visual observations have been made from manned submersibles.

The surface morphology of the mound (figure 3) is characterized by several main crater clusters that exhibit bathymetric relief of 2-6m with individual craters 5-60m in diameter. For reference purposes, the clusters are grouped into three principle complexes based on complexity of relief and relative venting activity. The three complexes are: the SE Complex which has low relief and no observable venting activity; the NW Complex with moderate-to-low relief and a moderate-to-low level of venting; and the SW Complex which exhibits moderate-to-high relief and a moderate-to-high level of venting activity. It is noteworthy that, although the SE Complex exhibits little activity at present, it does show evidence of past activity in the form of extensive pavements of methanotrophic clam shells.

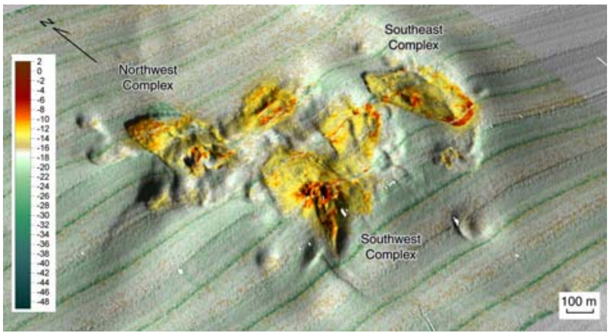


Figure 3 Backscatter image of mound showing locations of crater complex

Fluid expulsion events are suspected to occur episodically in the NW and SW Complexes where they are probably responsible for crater formation as well as for maintaining bottom relief despite burial effects of fine particulate sedimentation.
Bacterial mats thought to be the sulfide-oxidizing Beggiatoa commonly occur over the SE complex. The mats are observed more often in stable, flat-lying extra-crater areas and only rarely within the more active craters due to the inherent instability associated with crater activity. Bacterial mats are linked to the precipitation/formation of authigenic carbonate rocks. The contribution of the resident microbial communities, surface and subsurface, to the geology of the hydrate mound has been investigated only recently and their critical roll in hydrate mound evolution is now beginning to be appreciated fully.

GAS SAMPLING

Gas samples were collected in the SW Complex from three vents and one intact sample of outcropping hydrate. Chemical analyses [2] show the vent gas to average 95% methane, 3% ethane, 1% propane with minor other gases and to be thermogenic from deep hot source rocks. There is no significant biogenic component. The outcropping hydrate is Structure II with gas composition 70% methane, 7.5% ethane, 15.9% propane with minor other gases. The difference between the gas compositions from the vents and the hydrate is due to molecular fractionation during hydrate crystallization (Roger Sassen, personal communication).

LITHOLOGIC AND BIO-GEOCHEMICAL STUDIES

Gravity and box cores have been collected for lithologic and bio-geochemical studies. Mound lithology is composed mainly of Recent hemipelagic mud [3] with poorly cemented, bio-encrusted/eroded, authigenic carbonate rocks of varying size (10cm–5m). The rocks are scattered randomly over the mound surface and are observed to support deep-water corals at some sites in the SW and NW Complexes. Typically, the mud surfaces of the crater sites are littered with shell fragments from methanotrophic clams. In some areas, particularly in and around quiescent vent sites, these shells form pavements.
Carbonate rocks, where found more or less exposed on the crater floors, typically occur as tabular blocks (0.5-4m). They commonly form a uniformly horizontal surface and occur at a common elevation throughout the SW Complex (figure 4). Relatively fresh exposures occurring in the western crater of the SW Complex typically host gas hydrates. Such carbonate blocks can be observed where excavated from a thin (50cm-2m) overburden of hemipelagic mud, apparently exposed by the winnowing effect of the suspected periodical fluid expulsion events.

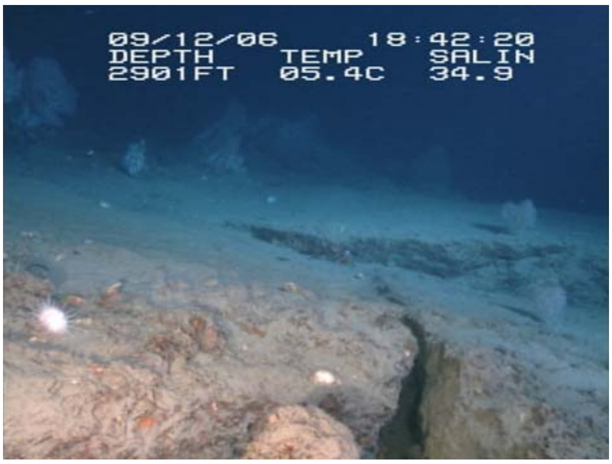


Figure 4 Carbonate blocks paving crater floor in SW Complex.

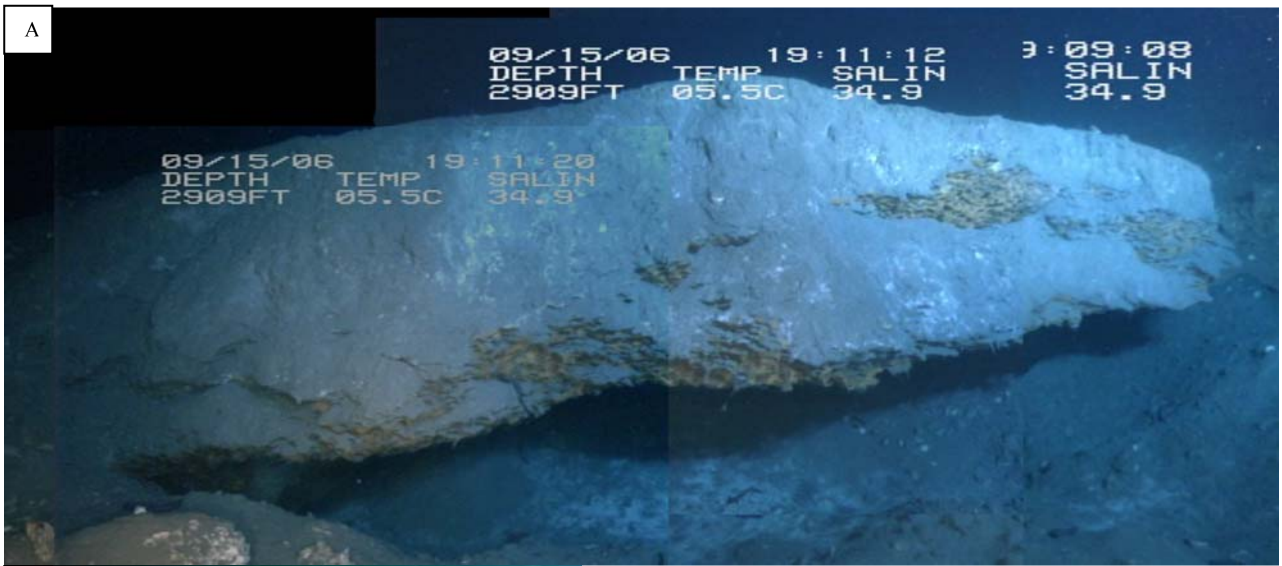
Where found, hydrates occur as irregular inclusions in void spaces and, in the instance of the eastern crater of the SW Complex, as rare interbedded tabular slabs.
The presence of authigenic carbonates at MC118 is intimately related to the activity of sedimentary microbes and bacterial mats on the surface of the sediments. Especially at seep sites, sedimentary microbial activity is dominated by sulfate reduction, anaerobic methane oxidation, and methane production [4, 5, 6, 7, 8]. To assess this activity, gravity cores were collected and down-core concentration gradients of dissolved methane and sulfate, isotope gradients of methane, dissolved inorganic carbon, and authigenic carbonate, and organic matter elemental ratios were measured [9].

VENTING ACTIVITY

The lack of evidence for recent venting in the SE Complex suggests that the conduits which once supplied sufficient methane to support an abundant population of methanotrophic clams have become blocked. Perhaps the blockage is due to hydrates forming in the fractures. If so, rising gases would follow routes that bypass the blockage and emerge elsewhere on the mound.
Venting in the NW Complex is not vigorous but there is evidence of a low-to-moderate level of activity. A recording pore-fluid array probe installed there measured salinities five times higher than that of sea water. A small bubble stream was observed at the northern periphery of the NW Complex by a drift camera and mass-spectrometer in-situ measurements recorded nearby indicate water-column methane approaching saturation. Also, the presence of extensive Beggiatoa mats further suggests that methane is seeping from the bottom sediment in the NW Complex. Thus it seems that the conduits leading to the NW Complex are at least partially open and carry some amounts of methane and brine.
The pore-fluid array in the NW Complex recorded a sharp spike in methane on 10 September 2006 at about the time that a magnitude 5 earthquake occurred some 80 kilometers to the south-southwest. Two days later, observers aboard a manned submersible found a crater, approximately 10m in diameter and 3m deep, that had developed in the central part of the NW Complex. The crater was defined by a peripheral berm of fine sediment that rose about 1.5m above the surrounding sea floor. The crest of the berm was sharply defined and had not yet been smoothed by the persistent bottom current. The outer depositional apron of the berm was seen to overlie the pre-crater sea floor which was characterized by scattered Beggiatoa mats and abundant indications of bioturbation. The overall impression was that the crater was produced by a very recent gas expulsion event, possibly linked to the seismic event that had occurred two days before.
The SW Complex contains the most active of the mound's craters in terms of venting activity and active expulsion features. It is divided into western and eastern parts, each comprised of several intersecting smaller craters. The two parts are separated by a ridge of fine-grained material that overlies a well-defined horizon of authigenic carbonate. That horizon consists of sub-horizontal tabular blocks about 1m thick. These blocks pave the floor of craters in the western part and are characterized by inclusions of hydrate that fill voids within the carbonate (figure 4). In some places, streams of gas bubbles rise from fractures.
In the eastern part there is a set of intersecting craters approximately 60m in diameter and 6m deep. Craters in the eastern part are about 5m deeper than those in the western part and appear to be more active in regard to venting of hydrocarbon fluids. Oil in various stages of microbial degradation occurs abundantly in the fine sediments of the crater floors. An exposure of authigenic carbonate rock in various stages of disintegration outcrops on the northern and eastern flanks of the intersecting eastern craters at the same elevation as the paving blocks in the western part. It is overlain by about 2m of sediment, the upper meter of which appears to be a berm of expelled material.Looking down into the eastern crater from a point on that berm, a large carbonate/hydrate outcrop (6m long by 2m wide by 1.5m thick) was seen to protrude from the crater's eastern flank. It was named the "Sleeping Dragon" (figure 5a). Also seen were the disintegrating carbonate rock horizon on the northern crater flank and a discontinuous low-relief linear depression oriented SW-NE across the crater floor which appeared to be the trace of a tensional fracture.
Two vertical dykes of hydrate, each approximately 1m high, 1m long and 30-50cm thick protruded from the depression (figure 5b). One was located about 7-8m west of the observation point. The

other was about 5m north and disappeared into the sloping flank of the crater wall. Both appeared to be in active states of disintegration, caving-in on approach of the vehicle and sending fine-to-medium particles lofting into the water column.

When revisited 14 months later, the “Dragon” edifice was found to be reduced in volume by about 70%. Apparently it had been severely Dissociated and/or eroded The dykes were not seen during the second visit due to poor visibility that seemed to accompany vent activity.



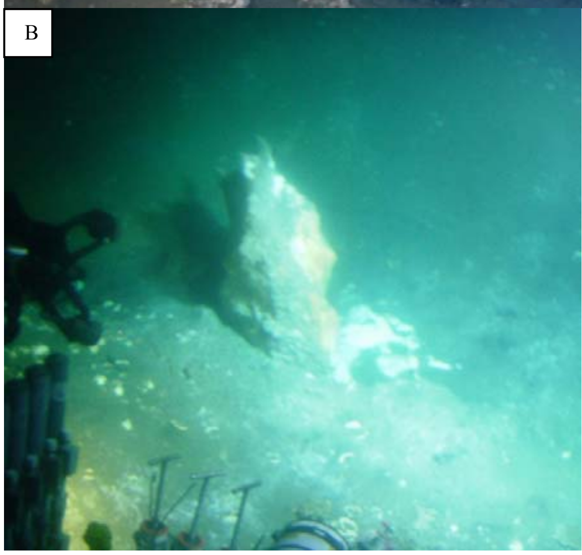


Figure 5 (a) Composite photo of the Sleeping Dragon hydrate outcrop (6m-by-2m-by-1.5m) in SW Complex, (b) A hydrate dyke (≈1 m tall) near Sleeping Dragon.

SEISMO-ACOUSTIC STUDIES

The sub-surface structure of the mound has been investigated using several seismo-acoustic techniques. Chirp-sonar profiles at 200m line spacing were recorded simultaneously with the AUV swath-bathymetry data. They provide about 30m penetration and sub-meter resolution except in portions of the mound where strong backscatter occurs at shallow depths, apparently caused by heterogeneities such as blocks of carbonate.

A grid of seismic profiles was acquired at 50-by-100m line spacing (figure 6a) using the shallow source/deep receiver (SSDR) field geometry (figure 6b).

The geometry allows a far-field source signature to be recorded for each shot so that the phase of the signature may be removed during post processing, thereby improving seismic resolution. Processed SSDR profiles provide 200-300m penetration at meter-scale resolution. Such profiles bridge the gap between shallow 2-D high-resolution acoustic data and deep 3-D industry-standard seismic data.

The deep seismic data clearly show that a salt diapir occurs some hundreds of meters beneath the mound and that a nearly vertical fault system extends from the diapir to the mound. Apparently, it is this system that provides conduits through which hydrocarbon fluids from deep sources reach the mound.

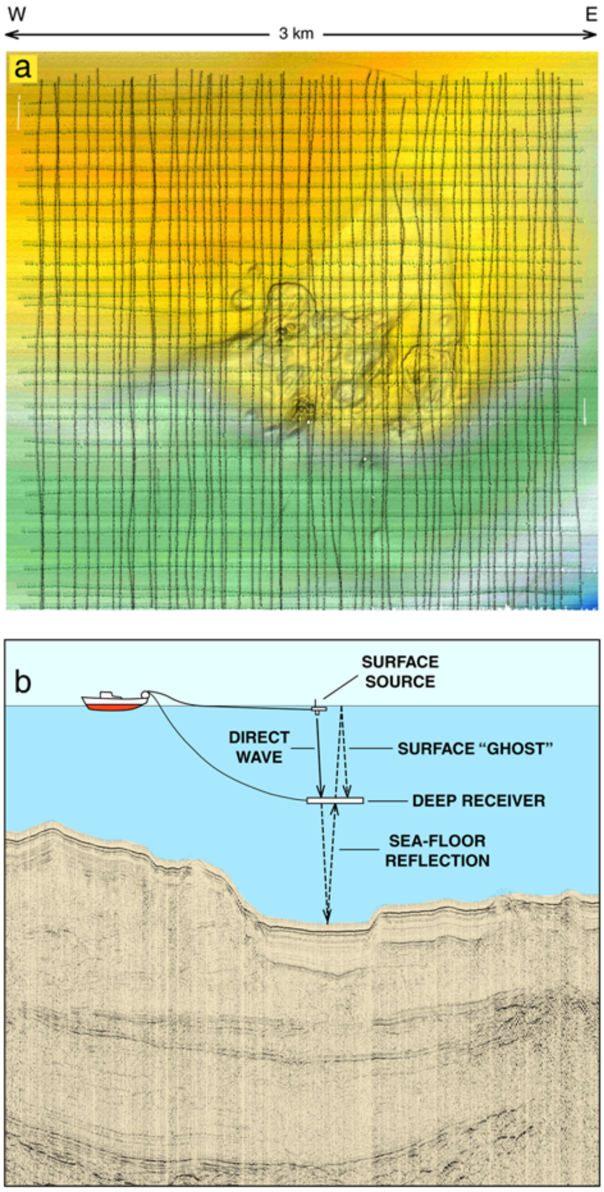


Figure 6 (a) Grid of seismic profiles acquired over the mound, (b) Illustration of SSDR recording geometry.

INTERNAL STRUCTURE OF THE MOUND

Figure 7 shows the locations of example SSDR profiles in figure 8a and figure 8b.

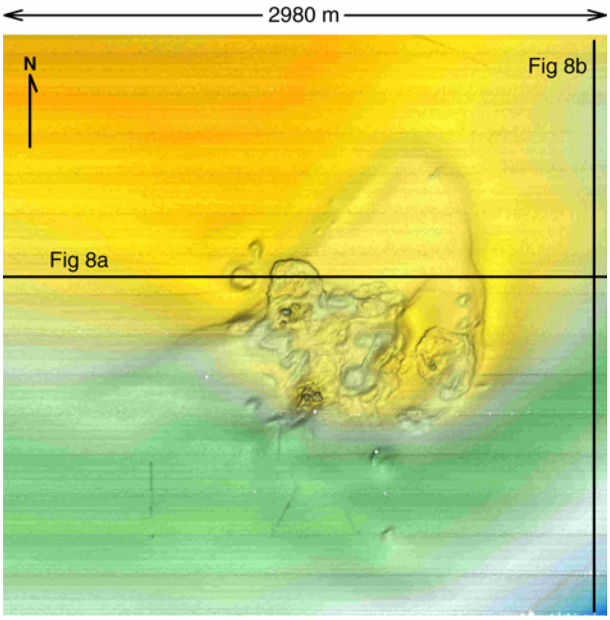


Figure 7 Location of profiles in figures 8a and 8b

Thermobaric modeling by one of us (Lapham) indicates that the upper 200m or so of the sub-bottom is within the gas hydrate stability zone. If so, the reflection in figure 8a marked "Gas?", occurs near the base of the hydrate stability zone (BHSZ), the question mark indicating that the interpretation is without ground truth. The "Gas?" reflection is of negative polarity, its reflection strength increases beneath local anticlines (figure 8a) and it appears on all profiles in the grid. Taken together, these considerations suggest that the "Gas?" reflection is generated by free gas trapped beneath the BHSZ.

The seismo-acoustic profiles show that several regions within the mound exhibit local reductions of coherent reflected seismic energy. Such regions are called "acoustic wipeout zones". They are interpreted to be the result of acoustic scattering by inhomogeneities such as zones of free gas and/or carbonate/hydrate blocks in the sediments. Strong wipeout zones are associated with all three of the principal crater complexes. Core samples collected within and outside of the wipeout zones in the NW and SW Complexes were tested for methane concentrations and microbial activity [9].

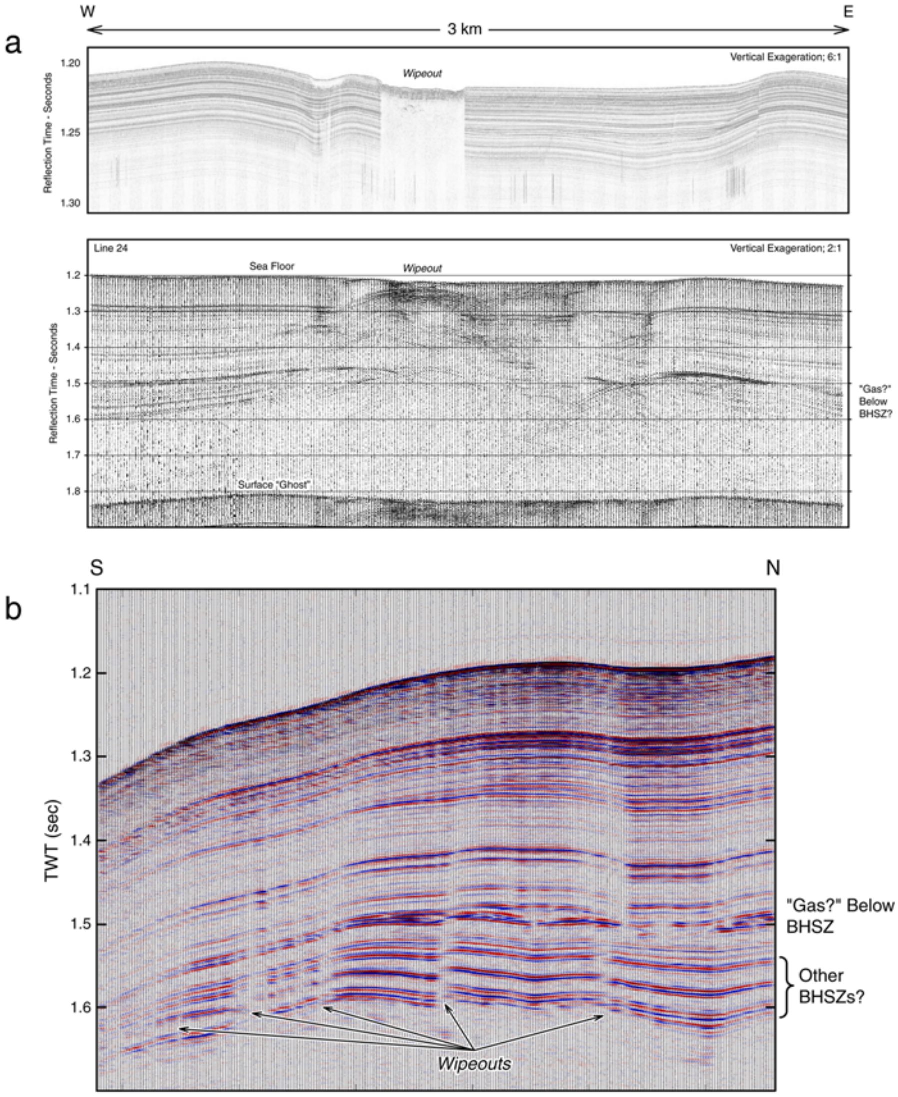


Figure 8 (a) Chirp-sonar and SSDR profiles showing a wipeout zone due to scattering from inhomogeneities,(b) SSDR profile showing near-vertical wipeout zones extending upward from faulted BHSZs.

It was found that microbial activity is concentrated within the wipeouts but is patchy, apparently being controlled by variations of upward hydrocarbon flux. The biogeochemical results provide evidence that the fluid flux varies over time and that the microbial activity responds to such variability. Images of the strong wipeout in the NW Complex are seen on the chirp-sonar and the SSDR profiles in figure 8a.

The "Gas?" reflection in figure 8b is on the same horizon as that in figure 8a. Figure 8b shows slender, nearly vertical wipeout zones that are similar in appearance to features observed in Cascadia and elsewhere. They are interpreted to be gas chimneys produced by vertical fluid flux through the BHSZ and modeling is cited to support that interpretation [10]. All of the wipeouts in figure 8b terminate in the shallow sub-bottom. On other SSDR profiles, some reach the sea floor and terminate at pockmarks.

The grid of SSDR profiles contains about 30,000 traces, each of which exhibits ten or more reflecting horizons. SSDR post processing allows normal-incidence P-wave reflection coefficients to be calculated for each horizon on each trace. Figure 9 is a 3-D image of the coefficients calculated for the sea floor and the "Gas?" horizon. Very weak coefficients are shown in the background color (white) to reduce speckling by low-amplitude noise. The magnitude of positive coefficients increases from green to blue and that of negative coefficients from yellow to red. Coefficients at the sea floor are mostly positive and those at the "Gas?" horizon are mostly negative.

Weak coefficients occur where little energy is reflected coherently. The two white regions on the sea floor in figure 9 mark the wipeout zones in the NW and SW Complexes. Perhaps the most striking feature of figure 9 is that the "Gas?" reflection is strongest in an annular zone around the white region that marks the diapir.

The 3-D image in figure 10 shows relative positions of the sea floor, the "Gas?" horizon and the surface of the diapir throughout the grid of SSDR profiles. It can be seen that the diapir pierces the "Gas?" horizon but does not reach the sea floor.

DISCUSSION AND COMMENTS

Microbial sulfate reduction, anaerobic methane oxidation, and methanogenesis have been found to be important processes in the upper four meters of sediment. These microbial processes seem to control the diffusive flux of methane from the sediments into the overlying water column. The activity of microbes is also focused within patches or "hot spots" near active vents. This activity is primarily dependent upon an active fluid flux of hydrocarbon-rich fluids. The geochemical evidence suggests that the fluid flux waxes and wanes over time and that the microbial activity is sensitive to such change. Based on 5m cores and box cores, it seems that vent activity in the past moved from the SE Complex to the SW Complex and now may be moving to the NW Complex. Longer cores would aid in refining or dismissing that scenario. An attempt will be made during the 2008 field season to recover 10m cores. In the more distant future, it may be possible to obtain 30m cores.

Thermobaric modeling based on measurements by a 5m temperature probe in the NW Complex indicates that the BHSZ occurs about 200m below the sea floor. If so, the strong reflection marked "Gas?" in figure 8a is located near the BHSZ. The "Gas?" reflection occurs on all profiles of the grid, is of negative polarity and its strength increases near local anticlines. These observations suggest that it be interpreted as free gas trapped beneath the BHSZ. Amplitude-versus-offset analysis of multi-offset data may be able to substantiate, or refute, that interpretation. A few profiles of industry-standard common-depth-point data have been obtained for the purpose of applying such analysis.

In figure 8b, some 700m east of the mound, the "Gas?" horizon occurs at about the same depth as in figure 8a. Sedimentary detail below the "Gas?" horizon is better resolved in figure 8b than in figure 8a. It is seen clearly that the near-vertical wipeout zones in figure 8b extend upward from fault offsets that cut across the "Gas?" horizon. It would be helpful if the size, shape and distribution of these wipeout zones would be determined. This could be done easiest by running closely spaced SSDR profiles with a hydrophone-equipped AUV. The most immediate reason for doing that would be to assess the accuracy of the AVO analysis. If the wipeouts are, indeed, gas chimneys, they are likely to consist of porous, sandy material containing gas at elevated pressure. If so, it would not be unreasonable to expect them to attenuate or scatter the long-offset signals associated with AVO analyses and thereby degrade its results.

The faults that cut across the "Gas?" horizon in figure 8b also cut deeper reflections, some of which are negative. It is theoretically possible that these are generated by free gas trapped beneath BHSZs of hydrates which are stable to depths greater than that of the "Gas?" BHSZ. The possibility could be tested by thermodynamically modeling the published chemical analysis [2] thermodynamically (Wenyue Xu, personal communication). An ability to correlate BHSZ model depths with particular SSDR reflections might indicate a method for mapping hydrates of different hydrocarbon gases.

It is noteworthy that no traditional bottom-simulating reflection (BSR) has been observed to cut across other reflections in MC118. The absence of a cross-cutting BSR has been discussed and it has been concluded that BSRs in low-frequency seismic data are produced by spatial averaging because the seismic resolution is too coarse to resolve sedimentary detail [10]. Thus the lack of a cross-cutting BSR in MC118 may be due to improved resolution provided by the SSDR technique.

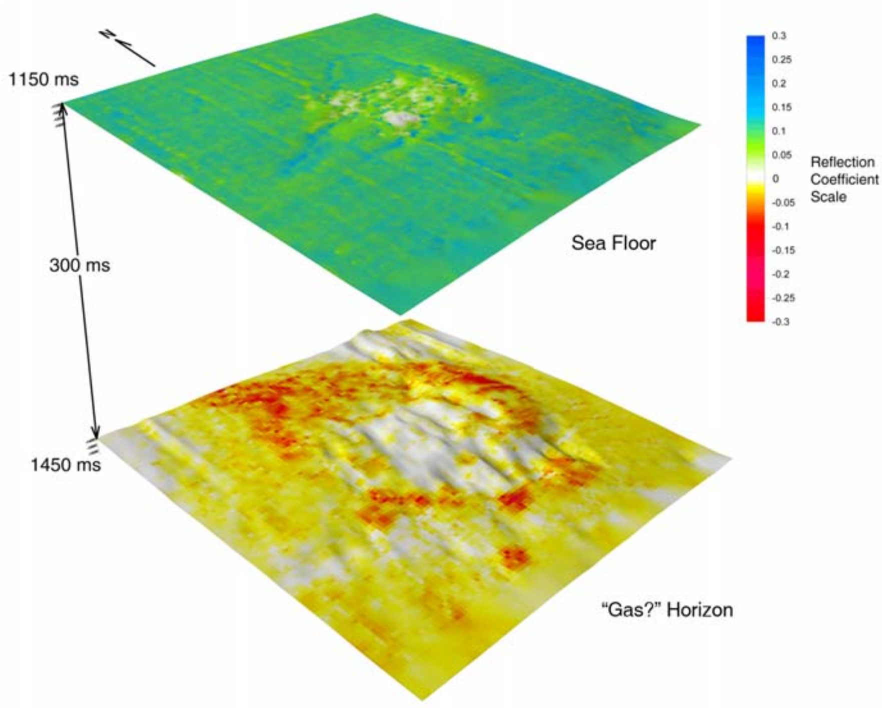


Figure 9 Normal-incidence P-wave reflection coefficients at the sea floor and the "Gas?" horizon.

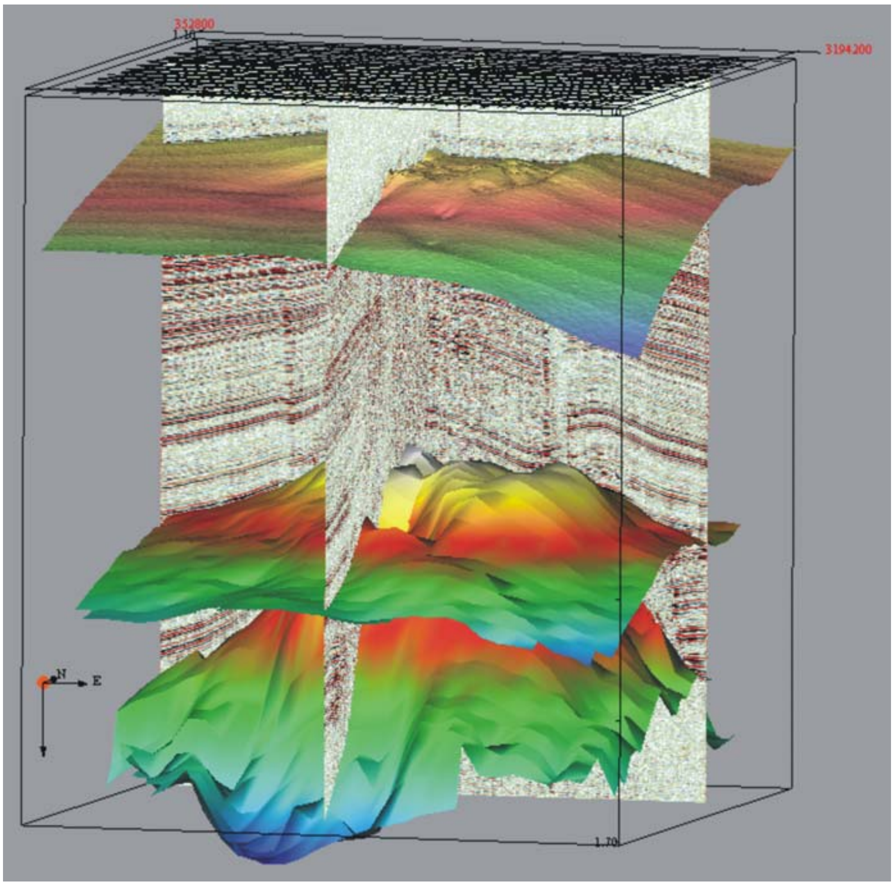


Figure 10 3-D image of the sea-floor, the "Gas?" horizon and the diapir. Note the diapir pierces the "Gas?" but not the sea floor.

ACKNOWLEDGMENTS

The observations and measurements reported here result from activities of many consortium members, not only the coauthors. The swath bathymetry and chirp sonar data were recorded by the AUV of C&C, Inc. Remote video was recorded by the Consortium's "Deep See" drift camera and the Consortium's ROV-SSD. Direct visual observations were made from the Johnson Sea Link manned submersible. Figures were prepared by Paul Mitchell.

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