**Mesoscale Biogeophysical Characterization of Woolsey Mound (Northern Gulf of Mexico), a
New Attribute of Natural Marine Hydrocarbon Seeps Architecture**

L. Macelloni^{*1, 2}, C.B. Lutken³, M. Ingrassia^{2, 4}, M. D'Emidio³, M. Pizzi⁵

1 NIUST (National Institute for Undersea Science and Technology), University of Mississippi,
University, MS, 38677 USA

2 CNR-IGAG (Istituto di Geologia Ambientale e Geoingegneria), UOS Roma, P.le A. Moro, 5,
00185, Rome, Italy

3 MMRI (Mississippi Mineral Resources Institute) University of Mississippi, University, MS,
38677 USA

4 Dipartimento di Scienze della Terra, Sapienza University of Rome, P.le A. Moro, 5, 00185,
Rome, Italy

5 Department of Earth Science and Engineering, Imperial College London South Kensington
Campus. London U.K.

* Corresponding author: Imacello@olemiss.edu (L. Macelloni)

Abstract

Located on the continental slope in 900m of water, Woolsey Mound dominates seafloor morphology at Mississippi Canyon 118. The carbonate-hydrate mound is the site of the Gulf of Mexico Hydrates Research Consortium's seafloor observatory to investigate and monitor hydrographic, geophysical, geological, geochemical and biological processes of the hydrocarbon system, northern Gulf of Mexico. Innovative survey and monitoring systems, sensors, and tools have been developed to extract samples and data to unravel the history, character and composition of the site. Many hours of visual data

have been collected to investigate benthic communities thriving at the cold seeps site associated with the mound. These communities' habitats are described here, for the first time, in terms of faunal assemblage, substrate nature, and presence/absence of chemosynthetic species. Based on these factors, we grouped them into four benthic meso-habitats. We speculate that the spatial distribution of these meso-habitats is large enough to make this characteristic comparable to the geophysical response of the seismo-acoustic systems. We have tested this hypothesis carefully analyzing the relationship between benthic habitats zonation and the geophysical response of Side Scan Sonar, Chirp Subbottom, Surface Source Deep Receive (SSDR) vertical incidence profiler and 3-D oil industry multichannel data.

We observe that the geophysical response is not unique, a single habitat may correlate with many geophysical attributes, or a single geophysical attribute span many habitats. However, we find that geophysical data can predict seep locations. They can also convey some information concerning community composition and complexity that function as proxies for seep duration/age while specific community components are believed to reflect composition of seep fluids.

Although preliminary, this approach represents a novel classification/characterization for seafloor hydrocarbon seeps, one that reflects an historical component.

Key words: biogeophysics, seafloor hydrocarbon seeps, seismic anomalies, mesoscale benthic fauna assemblage

1 Introduction

"Biogeophysics" is a novel discipline within the Earth sciences that addresses effects of biota and biological interactions with the geologic media on geophysical data signatures. In the last decade, "biogeophysics research" has included, primarily, investigations of microbes, microbial growth and microbes-mineral interactions with the geologic media (i.e. Abdel et al., 2004; Beaver et al., 2015; Revil

et al., 2012). These interactions are widely acknowledged to modify rock petrophysical properties and, therefore, their geophysical response (Atekwana and Slater, 2009 and references therein).

The prominent role played by microbes in modifying geological media in the deep sea, beyond the impact of photosynthetic organisms, makes deep-sea cold seeps an excellent natural laboratory for biogeophysical research (Atekwana and Slater, 2009). Here marine gas hydrates and/or seeping methane promote the growth of extensive microbial communities; however, traditional marine geophysical methods used in field surveys (mostly acoustic sonars and seismic profilers) present exceptional challenges for subsurface imaging of microbial processes, because changes in subsurface conditions affecting the geophysical response are very different at the field scale and can be used only as proxy of microbial activity (Lapham et al., 2008). It is possible to overcome this scale/dimension limitation if the geophysical signature correlates with additional "biological indicators".

In deep ocean cold seeps, microbial activity often engenders and sustains complex and laterally extensive benthic chemosynthetic communities. Deep-sea benthic fauna are found where cold seeps supply fluids from deep beneath the seafloor to the benthic zone (Fisher et al., 2007). These fluids, rich in methane and other hydrocarbons, and in concert with sulfate from the water column, undergo bacterial methane oxidation and sulfate reduction thereby providing nutrients – H_2S and CO_2 - to an otherwise nutrient-starved environment (Boetius et al., 2000). Spatial distribution of a benthic assemblage can reach dimensions of tens of meters making it comparable to the resolution of traditional field-scale geophysics imaging capabilities; biologists refer to this dimensional pattern as mesoscale habitat assemblage (Green et al., 1999). Together with microbial activity, these mesoscale benthic assemblages can provide a more compelling link between biological processes and geophysical signature.

In this study, we present the initial effort to integrate analyses of multiple resolution seismic and acoustic datasets with biological data from Woolsey Mound a cold seeps site on the Northern Gulf of Mexico lower continental slope. We attempt to establish qualitative relationships between geophysical signature - specifically seismo-acoustic amplitude anomalies - seafloor and shallow subsurface geology, and mesoscale faunal assemblages. The ultimate goal is to explore the possibility that geophysical signature can predict seafloor type, including biology, and therefore build a classification scheme of “biogeophysics attributes” Although preliminary and mostly qualitative; this work represents a novel approach for "classifying" seafloor hydrocarbon seeps.

"Biogeophysical characterization" - how biological processes connect with geophysical and geological characteristics - adds a new dimension to mound/cold seep analyses and represents an effort to integrate the poorly known interrelationships between the lithosphere, the hydrosphere and the biosphere of these extreme environments.

2 Background

The ancestral Mississippi River drained all of central North America during the melting of the Laurentide ice sheet, carrying a tremendous sediment load to the ancestral Gulf of Mexico (GOM) and the extreme edge of the continental shelf in ancient deltaic sediments (Lutken et al., 2006). The opening of the Mississippi Canyon, an erosional feature to the west of the present-day Mississippi River Delta, was initiated by slumping on the fore slope of that ancestral delta (Coleman and Prior, 1983). Since that time, sea level has risen but the Canyon remains geologically active with faulting, slumping, fluid expulsion and mud volcanism occurring along its flanks as well as along the ancestral shoreline - or present Continental Slope - now far out to sea. Typical of the northern GOM, the subsurface structure, sedimentation style and rates, thermal and fluid-flow patterns in the area are dominated by salt structures (Galloway et al., 2000; Martin, 1978).

At Mississippi Canyon Federal Lease Block 118 (MC 118, Figure 1), Sassen and Roberts (2004) documented a complex seafloor mound composed largely of calcium carbonate, distinguished by active seafloor venting, outcropping hydrate, and a thriving chemosynthetic community. This feature represents a distinct break in the otherwise even, seaward decent of the continental slope in this portion of the northern GOM. A 1km-diameter carbonate-gas hydrate complex in 900m of water, Woolsey Mound (USGS Geographic names Committee) now hosts the Gulf's only seafloor observatory/monitoring station (Lutken et al., 2011; McGee, 2006) in its only research reserve (Figure 1). Studies performed since MC118's designation as a Research Reserve in 2005 have been many and varied, resulting in a wealth of data from this unique site on the GOM Continental Slope.

Woolsey Mound comprises local bathymetric highs as well as lows. Crater complexes, mini-basins, pockmarks, ridges, scarps and plains contrast with the remainder of the block whose only other morphological feature, a submarine canyon, marks the faulted border of a prominent slump block (Figure 1). Sleeper et al. (2006) attempted the first morphological characterization of the mound, recognizing three main crater complexes each 5-60m in diameter and with bathymetric relief as high as 6m (Figure 2). Macelloni, et al. (2010) assigned geographic names to the complexes: the Northwest (NW) Crater, the Southwest (SW) Crater, and Southeast (SE) Crater (Figure 2). In addition, they map two other morphological units within the mound complex that exhibit bathymetric complexity but lack craters, the Northern Sector and the Middle Area. Pockmarks populate the seafloor in the vicinity of the Woolsey Mound (Figure 2).

The mound appears to have evolved in close association with the crestal fault system developed above and around a dome-shaped salt body that rises to about 400m beneath the seafloor (Figure 3, Knapp et al., 2010). Macelloni et al. (2012) describe as master faults those faults that can be traced from the salt body to the seafloor (Figure 3); each crater complex is associated with a master fault; the NW

complex with the blue and red faults, the SW complex with the magenta fault, and the SE complex with the yellow fault (Figure 3). Integrated analyses of multiple-resolution seismic datasets (Macelloni et al., 2012) support these conclusions: (1) the crestal faults developed episodically, in close association with sediment loading and salt movement, (2) the salt body is “rooted” into the deep portions of the adjoining basin to the northeast, to depths consistent with GOM hydrocarbon generation, (3) the latest quaternary section is characterized by intense small scale tectonic activity proving that the system has been tectonically active very recently, (4) shallow “bright spots,” which represent the ultimate “gas reservoirs” of the thermogenic system, occur in close spatial association with the master faults.

Through core analyses, Ingram et al. (2010) confirmed that the mound has remained tectonically active into recent times. They found that, sedimentation rates of the surrounding area ($>17.1\text{cm/ky}$), exceed those over the mound ($<8.6\text{cm/ky}$), over thousands of years by a factor of more than 2X and at some intervals, more than 5X. Their study supports the delivery of a vast sediment load to the vicinity in spite of very thin/no cover over parts of the mound complex. In addition, their biostratigraphic studies show reworking of fossil material, implying periodic expulsions of material from depth to the surface of the mound, a possible explanation for the very thin and inconsistent sediment cover over the Crater complexes and Middle Area. The migration of the area of sediment thinning to the north supports the shoreward migration of the seepfield/crater complex through time.

Sassen, et al. (2006) sampled the free gas venting at the seafloor and found that it contains C1-C5 hydrocarbons as well as CO_2 . The gas hydrate is structure II and relatively deficient in methane (70.0%). Significant ethane (7.5%) and propane (15.9%) distinguish the site from other hydrate sites in the northern Gulf; Wilson et al., (2014) found compatible composition of solid hydrate sampled from the seafloor expression of a master fault, confirming the thermogenic origin of the hydrocarbon fluids.

Analyses of biogeochemical cycling of carbon and sulfur of over 40 sediment cores corroborates a deep thermogenic gas signature but also shows a shallow, biogenically-altered component (Lapham et al., 2008). Results from pore-water gradients of sulfate and methane show patchy distribution of microbial activity that is typically higher within the main mound than outside it; hot spots of microbial activity correspond to intersections of faults with the seafloor and support the hypothesis that these act as migration conduits for thermogenic hydrocarbons (Macelloni et al., 2013; Wilson et al., 2014). Geochemical evidence also suggests that fluid flux varies among the fault zones, with the lowest flux at the southeast complex, moderate in the southwest complex and highest in the northwest complex (Lapham et al., 2008).

Simonetti et al. (2013) combined the results of seismic data interpretation and Jumbo Piston Core (JPC) analyses, to provide a conceptual model of hydrate accumulation at the mound's subsurface. They conclude that hydrates form primarily as veins and nodules in fractures in the vicinity of fault zones and/or as hydrates/carbonate chunks or slabs at the fault plane.

Complexity of the subsurface hydrocarbon plumbing system and differences in flux regimes along the faults are reflected in the bio-geological processes occurring at the mound's surface. Macelloni et al. (2013) inferred the fluid flux regime by documenting the spatial distribution of venting indicators such as authigenic carbonate, hydrates outcrops, chemosynthetic and other benthic communities, etc.; the presence of these features allowed characterization of the relative upward fluid flux, similar to that presented by Roberts (2001) and modified by Lapham et al. (2008). Briefly, the authors found that the SE complex is in a quiescent/inactive phase. The SW complex is a mature hydrate system, showing a steady flux regime while the NW complex is a young, active vent with vigorous episodic fluid outflow.

Recent high-resolution heat-flow investigations at each of the master faults (Macelloni et al., 2015) have confirmed that the differences in bio-geological processes at the mound's surface are due

mostly to differences in volumes of deep thermogenic fluids migrating through these conduits. In fact, the blue and red faults exhibit the highest heat-flow and the magenta fault a more moderate heat-flow. The yellow fault, which exhibits the lowest heat-flow, of mound sites appears to be either no longer functioning as a conduit for fluids, or greatly reduced in this function. Possibly fluid migration pathways have been sealed by the formation of solid hydrates within the formerly open pore-spaces and/or fractures.

At cold-seep sites such as that found at Woolsey Mound, deep-sea fauna are found where fluids from deep beneath the seafloor migrate from depth into the benthic zone providing nutrients – H_2S and CO_2 – sufficient to sustain benthic communities. Using the large collection of video surveys and photographs available to the Consortium, researchers are beginning characterize the observatory site in terms of benthic faunal types and their distributions, clearly dependent upon seeping of nutrient-rich fluids from depth. Together with the multiple sets of geophysical data we present an effort to merge seismic and acoustic data sets with the biology of cold seeps and the community succession at the sites.

3 Data

All data used in this study were collected for other purposes. Because the study was inspired during different phases of data evaluation by multiple researchers for a variety of projects, the methods of data acquisition are quite disparate. This introduces a considerable variation in data quality and resolution, as well as challenges in how to merge datasets. However, the composite of the datasets represents so much information that we strove to integrate the different sets in a manner that we feel is both useful and compelling.

3.1 Geophysical data:

Several seismo-acoustic datasets have been combined to implement this study and the complete geophysical data inventory with systems specifications is reported in Appendix A1.

We used a multiple-resolution approach (Figure 4a) that enabled us to relate deep structures to shallow processes and to “connect” the full range of cause and effect possibilities through a middle range by integrating analyses of multiple-resolution seismic datasets.

A critical component of the multiple resolution dataset approach is the inclusion of a seismic system that can image the hydrate stability zone, that depth too shallow to be imaged adequately by either the low frequency industry data or the high frequency shallow sub-bottom chirp profiling system. The surface-source/deep-receiver (SSDR) high resolution seismic data system was developed specifically to image this depth (Macelloni, 2005; McGee, 2000). In the northern GOM, where hydrates are stable at around 400-600mbsf (Milkov and Sassen, 2001), the SSDR fills this gap. Using these methods, we produced the integrated geophysical profiles for this study. Briefly, geophysical data used include:

- Autonomous Underwater Vehicle (AUV)-borne multibeam - provided the high resolution bathymetry (bin size 3m)
- Multibeam Echosounder (MBES) Backscatter - together with NR1 Side Scan Sonar (SSS) data were used to derive seafloor reflectivity (pixel resolution 20cm) and to map bottom sediment texture (hardgrounds, mud, sand, shell beds, etc.). The use of NR1 SSS data was done to push the resolution of backscatter data from 1m (the limit of the EM 2000 multibeam system installed on the AUV), to 20cm pixel resolution, achievable with high-frequency sonar aboard the NR1.
- Chirp profiler data, collected via AUV - used to decipher structure - sedimentary layering, seismic anomalies, faults - within the shallowest sediments (up to 50mbsf). Chirp profiles were collected along east-to-west direction lines spaced 200m apart, and can provide a vertical resolution of about 10cm.

- Surface-source-deep-receiver (SSDR) data – collected in a pseudo-3D grid (north-south lines spaced 50m, east-west lines spaced 100m apart). After appropriate signal processing (Macelloni, 2005), SSDR data can provide vertical resolution of about 1m.
- TGS high quality industry 3D multichannel seismic data - binned at 12.5m and cut at 3 seconds - used to interpret deep geology and structure beneath the mound and the mound's vicinity; provides vertical resolution at of about 20m.

3.2 Biological data:

The primary source of macro- and micro-benthic community data is visual images. More than 70 hours of photo-data, both video and still photography, have been collected from numerous cruises to the site. These include 2002 and 2006 dives of the Johnson SeaLink manned submersible, the Jason II unmanned submersible, Alvin manned submersible, the HOS Sweetwater Remotely Operated Vehicle (ROV), multiple dives of the GOM-HRC's Station Service Device ROV and DeepSee video camera. Biological data Inventory is reported in Appendix A2.

3.3 Geologic data:

Sediment cores have been collected from MC118 in several stages from 2005-2014 and include gravity cores (up to 7.5m penetration), jumbo piston cores (up to 18m penetration) and push-cores (up to 0.5m penetration) collected via ROV. Various purposes have been served in these collections but the cores provide some ground-truthing both for the shallow sections of the seismic data and for the backscatter data. Geological Data Inventory is reported in Appendix A3.

4 Methods

The methods employed to attempt to evaluate and possibly link seafloor biology to sub-seafloor geology are novel to this project. They derive from years of data-collection and observation of the

seafloor and sub-seafloor at the same research site, MC118. During a 2011 inventory and analyses of the faunal data from the mound, we began to notice some predictability in the associated geophysics. While we assumed that the faunal assemblages were dependent upon fluids seeping/venting from the sub-seafloor, we did not know of any work that had been done attempting to relate faunal types or abundances to particular seismo-acoustic signatures. We began our procedure by compiling and mapping, meticulously, the faunal lists for which we had accurate location information. As we plotted these locations on the geophysical maps and profiles, patterns began to emerge. In the process of documenting these patterns, we noted some predictability that we were able to translate from the geophysics to the biology. We believe the methods described herein can be used to locate seafloor seeps and anomalies using only visual data and without benefit of seismic data. We also anticipate the location of sites hosting benthic fauna using only geophysical records.

4.1 Geophysical Characterization.

Chemosynthetic communities and other deep-sea benthic assemblages are present at the seafloor and within the upper few meters of the sub-seabed where bacterial activity is focused. Therefore, the geophysical systems that best link the biology directly to geophysical character are the sonar imagery and the chirp subbottom profiler data that provide the optimal resolution for that specific zone. Per contra, our hypothesis is that the genesis and sustainability of the biological processes in this environment are dependent upon the availability of hydrocarbon fluids, the structure of the shallow hydraulic plumbing system (how the hydrocarbon fluids travel through the subsurface and reach the seafloor), and the rates and duration of venting emissions. Consequentially, we implemented the multiple resolution seismic data analysis (Figure 4a) to identify indicators of the presence of hydrocarbon fluids, and to track these fluids from where they appear to originate in the deep subsurface, up to the seafloor. TGS oil industry data (low resolution, maximum depth) were employed to locate deep

structures; we employed SSDR data (high resolution, medium depth) to image the shallow hydraulic plumbing system that connects the deep subsurface to the shallow subsurface. Finally, to understand how and where the fluid migration pathways reach the seafloor, intersect it and interact with the benthic life, we used the chirp data (very high resolution, only shallow depths, <50 mbsf) coupled with the seabed reflectivity (SSS and MBES). This approach enabled us to map faults and fractures and to individuate particular seismic amplitude anomalies widely recognized as indicators of gas/fluids in seismic records (Løseth et al., 2009). Those anomalies, summarized in Figure 4b, include:

- Discontinuity zone: reflections from stratigraphic layer(s) lose continuity with respect to adjacent areas.
- Seismic blanking: area with localized low or no amplitude;
- Acoustic wipe out: region without recorded reflection or a zone with very little internal contrast;
- Chaotic reflection zone: reflections assume a chaotic mélange compared to adjacent areas;
- Reversed Polarity bright spots: a local increase in negative amplitude on a seismic section, frequently associated with free gas accumulation.

We have mapped these features on oil industry, SSDR, and Chirp Sonar profiles that correspond most closely to areas of best-known faunal distribution, determined from the SSS and visual data. Emphasis was given to areas of known seabed reflectivity anomalies and ground-truthed samples.

4.2 Biological Characterization.

We first defined the biological processes at the seabed. We adopted the approach used in modern GIS-based benthic studies in which the habitat map is the result of the combination of the sediment types distribution map, the seafloor reflectivity map, and the faunal lists compiled from visual data (Brown et al., 2011). The list of fauna, with a brief description of their habitat/ecology, is reported in Appendix B, while the procedure adopted to build the final habitat map for this study is described in

Appendix C. Limitations to this project derive from two important differences in the data: 1) the intrinsic small-scale dimension of benthic biology compared to that of geophysical data (10s of cms compared to 10s of meters), and 2) the difference in spatial coverage of biological observations and geophysical data (the first much more sparse and incomplete, the second relatively uniform in coverage and spacing). We recognize 4 meso-habitats (Figure 5).

- I. Deep-sea mud - no fauna visible on visual records;
- II. Carbonate Debris - shells of dead organisms are abundant; sparse macrofauna and bacterial mat;
- III. Chemosynthetic Community – micro- and macro-fauna diverse and abundant;
- IV. Deep-Sea Coral and non-chemosynthetic macrofauna.

4.3 Building the "Biogeophysical Characterization"

Once we established the seafloor habitat zonation we analyzed the relationship of the biological pattern with the seismo-acoustic anomalies. To illustrate our approach, we selected four west-east transects (1-4 in Figure 5). All transects were chosen because they cross the complete spectrum of biological patterns and, together, they pass through all the mound's relevant morphological structures. Owing to differences in acquisition geometry, only the 3-D TGS dataset offered the option to select lines that passed within 12.5m of the areas of faunal interest contained in the visual data. Both chirp and SSDR data were collected in 2D forcing us to select lines that were closest to the areas of faunal interest. Therefore, we have selected the "best fits" for the locations when transferring them from the benthic habitat map to the seismic profiles. The resulting lines of maximum overlap of information are displayed in Figures 6, 7, 8, and 9. In these figures we tried to provide a complete synoptic representation of the geophysical response versus the habitat zonation. At the top of each figure is the plan view of a 100m-wide sonar mosaic strip, draped over the bathymetry and centered on each seismic line. Beneath this view are 3 profiles of the survey line, each representing equivalent lateral distance and showing the

geophysical response of a different system. From top to bottom they are: the chirp record, the SSDR record, and the TGS record. SSDR records image to greater depths than do chirp records. TGS records extend to even greater depth than SSDR. Therefore, we used the shallowest portions of these two datasets while preserving the same lateral extent for all records. We used the top 75m below sea floor (mbsf) for the SSDR and 150mbsf for the TGS oil industry records. Acknowledging that this might result in some distortion of the seismic records and in diminished image quality; we tried to use the optimum combination of lateral and vertical scales. Seafloor reflectivity is color-coded in low (yellow), medium (brown), and high (green/blue), while seismic amplitude polarity is displayed using the standard Landmark color scale (positive polarity in black, negative polarity in red). In the four lines, we located each meso-habitat as derived from biological data (Appendix C, Figure C5). We then undertook a detailed description of the seafloor properties (seabed morphology and reflectivity) and subsurface characteristics (intensity of reflectors, continuity/discontinuity of reflectors, faults, presence/absence of seismic anomalies) observed at each site. The goal of this effort was to answer the question “Are particular faunal assemblages linked to specific seafloor and subsurface conditions?” In other words, is each faunal assemblage determined by specific geophysical attributes? Further, can these attributes be used to predict seafloor biotypes/meso-habitats when faunal data are not available? We define these sites as "biogeophysics habitats". Subsequently, in order to infer the possible presence of faunal assemblage only from geophysical data, we reversed the process and selected sites with no surface information of fauna but whose geophysical signature “matched” that of the biogeophysics habitat. This exercise is offered as an example of the possible utility of the method, while we hope to test our hypotheses at the earliest opportunity to collect additional visual data.

Since the shallow subsurface of Woolsey Mound lies within the hydrates stability zone, we have tried to evaluate seismic records for possible presence of hydrates, an additional possible source of hydrocarbon nutrients to the deep-sea environment. The presence of hydrates adds an extra element of complexity to the system; free gas, migrating from greater depths might enter the stability zone, become bound in the hydrates structure, and become unable to vent to the surface. So the fate of hydrocarbons at this site and similar ones depends not only on the mechanism of gas migrating through the sediments (salt tectonics, slope stability, etc.) but also on the physical parameters governing the hydrates stability field (temperature, pressure, gas concentration). Due to the lack of any appropriate petrophysical data (p- and s- velocity, temperature, salinity, etc.) this interaction remains only speculative.

5 Results and discussion

5.1 Biogeophysics habitats: benthic habitat versus geophysical attributes

Biogeophysics Habitat I (I). Deep-sea mud covers much of the seafloor in the vicinity of Woolsey Mound. Visual data reveal no fauna at these sites. Surface reflectivity is low, seismic profiles reveal generally parallel to subparallel reflectors without seismic amplitude anomalies (Figure 4b, Figure 6, 7, 8, and 9). These characteristics describe most of the seafloor at MC118. Biogeophysics Habitat I characteristics can be summarized as:

Biology: none.

Seafloor morphology: flat.

Geology: mud (Type A).

Geophysical attributes:

Seafloor reflectivity (MBES, SSS): backscatter = low.

Chirp: Continuous seafloor reflector, continuous parallel or occasionally sub-parallel reflectors; occasional discontinuity zones with no other anomalies.

SSDR: Continuous seafloor reflector, continuous parallel or occasionally sub-parallel reflectors, no seismic anomalies.

TGS: Continuous seafloor reflector, continuous parallel or occasionally sub-parallel reflectors, no seismic anomalies.

A subset of Biogeophysics Habitat I comprises pockmarks (I-PM). Pockmarks are visible in the bathymetry map due to the depressed seafloor (Judd and Hovland, 2009). They are associated with fine-grained sediments and no seafloor fauna. They exhibit low backscatter reflectivity. However, all exhibit discontinuity zones - small faults/columns of acoustic wipe-out - some meters beneath the surface (Figures 6, 7 and 8). Some exhibit blanked signal immediately beneath the surface (Figure 6 and 7). We interpret the acoustic wipeout and blanking to represent gas in the shallow subsurface that has accessed the seafloor via small faults and fractures, and to be responsible for surface "blow-outs" that formed the pockmarks. Pockmarks occur in areas of low backscatter intensity or, less often, in areas of moderate backscatter intensity that occur within the mound complex. We believe that the absence of fauna at pockmark sites is attributable to gas expulsion here, violent enough to produce the depressions we see, and too sudden and/or sporadic to support seep communities at these sites (Roberts, 2001) though there are many we have not yet visited. We treat pockmarks as a subset of Biogeophysics Habitat I, distinguished mainly by the vertical anomalies in the chirp and SSDR data. These anomalies are so distinctive that we have noted some seafloor locations that exhibit the subseafloor anomalies as likely sites of future pockmarks. Biogeophysics Habitat I, Pockmarks sub-type can be summarized as:

Biology: none.

Seafloor morphology: negative/depressed.

Geology: mud (Type A).

Geophysical attributes:

Seafloor reflectivity (MBES, SSS): backscatter = low/medium.

Chirp: continuous parallel or occasionally sub-parallel reflectors; **all exhibit discontinuity zones**; most are associated with seismic blanking immediately beneath the seafloor.

SSDR: **all are associated with acoustic wipe-out** (narrow columns).

TGS: continuous parallel or occasionally sub-parallel reflectors.

Biogeophysics Habitat II (II). This habitat is largely distinguished by the carbonate debris that covers much of the Woolsey Mound. Living fauna are not abundant but include individual pogonophora, and occasional bacterial mat. Shell beds and pieces of coral, remains of once-living organisms, are found in abundance at some sites, in soft sediment on the periphery of the hardgrounds and from areas of moderate backscatter. These locations are often associated with a break in the surface reflector, underlain by seismic blanking in the chirp records, adjacent to a chaotic sequence in the SSDR records and adjacent to a reversed-polarity bright spot in the TGS data (Figure 7 and 8). This biogeophysics habitat is found at much of the Southeastern crater complex (Figure 4). Biogeophysics Habitat II attributes can be summarized as:

Biology: sparse living organisms; abundant shell debris.

Seafloor morphology: flat or undulating.

Geology: mud adjacent to/thinly covering authigenic carbonate (Type B/C).

Geophysical attributes:

Seafloor reflectivity (MBES, SSS): backscatter = intermediate.

Chirp: continuous parallel or sub-parallel reflectors adjacent to seismic blanking; near faults with surface expression.

SSDR: adjacent to chaotic reflection zone.

TGS: adjacent to reversed-polarity bright spot.

Biogeophysics Habitat III (III) is found where living chemosynthetic benthic fauna populate a mixed seabed consisting of authigenic carbonate crust and nodules as well as hemipelagic mud. Many of the best documented sites are located within the Southwest and Northwest crater complexes (Figure 7) but also along the horse-shoe shaped rim in the Northern Sector (Figure 6). Abundant gastropods hosting symbiotic bacteria, as well as symbiotic mussels and bivalves have been documented in this zone as have bacterial mat and occasional tubeworms (see Appendix B for a complete faunal list). Both CH₄ and H₂S consumers are found in this zone.

Seismic characteristics include high surface backscatter reflectivity, and a strong, distinct, seabed reflector, sometimes discontinuous due to the heterogeneity of the seafloor and proximity to faults. Distinct seismic blanking in chirp records occurs beneath all sites. All are underlain by a chaotic sequence in the SSDR data (Figures 6-9), associated with a break in the surface reflector, and columns of blanked signal farther beneath. The reversed polarity bright spot in the industry data (~20mbsf) is present beneath all locations identified as Biogeophysics Habitat III. Some Biogeophysics Habitat III exhibit other anomalies that may indicate maturity of the individual sites. We believe the distinct negative reflector in the industry data represents the presence of gas or fluids, the source of nutrition for the chemosynthetic communities.

Biogeophysics Habitat III attributes can be summarized as:

Biology: **abundant living organisms, many symbiotic**; chemosynthetic consumers of H₂S and CH₄.

Seafloor morphology: uneven.

Geology: authigenic carbonate rocks, crusts, shells; thin cover of hemipelagic mud (Type C/D).

Geophysical attributes:

Seafloor reflectivity (MBES. SSS): backscatter = high.

Chirp: **seismic blanking immediately beneath the seafloor at all sites.**

SSDR: **underlain immediately (<20m) by a chaotic reflection zone.**

TGS: **reversed-polarity bright spot ~20m beneath.**

Biogeophysics Habitat IV (IV) represents the sites of thriving colonies of the coral, *Madrepora oculata*. This coral is very abundant at Biogeophysics Habitat IV sites, indicating that chemosynthesis has advanced to the point that the chemicals toxic to deep sea corals have been significantly diminished. Otherwise, this coral could not persist. These locations exhibit high backscatter intensity and the seafloor is paved by thick authigenic carbonate slabs off the rim of the SW crater complex. The SSDR data show blanking and the chaotic sequence, adjacent to the immediate subsurface but the industry data show a bright spot in the shallow subsurface only off to the side, not immediately under the *Madrepora* sites. We hypothesize that though seepage continues at these sites, surface seep activity has migrated far enough from the hard grounds colonized by corals that the corals have been able to survive the detrimental effects of the fluids. Biogeophysics Habitat IV can be summarized as:

Biology: abundant living macroorganisms; **large colonies of *Madrepora* as well as other corals, crabs, and brittle stars.**

Seafloor morphology: uneven.

Geology: authigenic carbonate, crusts, nodules, shells (Type D).

Geophysical attributes:

Seafloor (MBES. SSS): backscatter =high.

Chirp: **seismic blanking immediately beneath the seafloor.**

SSDR: subsurface **adjacent to (<20m) a chaotic reflection zone.**

TGS: subsurface **adjacent to reversed-polarity bright spot ~20m beneath.**

5.2 What do the biogeophysics habitats tell us?

We have summarized the results of the geophysical characterization of the benthic habitats in Table 1. We did not find a one to one relationship between any particular geophysical anomaly/anomalies and a specific faunal assemblage. Each benthic habitat can have several geophysical characteristics that describe it, although some anomalies are associated with particular Biogeophysics Habitats and not others. Possibly, the differences in character and coverage of data – i.e. visual vs. acoustic or seismic, gridded vs. non-gridded, sparse vs. dense, etc. – account for this shortcoming. Denser data coverage would certainly help better define faunal assemblages over the mound and acoustic anomalies in the shallow subsurface. However, when considering the data summary in Table I, we are able to make some interesting qualitative conclusions:

1. Gas is present in very shallow reservoirs (about 20m below the seafloor). TGS data depict this anomaly better than the other methods examined. The gas seems to be trapped by a combined action of carbonate crust and hydrates formation, interpreted as the chaotic reflection zone in the SSDR data.
2. Complex benthic activity seems to develop only above these shallow gas anomalies; deep-sea corals and associated non-chemosynthetic macrofauna seem to thrive only on hardgrounds that are offset from the gas anomalies, while bacterial mats and chemosynthetic Mollusca and gastropods appear to prosper on top of the anomalies.

3. The only seismic anomalies we found off the mound, are narrow discontinuity zones and acoustic wipe-out at the seafloor immediately under pockmarks. These are not related to the shallow gas anomalies, but seem to originate at greater depth. No fauna are associated with these pockmarks.

5.3 From the Biogeophysics sites to cold seeps activity classifications

The spatial distribution of the Biogeophysics Habitats at the Woolsey Mound suggest a relationship with cold seep activity, as reflected in the biological and geophysical data, in terms of age and or emission fate. Although corresponding data are not abundant from the biological and geophysical sites, we do find interesting and repeated correspondence at many sites where fauna are clearly distinct. These sites are categorized in Section 4.2, and described, geophysically, in section 5.1. Here, we note the character of the Biogeophysics Habitats as they relate to the established evolution of cold-seeps. We recognize the following categories:

Pockmark/Deep-sea mud. Fauna: no visible macrofauna or bacterial mat on the seafloor, but very high bacterial activity in the shallow subsurface (>1.5m, Lapham et al., 2008). Surface backscatter is low; multibeam shows surface depression at pockmarks; sediment cover is fine-grained sediments. Subsurface data show clear pathways by which fluids may gain access to the seafloor and the water-column beyond. Evidence for gas appears in the profiles.

A seep community begins when chemical-rich fluids with high levels of sulfide and methane begin to seep out of the sediment and into the surrounding water. Generally, this means microbes; Archaea and bacteria are common pioneer species to these deep-sea environments. Although the deep-sea mud mesohabitat shows no signs of seepage, the pockmarks, with their disturbed zones in the shallow subsurface and seismic blanking just beneath the seafloor provide evidence that these locations have the potential to develop into earliest stage seep environment.

Early Stage Cold Seep: Fauna: bacterial mats are present; macrofauna, though not dense, are typical of early stage seep communities and may include any or all of the following: pogonophora, small gastropods and/or clams (with symbiotic bacteria). Surface backscatter is low to medium (shells are usually present); multibeam shows flat, sometimes undulating surface; sediments are soft, fine-grained. Subsurface shows a break in the surface reflector underlain by seismic blanking adjacent to a chaotic sequence. Bright spots in the industry data imply gas in the shallow subsurface sediments. The presence of abundant carbonate debris, including broken shell and coral, also indicates that the fauna of this meso-habitat was formerly more diverse and/or abundant but something happened to interrupt the supply of nutrients.

Pathways by which nutrient-rich fluids may access the seafloor are evident in the many small faults of the chirp data, found primarily at the periphery of and within the Woolsey Mound. The chaotic reflector, adjacent to the subsurface immediately beneath, may represent gas hydrates in the subsurface sediments. This possibility may provide additional nutrients if/when the hydrate dissociates and releases gas molecules into the plumbing system beneath the mound. It is also feasible that once-abundant nutrients are now either bound or blocked by hydrates in the shallow subsurface sediments.

Middle to Mature Stage-Hydrates. Fauna: bacterial mat with small gastropods and/or clams. More mature sites will have tubeworms as well as bacterial mats and chemosynthetic gastropods, mussels, and clams. Some sites exhibit outcropping hydrate that hosts abundant ice worm populations. Surface backscatter is high; multibeam shows a somewhat irregular seafloor. Fine-grained sediments will generally be covered with living organisms and the disarticulated shells of dead organisms. Higher backscatter is associated with authigenic carbonate and carbonate slabs, crusts, plates and nodules as well as outcropping gas hydrate. Symbiotic gastropods may indicate a brine seep (Van Gaest et al., 2007). The irregular seafloor (MBES), very high amplitude seafloor reflector is directly underlain by a

chaotic zone in the SSDR data and a very high amplitude negative reflector (industry data) that likely represents gas in the subsurface, 20mbsl. SSDR data show narrow but vertically persistent blanked sections beneath these sites. We believe that the high amplitude chaotic sequence beneath the seafloor may represent a mix of solid and fluids in the pore spaces. This chaotic zone generally appears adjacent to a master fault (Figure 2). The acoustic blanking or wipe-out zones may represent gas/open migration pathways through the sediments.

As a seep site transitions from early to middle and later stages, seep fluids decline in volume, even as uptake by secondary consumers that depend upon symbiotic bacteria decrease the toxicity of the habitat. Secondary consumers – those dependent upon the bacteria as a food source – increase. Production of authigenic carbonate by the colonies of microbes provides additional habitat for a greater variety of organisms, adding to the diversity and productivity of the site. Again, the seismic data provide evidence that hydrates and gas in the shallow subsurface are finding their way to the seafloor via faults, large and small.

Steady stage Biocoenosis of Corals. The deep-sea coral, *Madrepora oculata*, occurs in thickets, forming nursery for neritic fauna as well as for seafloor dwellers such as urchins and crabs. Other corals -*Paramuricea sp.* (usually with the symbiotic brittle star *Asteroschema ophiuroidis*) and, *Crysogorgia sp.*- are found nearby, often together with crabs and other crustaceans, urchins, bivalves and fish commonly found in association with corals. Seafloor backscatter is high; multibeam and sidescan show an irregular seafloor; sediment type is hardground, authigenic carbonate. Subsurface SSDR show a break in the surface reflector, a chaotic sequence beneath and columns of blanked signal farther beneath. Deep-sea corals, acknowledged indicators of habitat health, are present at MC118 on and around the crater complexes at Woolsey Mound. Thriving colonies of *Madrepora oculata* are located in the northwestern and southwestern and, possibly, in the eastern portions of Woolsey Mound. A Scleractinian

(hard) coral, also known as zigzag coral because of its growth habit, *Madrepora oculata* is found growing in colonies that form fan-shaped thickets 30-50cm in height. These coral colonies constitute a remarkable find at this site and indicate that seepage here began quite some time ago. *Madrepora* size can be used to estimate age of the colony, growth rates being ranging from 4-25 mm/year. With components of several meters, the *Madrepora* at Woolsey Mound tell us that the seepage at this site essentially stopped hundreds of years ago, and that this area has transitioned from a mature seep site to a non-chemosynthetic deep-coral habitat.

In sequence, progressing from the featureless seafloor toward the mound complex, meso-habitats become increasingly complex. Seismo-acoustic records portray an increase in subsurface complexity which appears to equate with accessibility of the seafloor to the deeper geologic sections. It is probably significant that the rare but large colonies of living corals have been found only where Biogeophysics Habitat IV occurs, i.e. not directly over or in communication with a shallow bright spot or open faults.

The evolution of the mound appears to have been from the east to the west and north and follows an apparent progression from simple to complex fauna and in the evolution of seep communities from none, through the early, middle and late stages of seep community and on through the biocenosis of a cold seep community, or mature deep-sea coral community.

5.3 Limitations and further research

The overarching goal of this study is to investigate the biological effect on seafloor and shallow subseafloor geological media and therefore on the geophysical signature. Alternatively, we wanted to investigate the possibility that the geophysical signature could provide indirect information of biological occurrences. To date we are not able to quantify the biological effect on the geophysical data; our study lacks supporting data to verify the mechanism which causes the alterations observed in the seismo-acoustic images as well as established petrophysical relations linking the geophysics to biological

alterations. Despite these weaknesses, this study does support a link between geophysical anomalies and biological assemblage, confirming that, in these extreme, deep-sea environments, geophysical data can be used as a proxy of biological hot-spots. Significantly, this study is the first, to our knowledge, that attempts to assess, for deep sea cold seeps, an "in situ biological effect" exploring not only microbial activity, but that of the benthic fauna. We observe, in fact, that epi- and in-faunal species, such as chemosynthetic mussels and gastropods, play a key role in biological activity.

The seismic multiple resolution approach is effective in illustrating how deep hydrocarbon structures are responsible for surficial biological hotspots; however, more detailed study is needed at the water-sediment interface. We believe that investigation at higher resolutions, including use of high frequency sound velocity probes, unconventional analysis of absorption of acoustic backscatter and chirp subbottom signals and, overall, high resolution electromagnetic surveys may provide more quantitative data supporting connections between biological processes and geophysical signatures. It would be particularly useful to have access to a high-resolution chirp sub-bottom profiling survey of the areas of known meso-habitats. With line spacing of 200m, the survey used in this study, has abundant room for seafloor information to be missed.

6 Conclusions

Mississippi Canyon 118 hosts a carbonate-hydrate mound complex, Woolsey Mound. The mound formed directly over a salt diapir from which crestal faults emanate. Some of these extend from the diapir to the seafloor while additional smaller faults derive from these larger ones and from continued mound movements. This fault network provides fluid migration pathways through the hydrate stability zone capable of delivering fluids, including hydrocarbons, from great depth to the seafloor. Surface and subsurface evidence support the existence of numerous hardgrounds in the complex. Seeps appear to be concentrated in the vicinity of the hardgrounds and support a variety of faunal communities.

These communities' habitats have been described here, for the first time, in terms of faunal assemblage, substrate nature, presence/absence of chemosynthetic species. Based on these factors, we grouped them into four benthic meso-habitats: deep-sea mud (including pockmarks), carbonate debris, chemosynthetic community, and deep-sea coral/non-chemosynthetic macrofauna.

We speculate that the spatial distribution of these meso-habitats is large enough to make this characteristic comparable to the geophysical response of the seismo-acoustic systems that are generally employed to explore the seafloor and the subsurface. We have tested this hypothesis carefully analyzing the relationship between benthic habitats zonation and the geophysical response of 4 major seismo-acoustic systems (Side Scan Sonar, Chirp Subbottom, SDDR, 3-D oil industry multichannel data).

We built a classification scheme of habitat zonation versus geophysical attributes. We defined this classification as "Biogeophysical characterization". The ultimate goal of this research is to explore the possibility that geophysical data infer/detect a particular faunal assemblage or, alternatively, that a particular faunal assemblage could generate a specific geophysical signature.

We observe that the geophysical response is not unique, a single habitat may correlate with many attributes, or a single attribute span many habitats. Per contra, our classification scheme offers interesting qualitative outcomes when geophysical attributes and benthic habitats are compared together with mound morphology and seabed geology. The most relevant of these outcomes suggest that the primary engine of biological activity is shallow gas trapped in the first 20m of the shallow subsurface (TGS Reversed Polarity Bright Spot). This gas resides in this shallow zone probably capped by a complex and still unknown mechanism of sealing effected jointly by buried carbonate and solid hydrates (SDDR Chaotic Reflection Zone). However, this seal leaks allowing the gas to reach the sediment-water interface and initiate the microbial activity that is focused in the upper 1.5m below the seafloor (Lapham et al, 2008). Faunal assemblage seems to respond to the local variation of this leaking process; where the

chirp data are able to image very small-scale fractures and faults (discontinuity zones) these serve as “capillary conduits” for the gas to reach the seafloor. We often observe the presence of chemosynthetic communities immediately over these leaky zones, while mature deep coral colonies seem to prefer the periphery of the shallow gas anomaly, where the direct delivery of gas is reduced.

The preliminary classification system proposed here derives from an effort to better understand how sub-seafloor physical and chemical conditions determine and/or alter seafloor surface conditions and communities. With additional site descriptions, chemical data and seismic data examinations, this system should improve. Our goal is to utilize this approach to expand our seafloor habitat mapping at MC118 and possibly to extend the practice to other locations in the Gulf and elsewhere.

Acknowledgments

The authors gratefully acknowledge the financial support of our U.S. federal sponsors: The Bureau of Ocean Energy Management (BOEM, Department of the Interior), The National Energy Technology Laboratory (NETL, Department of Energy) and the National Institute for Undersea Science and Technology (NIUST NOAA, Department of Commerce).

L. Macelloni is supported by Marie Curie Fellowship Co-funded by the European Union under FP7-People - Co-funding of Regional, National and International Programmes, GA n. 600407 and RITMARE Flagship.

Project Photos of the benthic fauna appear courtesy of Lophelia II 2010 Expedition, NOAA-OER/BOEM, Dr. Chuck Fisher, Pennsylvania State University, Chief Scientist whom we also gratefully recognize for the support given to M. Ingrassia.

We are thankful to TGS Nopec for providing the 3d seismic volume and to IHS for the educational license of Kingdom Suite software.

We are indebted to Paul Mitchell for his considerable technical expertise, to the MMRI shop-team Brian Noakes, Matt Lowe, Andy Gossett, Larry Overstreet and SDI team Paul Higley and Scott Sharpe for their creative and at-sea capabilities.

We found the input of the two anonymous reviewers to be extremely insightful. The final version of this paper has greatly benefitted from their suggestions.

Finally, we acknowledge the vision and inspiration of project and Consortium founder, the late J. Robert, “Bob,” Woolsey, MMRI geophysicist and SDDR innovator, the late Tom McGee, and former NIUST Director, the late Raymond Highsmith.

Appendix A

Appendix B

Appendix C

Figure Captions

Figure 1. Location of the study area. Mississippi Canyon Federal Lease Block 118 (MC 118) is located in the northern Gulf of Mexico (red star on the upper right panel) in about 900m water depth on the lower continental slope. This area is affected by the intense erosional activity of the Mississippi Canyon and is characterized by the typical morphology of domes and intraslope basins. The shaded relief bathymetric map (bottom right panel) displays the position of Woolsey Mound within MC118 and the boundary of the BOEM research reserve.

Figure 2. Orthographic 3d shaded relief view of the Woolsey Mound. The position of the light for the shaded effect is 135 degrees horizontally and 90 degrees vertically; seafloor topography is vertically exaggerated 10 times. Main morphological units are after Macelloni et al. (2012) and Sleeper et al. (2006).

Figure 3. Three dimensional reconstruction of Woolsey Mound subsurface (after Macelloni et al., 2012). Woolsey Mound is located directly above a salt dome, which tops at about 400mbsf. A complex network of normal crestal faults (red planes) radiates from the top of the salt; four master faults intersect the seabed: Red and Blue faults at the Northwest Crater, Magenta fault at the Southwest Crater, Yellow fault at the Southeast Crater. The footwall of each fault is indicated by line hachures.

Figure 4. Seismic multiple resolution approach. A) Three seismic datasets at different penetration and vertical resolution were evaluated for this study. The top profile was acquired using a chirp subbottom profiler of ~8kHz frequency and 10cm vertical resolution. The middle profile was acquired using a

shallow-source-deep- receiver system (SSDR) of ~1.5kHz frequency and 1m vertical resolution. The bottom profile was extracted from TGS industry 3D data of ~50Hz frequency and 20-30m vertical resolution. Note difference in scales and coverage highlighted by the boxed areas. B) Synoptical canvas of amplitude seismic anomalies. Seismic data were analyzed in terms of seismic amplitude anomalies (after Løseth et al., 2009) as possible indicators of fluids and/or gas in the subsurface.

Figure 5. Habitat map of Woolsey Mound derived by combining sediments distribution map backscatter imagery and faunal distributions (Appendix C). The base map is represented by the 3d bathymetric map as in figure 2, color-coded according to the sediments types A, B, C and D, which indicate respectively: deep sea mud, deep sea mud covered less than 50% by carbonate debris, deep sea mud covered more than 50% by carbonate debris, authigenic carbonate rocks and crust. The spatial distribution of four benthic meso-habitats is illustrated using polygons filled with different patterns, while the still pictures provide a visual example of the faunal assemblage for each meso-habitat. The black lines on the map display the position of the geophysical transects presented in Figures 6, 7, 8 and 9.

Figure 6. Synoptical representation of benthic habitats versus geophysical attributes. The composite cartoon displays the relationship between benthic faunal assemblage and geophysical data along transect 1 of Figure 5. At the very top is the plan view of a 100m-wide sonar mosaic strip, draped over the bathymetry and centered on the seismic line. Beneath this view are three seismic profiles, each representing equivalent lateral distance and showing the geophysical response of the three different systems. Seafloor reflectivity is color-coded in low (yellow), medium (brown), and high (green/blue), while seismic amplitude polarity is displayed using the standard Landmark color scale (positive polarity in black, negative polarity in red). Each meso-habitat (as derived from biological data presented in

Appendices B and C) is approximately located along the lines using the notation I, II, III, IV, while the seismic anomalies (Figure 4) are reported within the seismic profiles using the different symbols listed in the legend at the very bottom.

Figure 7. Synoptical representation of benthic habitats versus geophysical attributes. The composite cartoon displays the relationship between benthic faunal assemblage and geophysical data along transect 2 of Figure 5. At the very top is the plan view of a 100m-wide sonar mosaic strip, draped over the bathymetry and centered on the seismic line. Beneath this view are three seismic profiles, each representing equivalent lateral distance and showing the geophysical response of the three different systems. Seafloor reflectivity is color-coded in low (yellow), medium (brown), and high (green/blue), while seismic amplitude polarity is displayed using the standard Landmark color scale (positive polarity in black, negative polarity in red). Each meso-habitat (as derived from biological data presented in Appendices B and C) is approximately located along the lines using the notation I, II, III, IV, while the seismic anomalies (Figure 4) are reported within the seismic profiles using the different symbols listed in the legend at the very bottom.

Figure 8. Synoptical representation of benthic habitats versus geophysical attributes. The composite cartoon displays the relationship between benthic faunal assemblage and geophysical data along transect 3 of Figure 5. At the very top is the plan view of a 100m-wide sonar mosaic strip, draped over the bathymetry and centered on the seismic line. Beneath this view are three seismic profiles, each representing equivalent lateral distance and showing the geophysical response of the three different systems. Seafloor reflectivity is color-coded in low (yellow), medium (brown), and high (green/blue), while seismic amplitude polarity is displayed using the standard Landmark color scale (positive polarity

in black, negative polarity in red). Each meso-habitat (as derived from biological data presented in Appendices B and C) is approximately located along the lines using the notation I, II, III, IV, while the seismic anomalies (Figure 4) are reported within the seismic profiles using the different symbols listed in the legend at the very bottom.

Figure 9. Synoptical representation of benthic habitats versus geophysical attributes. The composite cartoon displays the relationship between benthic faunal assemblage and geophysical data along transect 4 of Figure 5. At the very top is the plan view of a 100m-wide sonar mosaic strip, draped over the bathymetry and centered on the seismic line. Beneath this view are three seismic profiles, each representing equivalent lateral distance and showing the geophysical response of the three different systems. Seafloor reflectivity is color-coded in low (yellow), medium (brown), and high (green/blue), while seismic amplitude polarity is displayed using the standard Landmark color scale (positive polarity in black, negative polarity in red). Each meso-habitat (as derived from biological data presented in Appendices B and C) is approximately located along the lines using the notation I, II, III, IV. Notation III with red border indicates chemosynthetic community, specifically ice worms (*Hesiocaeca methanicola*) and yellow bacterial mat, growing on exposed hydrates. Seismic anomalies (Figure 4) are reported within the seismic profiles using the different symbols listed in the legend at the very bottom.

References

- Abdel Aal, G. Z. A., Atekwana, E. A., and Slater, L. D., 2004. Effects of microbial processes on electrolytic and interfacial electrical properties of unconsolidated sediments. *Geophysical Research Letters*, 31, L12505, doi:10.1029/2004GL020030.
- Atekwana, E. A. and Slater, L. D., 2009. Biogeophysics: A new frontier in Earth science research, *Reviews of Geophysics*, 47, RG4004.
- Beaver, C. L., Williams, A. E., Atekwana, E. A., Mewafy, F. M., Aal, G. A., Slater, L. D., and Rossbach, S., 2015. Microbial communities associated with zones of elevated magnetic susceptibility in hydrocarbon-contaminated sediments. *Geomicrobiology Journal*, *in press*.
- Boetius, A., Ravensschlag, K., Schubert, C., Rickert, D., Widdel, F., Gieseke, A., Amann, R., Jørgensen, B.B., Witte, U., Pfannkuche, O., 2000. A marine microbial consortium apparently mediating anaerobic oxidation of methane. *Nature* 407, 623–626.
- Brown, C. J., Smith, S. J., Lawton, P., and Anderson, J. T., 2011. Benthic habitat mapping: A review of progress towards improved understanding of the spatial ecology of the seafloor using acoustic techniques. *Estuarine, Coastal and Shelf Science*, 92(3), 502-520.
- Coleman, J. M., and Prior, D. B., 1983. Deltaic influences on shelfedge instability processes. *SEPM special publication*, 33, 121-137.

Fisher, C., Roberts, H. H., Cordes, E. C., Bernard, B., 2007. Cold seeps and associated communities. *Oceanography*, 20(4), 118.

Galloway, W. E., Ganey-Curry, P. E., Li, X., and Buffler, R. T., 2000. Cenozoic depositional history of the Gulf of Mexico basin. *AAPG bulletin*, 84(11), 1743-1774.

Greene, H. G., Yoklavich, M. M., Starr, R. M., O'Connell, V. M., Wakefield, W. W., Sullivan, D. E., Cailliet, G. M., 1999. A classification scheme for deep seafloor habitats. *Oceanologica acta*, 22(6), 663-678.

Ingram, W. C., Meyers, S. R., Brunner, C. A., and Martens, C. S., 2010. Late Pleistocene–Holocene sedimentation surrounding an active seafloor gas-hydrate and cold-seep field on the Northern Gulf of Mexico Slope. *Marine Geology*, 278(1), 43-53.

Judd, A., and Hovland, M., 2009. Seabed fluid flow: the impact on geology, biology and the marine environment. Cambridge University Press.

Knapp, J. H., Knapp, C. C., Macelloni, L., Simonetti, A., Lutken, C. B., 2010. Subsurface structure and stratigraphy of a transient, fault-controlled thermogenic hydrate system at MC-118, Gulf of Mexico AAPG 2010 Annual Convention Oral Presentation, Abstracts Volume, p. 134.

Lapham, L. L., Chanton, J. P., Martens, C. S., Woolsey, J. R., 2008. Microbial activity in surficial sediments overlying acoustic wipe-out zones at a Gulf of Mexico cold seep. *Geochemistry. Geophysics. Geosystem.* 9, Q06001.

Løseth, H., Gading, M., and Wensaas, L., 2009. Hydrocarbon leakage interpreted on seismic data. *Marine and Petroleum Geology*, 26(7), 1304-1319.

Lutken, C. B., McGee, T. M., Lowrie, A., Brunner, C., Rogers, R., Macelloni, L., Bosman, A., Sleeper, K., Dearman, J., Woolsey, J. R., and Lynch, L., 2006. Comparison of two gas hydrates sites for seafloor monitoring, Transactions of the 56th Annual Meeting of the GCAGS, Lafayette, LA.

Lutken, C. B., Macelloni, L., Sleeper, K., D'Emidio, M., McGee, T., Simonetti, A., Knapp, J. H., Knapp, C.C., Caruso, S., Chanton, J. and Lapham, L., 2011. New discoveries at Woolsey Mound, MC118, northern Gulf of Mexico. Proceedings of the 7th International Conference on Gas Hydrates (ICGH 2011), Edinburgh, Scotland, United Kingdom, July 17-21, 2011.

Macelloni, L., 2005. La sismica ad alta risoluzione digitale a mare: vincoli teorici, elaborazione numerica e nuovi sviluppi (High-resolution marine digital seismic method: theoretical constraints, digital processing, new developments). Pp. 171, PhD Dissertation, La Sapienza University of Rome. Available at: PADIS - Pubblicazioni Aperte Digitali Interateneo Sapienza [PHD--2005-187] <http://padis.uniroma1.it/>

Macelloni, L., Caruso, S., Lapham, L., Lutken, C., Brunner, C. and Lowrie, A., 2010. Spatial distribution of seafloor biogeological and geochemical processes as proxy to evaluate fluid-flux regime and time evolution of a complex carbonate/hydrates mound, northern Gulf of Mexico: Gulf Coast Association of Geological Societies Transactions, v. 60, p. 461-480.

Macelloni, L., Simonetti, A., Knapp, J. H., Knapp, C. C., Lutken, C. B. and Lapham, L. L., 2012. Multiple resolution seismic imaging of a shallow hydrocarbon plumbing system, Woolsey Mound, northern Gulf of Mexico. *Marine and Petroleum Geology*, 38(1), 128-142.

Macelloni, L., Brunner, C. A., Caruso, S., Lutken, C. B., D'Emidio, M. and Lapham, L. L., 2013. Spatial distribution of seafloor bio-geological and geochemical processes as proxies of fluid flux regime and evolution of a carbonate/hydrates mound, northern Gulf of Mexico. *Deep Sea Research Part I*, 74, 25-38.

Macelloni, L., Lutken, C. B., Garg, S., Simonetti, A., D'Emidio, M., Wilson, R. M., Sleeper, K., Lapham, L., Lewis, T., Pizzi, M., Knapp, J., Knapp, C., Brooks, J., and McGee, T. M., 2015. Heat-flow regimes and the hydrate stability zone of a transient, thermogenic, fault-controlled hydrate system (Woolsey Mound northern Gulf of Mexico). *Marine and Petroleum Geology* 59 (2015) 491-504.

Martin, R. G., 1978. Northern and eastern Gulf of Mexico continental margin: stratigraphic and structural framework. *AAPG Studies in Geology*, v. 7, p. 21-48.

McGee, T. M., 2000. Pushing the limits of high-resolution in marine seismic profiling. *Journal of Environmental & Engineering Geophysics*, 5(4), 43-53.

McGee, T. M., 2006. A seafloor observatory to monitor gas hydrates in the Gulf of Mexico. *The Leading Edge*, 25(5), 644-647.

Milkov, A. V. and Sassen, R., 2001. Estimate of gas hydrate resource, northwestern Gulf of Mexico Continental Slope. *Marine Geology* 179, 71 – 83.

Revil, A., Atekwana, E., Zhang, C., Jardani, A., and Smith, S., 2012. A new model for the spectral induced polarization signature of bacterial growth in porous media. *Water Resources Research*, 48(9).

Roberts, H. H., 2001. Fluid and gas expulsion on the Northern Gulf of Mexico Continental Slope: mud-prone to mineral-prone responses. *Natural gas hydrates: occurrence, distribution, and detection*, 145-161.

Sassen, R., and Roberts, H. H., 2004. Site selection and characterization of vent gas, gas hydrate, and associated sediments. *Final Technical Progress Report of the Gulf of Mexico Seafloor Stability and Gas Hydrate Monitoring Station Project*, 28-227.

(Available at: <http://www.osti.gov/bridge/purl.cover.jsp?purl=/838881-59VaGw/native/>).

Sassen, R., Roberts, H. H., Jung, W., Lutken, C. B., DeFreitas, D. A., Sweet, S. T. and Guinasso, N. L., 2006. The Mississippi Canyon 118 gas hydrate site: a complex natural system, OTC 18132, Offshore Technology Conference, May 2006.

Simonetti, A., Knapp, J. H., Sleeper, K., Lutken, C. B., Macelloni, L., and Knapp, C. C., 2013. Spatial distribution of gas hydrates from high-resolution seismic and core data, Woolsey Mound, Northern Gulf of Mexico. *Marine and Petroleum Geology*, 44, 21-33.

Sleeper, K., Lowrie, A., Bosman, A., Macelloni, L. and Swann, C. T., 2006. Bathymetric mapping and high resolution seismic profiling by AUV in MC118 (Gulf of Mexico). OTC 18133, 2006 Offshore Technology Conference, Houston, Texas, U.S.A., 1–4 May 2006.

Van Gaest, A. L., Young, C. M., Young, J. J., Helms, A. R., & Arellano, S. M., 2007. Physiological and behavioral responses of *Bathynnerita naticoidea* (Gastropoda: Neritidae) and *Methanoaricia dendrobranchiata* (Polychaeta: Orbiniidae) to hypersaline conditions at a brine pool cold seep. *Marine Ecology*, 28(1), 199-207.

Wilson, R. M., Macelloni, L., Simonetti, A., Lapham, L., Lutken, C., Sleeper, K., D'Emidio, M., Pizzi, M., Knapp, J., Chanton, J., 2014. Subsurface methane sources and migration pathways within a gas hydrate mound system, Gulf of Mexico. *Geochemistry Geophysics Geosystem*. 15, 89–107.

Seismic Multiple Resolution Data

A

Seismic Amplitude Anomalies

Discontinuity Zone:
reflections from
stratigraphic layer(s)
lose continuity with
respect to adjacent
areas

Seismic Blanking:
Area with localized
low or no amplitude

Acoustic Wipe-out:
region without
recorded reflection
or a zone with very
little internal contrast

**Chaotic Reflection
Zone:**
reflections assume
a chaotic mélange
compared to adjacent
areas

**Reversed Polarity
Bright Spots:**
a local increase
in negative amplitude
on a seismic section
which is mostly
associated
with free gas
accumulation

B

W ← ~ 1800 m → E

W ← ~ 1800 m → E

W ← ~ 1800 m → E

W ← ~ 1800 m → E

	Benthic Habitats				
	I	I-PM	II	III	IV
Seabed topography	(=)	(-)	(=)	(+/-)	(+/-)
Seabed sediments	Type A	Type A	Type B/C	Type C/D	Type D
Backscatter	L	L/M	M/H	H	H
Faulting	0	(*)	adj	(?)	(?)
Blanking	0	(*)	0	(*)	(*)
Discontinuity Zone	0	(*)	0	0	0
Chaotic Reflection Zone	0	0	adj	(*)	adj
Wipe-out	0	(*)	0	0	0
Reversed Polarity Bright Spot	0	0	adj	(*)	adj

Table I Biogeophysics Habitats Synopsis:

Seabed topography (=) is flat, (-) is negative, (+) is positive

Seabed sediments: designation per Appendix C: A=mud, B=carbonate debris covers <50% of the seafloor, C=carbonate debris covers >50% of the seafloor, D=authigenic carbonate rocks and slab

Backscatter: L=low, M=moderate, H=high

Geophysical attributes 0 = none; (*) present; adj present but adjacent; (?) not determined