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SPATIAL AND TEMPORAL CHARACTERIZATION OF A COLD SEEP-HYDRATE SYSTEM (WOOLSEY MOUND, DEEP-WATER GULF OF MEXICO)

by

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DEDICATION

To my parents Federico Simonetti and Maria Di Salvatore, my brother Cristian Simonetti, and my girlfriend Silvia Berardini for their support, encouragement and love throughout this marvelous and challenging journey overseas.
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family, my girlfriend, all my friends in the United States and in Italy, thank you with all of my heart for making this experience so special.
ABSTRACT

Cold seeps are areas where methane is transferred from the lithosphere into the hydrosphere, accounting for the major source of hydrocarbons in seawaters. Formation of gas hydrate in cold seeps modulates the global discharge of methane to the environment. However, cold seeps are dynamic settings where hydrates dissociate on short and long time-scales triggering substantial methane fluxes to the oceans. These methane vents sustain unique ecosystems at the ocean floors and contribute to ocean acidification. Also, the methane can potentially reach the sea surface and be exchanged with the atmosphere contributing to global warming. Understanding how cold seep-hydrate systems (CSHSs) operate through time and space is therefore crucial to evaluate their global impact on ocean biogeochemistry and climate.

The area investigated is Woolsey Mound, a CSHS located in the Northern Gulf of Mexico.

For the first part of the research, the goal was to determine the spatial distribution of subsurface gas hydrate at this site. In terms of hydrate-reservoir category, Woolsey Mound is classified as “seafloor mound” and “fractured mud”. To date, these two categories are poorly constrained worldwide. This study documents a successful integration of high-resolution seismic and core data to detect the spatial distribution of hydrates in such settings. The approach adopted and the model may be applied globally for these reservoir categories.
The aim of the second part was to untangle the contentious long-term (thousands to millions of years) dynamics driving methane hydrate dissociation and seepage in CSHSs. Analyses on high-resolution seismic data suggest that tectonics is the main forcing mechanism and that CSHSs may operate independently from eustatic fluctuations. This contradicts the broad consensus in the literature about methane seepage in CSHSs being systematically triggered during sea-level lowstand.

The third part of the research aimed to characterize the short-term (years) dynamics of Woolsey Mound via time-lapse seismic monitoring. Quantitative 4-D seismic analysis through amplitude differencing of two sets of 3-D data suggests that CSHSs may release considerable volumes of methane on a 3-year time-scale. Also, short-term methane hydrate destabilization and seepage appear to be triggered primarily by transient migration of overpressure thermogenic methane through the system.
PREFACE

Woolsey Mound has been designated by the Bureau of Ocean Energy Management (BOEM) as a Research Reserve in the Gulf of Mexico and the site of a permanent seafloor observatory. My research is part of the collaborative effort that the Gulf of Mexico Hydrate Research Consortium (GoM-HRC) has been dedicating since 1999, aiming to understand the dynamics of this complex cold seep-hydrate system.

The material covered in the second Chapter has been published in the Journal of Marine and Petroleum Geology with the following reference:


The content of the third Chapter has been submitted for publication to Earth and Planetary Science Letters and it is currently under review with the following reference:


The fourth Chapter will be submitted for publication prior to the end of 2013 to the Journal of Geophysical Research with the following title:

*Detecting the Short-Term Dynamics of a Cold Seep-Hydrate System via 4-D Seismic Imaging.*
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<tr>
<td>AUV</td>
<td>Autonomous Underwater Vehicle</td>
</tr>
<tr>
<td>BHSZ</td>
<td>Base of Hydrate Stability Zone</td>
</tr>
<tr>
<td>B.P.</td>
<td>Before Present</td>
</tr>
<tr>
<td>b.s.f.</td>
<td>Below Sea Floor</td>
</tr>
<tr>
<td>BSR</td>
<td>Bottom Simulating Reflector</td>
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<tr>
<td>BSS</td>
<td>Below Sea Surface</td>
</tr>
<tr>
<td>CSHS</td>
<td>Cold Seep-Hydrate System</td>
</tr>
<tr>
<td>DHI</td>
<td>Direct Hydrocarbon Indicator</td>
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<tr>
<td>EMD</td>
<td>Empirical Mode Decomposition</td>
</tr>
<tr>
<td>GHSF</td>
<td>Gas Hydrate Stability Field</td>
</tr>
<tr>
<td>HFS</td>
<td>High-Frequency Scattering</td>
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<tr>
<td>HSZ</td>
<td>Hydrate Stability Zone</td>
</tr>
<tr>
<td>IR</td>
<td>Infra-Red</td>
</tr>
<tr>
<td>JPC</td>
<td>Jumbo Piston Core</td>
</tr>
<tr>
<td>kyr</td>
<td>Thousand Years</td>
</tr>
<tr>
<td>MDAC</td>
<td>Methane-Derived Authigenic Carbonate</td>
</tr>
<tr>
<td>ROV</td>
<td>Remotely Operated Vehicle</td>
</tr>
<tr>
<td>SKS</td>
<td>Syn-Kinematic Sequence</td>
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<tr>
<td>SSDR</td>
<td>Surface Source-Deep Receiver</td>
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<tr>
<td>TWTT</td>
<td>Two-Way Travel Time</td>
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CHAPTER 1

INTRODUCTION

1.1 GAS HYDRATES AND SOCIETY

Gas hydrate, or clathrate hydrate (Sloan and Koh, 2008), is an ice-like crystalline substance formed by a mixture of water and light hydrocarbon gases, generally methane. Gas hydrates occur in oceanic sediments at water depths generally greater than 300 m and in permafrost regions (i.e. high pressure and low temperature settings). The hydrate stability zone (HSZ) is a subsurface area where hydrates can be stable and it is primarily a function of temperature, pressure, hydrocarbon availability/composition, and pore-fluid salinity. Each volume of subsurface hydrate can contain as much as ~160 volumes of gas at standard temperature and pressure (STP) (Sloan and Koh, 2008).

During the last forty years there has been a growing consensus on the idea that natural gas hydrates constitute the largest reservoir of methane on Earth, even though quantitative assessments seem to fluctuate within few orders of magnitude (Buffett and Archer, 2004; Collett et al., 2008b; Klauda and Sandler, 2005; Kvenvolden, 1988; Kvenvolden and Rogers, 2005; MacDonald, 1990; Milkov, 2004; Trofimuk, 1977). Should conventional natural gas resources keep dwindling and technologies continue to improve, gas hydrates may represent a valid future unconventional resource (Riedel et al., 2010a). Despite uncertainties in the long term commercial value, preliminary results from methane hydrate production tests conducted in the past (Dallimore and Collett, 2005;
Dallimore et al., 2008a; Dallimore et al., 2008b) and more recently (Hunter et al., 2011; Yamamoto 2013) are encouraging.

From an environmental perspective, methane is ~20 times more potent than carbon dioxide as a greenhouse gas (Ruppel 2011). Given the size of the global hydrates reservoir, large quantities of methane might be liberated in the environment by widespread destabilization of gas hydrate trapped in ocean and arctic sediments, thus contributing to global warming as a positive feedback (Ruppel 2011). Past widespread dissociation events, inferred mainly from negative δ^{13}C excursions in the stratigraphic record, have been documented around the world. They have been proposed to have:

- driven the termination of the Marinoan snowball ice age ~635 million years (Ma) ago (Kennedy et al. 2008);
- caused the Early-Toarcian Oceanic Anoxic Event in the Jurassic ~183Ma ago (Hesselbo et al. 2000);
- caused the Paleocene-Eocene Thermal Maximum (PETM) ~55Ma ago (Dickens 1995; Gu et al., 2011);
- caused rapid acidification of the oceans during the Paleocene-Eocene Thermal Maximum (PETM) (Zachos et al. 2005);
- influenced the Quaternary climate cycles (Kennett et al. 2003);
- limited the extent of Quaternary glaciations (Paull et al. 1991).

Finally, massive gas hydrate dissociations may trigger large-scale seafloor instability processes (Rothwell et al., 2003) and represent both a naturally-occurring and industrial geohazard (Boswell et al., 2012).
1.2 The Role of Cold Seep-Hydrate Systems in the Environment

Cold seeps transfer methane via faults from the lithosphere into the hydrosphere (Leifer and Boles 2005) and they account for the major source of thermogenic hydrocarbons in seawaters (Fig. 1.1) (NAS 2002). Transitory formation of hydrate in deep-water environments modulates the potential discharge of significant volumes of methane to the oceans. However, cold seeps are extremely dynamic settings where gas hydrates dissociate on both short (Bangs et al., 2011; Crutchley et al., 2013) and long (Teichert et al., 2003; Watanabe et al., 2008; Feng et al., 2010; Tong et al., 2013) time scales triggering substantial methane venting. These methane vents sustain rare chemosynthetic ecosystems at the ocean floors (Fisher et al., 2007) and contribute to ocean acidification (Dickens et al., 1995). Also, the methane released can potentially reach the sea surface, be exchanged with the atmosphere and contribute to global warming (Leifer and MacDonald 2003; Solomon et al., 2009). Therefore, understanding the mechanisms regulating the long-term fluxes of methane from cold seep-hydrate systems (CSHSs) is crucial to evaluate their past, present and future global impact on ocean biogeochemistry and climate.

Figure 1.1 Petroleum in marine waters. Average annual contribution (1990-1999) from major sources of petroleum in kilotonnes (NAS, 2002).
CHAPTER 2

SPATIAL CHARACTERIZATION

2.1 SEISMIC EXPLORATION OF GAS HYDRATES

Exhaustive volume estimates of gas hydrate resources have been carried out worldwide using primarily seismic data, either qualitatively or quantitatively. Numerous qualitative assessments to date have often been based upon the presence/absence of a bottom simulating reflector (BSR) as a valid seismic indicator for gas hydrates occurrence (Shipley et al., 1979; Paull et al., 2000; Takahashi and Tsuji, 2005).

However, gas hydrates have been shown to occur without an underlying BSR and vice-versa (Paull et al., 2000; Tréhu et al., 2004; Riedel et al., 2006; Collett et al., 2008). Therefore, a BSR cannot be used as a standalone predictor for gas hydrates occurrence (Kleinberg, 2006). If gas hydrate saturation in sediments is significant, quantitative estimates in terms of concentrations can be inferred from seismic data through the study of elastic properties (Dai et al., 2004, 2008; Riedel et al., 2009; Spence et al., 2010). On the other hand, if gas hydrates occur in lower and heterogeneous concentrations or in places where seismic data may be masked by the presence of massive hydrate/carbonate mounds at the seafloor, they will not be as easy to detect (Riedel et al., 2010a, b).

2.2 CHALLENGES IN DEEP-WATER SETTINGS

In-place methane hydrate resource assessments have been evaluated for many of the reservoir categories of the “gas hydrates resources pyramid” (Fig. 2.1) (Boswell and
Collett, 2006). Yet, two classes of hydrate-bearing sediment in deep waters are still poorly understood and therefore difficult to assess: fractured muds and seafloor mounds (Fig. 2.1).

Figure 2.1 Gas hydrates resource pyramid. The units are in trillion cubic feet (Tcf) of gas-in-place (Modified after Boswell and Collett, 2006).

The main technical issues related to the spatial characterization of these challenging gas hydrate systems stem from the general lack of seismic data capable of
imaging them in sufficient detail. The occurrence of gas hydrates in such restricted geometries (i.e. fractures, veins, etc.), requires optimal seismic resolution in order to provide an interpretable image.

Unfortunately, as pointed out by Riedel et al. (2010a,b), most gas hydrate assessments to date have been based entirely on 3-D seismic data that were acquired to explore deeper hydrocarbon targets, so the collection of these data was not optimal for imaging the much shallower gas hydrates deposits. Also, conventional high resolution methods are not powerful enough to image in detail the HSZ in deep waters. Optimal imaging of gas hydrates requires a seismic technique which provides hundreds of meters of sub-seafloor penetration while maintaining sub-meter resolution of layer thickness (McGee et al., 2009). Wood et al. (2008) and Macelloni et al. (2012) have demonstrated the benefit of integrating unconventional high resolution seismic data with conventional 3-D seismic reflection data to image in detail the subsurface of deepwater gas hydrate complexes.

In this study the subsurface of Woolsey Mound (deep-water Gulf of Mexico) has been investigated using primarily high-resolution unconventional surface-source deep-receiver (SSDR) data. The acquisition geometry, frequency, sample rate and optimal digital signal processing of the SSDR were designed to image at a sub-meter scale the HSZ in complex deep water settings (McGee, 2000). A coring cruise at this site was designed to calibrate our seismic models and five 20 m-long jumbo piston cores were retrieved from the subsurface of Woolsey Mound. On-board infra-red camera surveys, followed by opening of selected core sections, confirmed the presence of gas hydrates only in core JPC-1. This core was specifically collected to ground-truth a high-frequency
scattering anomaly noted on the SSDR data. Gas hydrates occurred as massive lenses in large fractures and vein-filling in small fractures, in fine-grained sediments. This study documents that the high-frequency scattering anomalies present on the SSDR data may be a seismic signature for heterogeneous hydrate accumulations in fracture porosity. Hence, the SSDR data may be an optimal exploration tool to detect the spatial distribution of gas hydrates in hostile deep-water settings (i.e. fractured muds and hydrate mounds – Fig. 2.1).

2.3 CASE STUDY: WOOLSEY MOUND

Woolsey Mound is a CSHS located in the Mississippi Canyon lease block 118 (MC118), Northern Gulf of Mexico (Fig. 2.2).

Figure 2.2 Geographic location of Woolsey Mound. Woolsey Mound is located at about 900 m water depth in the Northern Gulf of Mexico, within the Mississippi Canyon Lease Block 118 (MC118). Original data from NOAA (courtesy of Marco D’Emidio, MMRI – University of Mississippi).
Craters (Fig. 2.3), pockmarks, gas hydrate outcrops, authigenic carbonates, hydrocarbon vents, and thriving chemosynthetic communities are present at the seafloor (Sassen and Roberts, 2004; Sassen et al., 2006; Sleeper et al., 2006; McGee, 2006; Lapham et al., 2008; McGee et al., 2009; Lutken et al., 2011; Macelloni et al., 2013).

Figure 2.3 Geological baseline of MC118, seafloor cold seep elements at Woolsey Mound, coring sites and seismic transect locations. a) Three-dimensional perspective view of the subsurface at MC118 depicts the salt dome and the master faults through which thermogenic hydrocarbons (arrows) migrate towards the surface; b) AUV-multibeam seafloor reflectivity map of Woolsey Mound showing the coring sites and the location of the seismic transect used in this study. Prominent hydrocarbon seepage elements occur where the master faults intersect the seafloor: the south-east (SE) crater complex lies above the yellow fault; the south-west (SW) crater complex is related to the magenta fault, while the north-west (NW) complex is associated with the blue and red master faults. Red reflectivity colors indicate authigenic carbonate outcrops at the SW and NW craters and a large clam bed at the SE crater. (*Modified after* Macelloni et al., 2012).
Geochemical analyses of gas hydrate samples outcropping on the seabed have revealed a predominantly thermogenic signature for the gases encaged (primarily structure II clathrate – Sassen et al., 2006). This suggests that hydrocarbons are delivered to the seafloor from a deep petroleum system. All the aforementioned cold seep elements are spatially associated with major faults that intersect the seafloor (Fig. 2.3). These master faults are related to deep-seated salt tectonism, and they have been interpreted as primary hydrocarbon migration pathways from deeper reservoirs (Knapp et al., 2010; Macelloni et al., 2012). In support of this hypothesis, fluid-flow footprints (i.e. wipeout zones sensu Løseth et al., 2009) have also been found to follow the trend of the master faults on seismic data (Macelloni et al., 2012).

A thermo-baric model proposed by Lapham et al. (2008), suggests that gas hydrates in the vicinity of Woolsey Mound could be stable in the subsurface down to a depth of 185 m below the seafloor (b.s.f.) (Fig. 2.4). However, Macelloni et al. (2012) using conventional 3-D seismic data suggest that the base of the hydrate stability zone (BHSZ) is shallower. Their observation was based on the presence of discontinuous strong negative amplitude anomalies at about 150 m b.s.f. interpreted to be free gas. These anomalies are referred to as the discontinuous BSR widely documented in the Gulf of Mexico deep waters (Shedd et al., 2011).

2.4 DATA AND METHODOLOGY

2.4.1 HIGH-RESOLUTION SEISMO-ACOUSTIC SURVEYS

The seismo-acoustic data used in this study are:
Figure 2.4 Thermo-baric model and hydrates stability zone. Theoretical hydrates stability zone (HSZ) at Woolsey Mound calculated using thermogenic gas composition 70% methane, 8% ethane, 16% propane, and 6% n-butane from Sassen et al. (2006) and the thermo-baric model from Sloan (1998). A geothermal gradient of $17.2 \ ^\circ C/km$ was derived from borehole data available at an Arco Well (located 2 km northwest of Woolsey Mound); pore-fluid salinity values refer to seafloor measurements ($\sim 35$ g/L) and assume a constant salinity gradient influenced by a shallow cap-rock. However, as higher advection of heat and salinity can be expected along the master faults, the HSZ may locally shift further upwards throughout the Mound. (Modified after Lapham, 2008).

1) Unconventional SSDR single-channel seismic (McGee, 2000). These data consist of 96 lines organized in a pseudo 3-D grid spaced at 50 m (north-south) $\times$ 100 m (east-west). The dominant frequency of the SSDR is 1.5 kHz. The data were originally recorded at 125 kHz and subsequently down-sampled to 5 kHz in order to manipulate them with conventional seismic interpretation
software. “Oversampling” (McGee, 2000) and optimal filtering of the data in the time domain via Empirical Mode Decomposition (EMD) (Battista et al., 2007; Macelloni et al., 2011) resulted in a vertical resolution of less than 0.1 m near the seafloor and about 0.6 m more than 300 m b.s.f. (McGee, 2000) and a faithful preservation of the frequency content;

2) Autonomous Underwater Vehicle (AUV)-borne chirp sub-bottom profiler data (Sleeper et al., 2006; Macelloni et al., 2012). These data provide 50 m of sub-bottom penetration with about 0.1 m of vertical resolution (except underneath seafloor carbonate hard-grounds where most of the energy is reflected back).

### 2.4.2 JUMBO PISTON CORING (JPC) RESEARCH CRUISE

In January 2011, five jumbo piston cores were collected across the mound from the Research Vessel Brooks McCall. The primary goal of the jumbo piston coring cruise was to acquire deeper (20 m b.s.f.) geological, geophysical and geochemical information about the gas hydrate system at Woolsey Mound. In order to avoid potential damaging of the coring device, sampling locations had to be restricted in areas removed from carbonate crusts and hardgrounds (indicated by high multi-beam seafloor reflectivity anomalies in Fig. 2.3b). However, since two coring targets (JPC-1 and JPC-6) were adjacent to moderate seafloor reflectivity anomalies, the piston corer length was reduced from 20 m to 17 m to prevent damaging and allow recovering of cores from these targets. For each JPC, the elapsed time between the piston corer reaching the seabed and being recovered on board was about 30 minutes. Once retrieved on board, cores were sectioned (1 m sections) and tops were photographed and sampled for geochemical analyses.
Subsequently, cores were closed and scanned for temperature anomalies using infrared imagery to identify the sections with the greatest potential of gas hydrates occurrence.

2.4.3 Infra-red Imagery

Infra-red (IR) thermal imaging of sediment cores allows for on-site identification of gas hydrates to facilitate sampling and as a proxy for quantification of gas hydrate abundance (Long et al., 2010). In this study, as the cores needed to be preserved for subsequent logging at the Navy Research Laboratory (Stennis Research Facility, Mississippi) the core sections were not opened unless “cold spots” indicating possible hydrate occurrence were detected. Infrared thermography was conducted with a FLIR SC305 uncooled, 320 × 240, microbolometer, laboratory grade camera. Each thermal image is built from over 76,000 individual picture elements that are sampled by the camera’s on-board electronics and software to measure temperature over a range from -20 °C to +20 °C with 0.01 °C sensitivity and 2% accuracy. A small sled with a camera stand was constructed to move the camera down the length of each core. The camera height was positioned for a 15 cm field of view and the camera was advanced down the core, by hand, at a rate of approximately one frame every 5 cm. A National Instruments Lab View controller and servo-driven track system has been developed for more accurate tracking and data acquisition but was not available in time for this cruise.

2.5 Coring Rationale

Despite the wide documentation of gas hydrate outcrops at the seafloor (Sassen and Roberts, 2004; Sassen et al., 2006; Lapham et al., 2008; McGee et al., 2009; Lutken et al., 2011; Macelloni et al., 2013), all previous direct observations of the subsurface at Woolsey Mound were limited to less than 10 m b.s.f. and little or no hydrates were found.
Therefore, important gaps on the nature of the subsea gas hydrate system remained to be addressed. The following conceptual model was used to design the coring cruise and test our hypothesis:

1) there are no shallow coarse-grained sediments in the upper 20 m. The upper 10 m of the subsurface are dominated by hemipelagic mud (Ingram et al., 2010) and the seismic stratigraphy down to 20 m b.s.f. appeared to be comparable with the upper 10 m;

2) Gas hydrates outcropping at the seafloor are predominantly of thermogenic origin (Sassen et al., 2006);

3) Thermogenic gases are delivered to the shallow gas hydrate system via the master faults (Knapp et al., 2010; Macelloni et al., 2012).

The coring cruise aimed to substantiate the hypothesis that, in absence of coarse-grained sediments in the shallow subsurface, gas hydrates can only form and accumulate significantly in fracture porosity along the fault segments intersected by transit of thermogenic gas.

2.5.1 CORE JPC-1

JPC-1 (17 m recovery) is located on the edge of the northwest crater proximal to the blue fault (Fig. 2.3b), one of the active structures of Woolsey Mound through which thermogenic gases are delivered into the gas hydrate system (Knapp et al., 2010; Macelloni et al., 2012). The core site was selected to ground-truth an anomalous seismic pattern detected on the SSDR data (Fig. 2.5) referred as the high-frequency scattering anomaly (Macelloni et al., 2011). The high-frequency scattering (HFS) consists of a
Figure 2.5 Cores JPC-1 and JPC-3. Core JPC-1 meant to ground-truth the high-frequency scattering anomaly (HFS) interpreted as gas hydrate (GH) accumulation. JPC-3 was chosen as a background site removed from the blue fault and the HFS; also, JPC-3 intended to reach the base of a relatively young growth sequence (highlighted in yellow) to provide an age constraint for past tectonic activity along the blue fault.

chaotic short-period amplitude brightening of the seismic trace (Fig. 2.6a). The spatial distribution of the HFS can be better visualized through the instantaneous amplitude seismic attribute (Fig. 2.6b). The instantaneous amplitude or “amplitude envelope” (Taner et al., 1979) defines the reflection strength along the seismic pulse and it is critical
Figure 2.6 Wiggle trace and amplitude envelope displays related to cores JPC-1 and JPC-3.  

a) A SSDR close-up of Figure 2.5 in wiggle trace display shows the nature of the high-frequency scattering (HFS); b) a coincident transect imaged through the amplitude envelope seismic attribute showing the distribution of the HFS to be confined to an area immediately adjacent to the blue fault (shown here in white for display purposes). The amplitude envelope defines the reflection strength and it emphasizes changes in acoustic impedance contrasts. The acoustic impedance changes of the HFS are interpreted to be produced by discontinuous gas hydrate (GH) occurrence along the blue master fault.
in identifying changes in acoustic impedance. Such changes correlate with the HFS and are clearly visible in a halo shape around the blue fault (Fig. 2.6b). This anomaly was hypothesized to be produced by the occurrence of gas hydrate.

2.5.2 CORE JPC-3

JPC-3 (20 m recovery) is located 300 m northward of JPC-1 (Fig. 2.3b). The core served as the background control site for sediments and pore fluids removed from the influence of the blue fault and the HFS (Figs. 2.5 and 2.6a, b).

2.5.3 CORE JPC-6

The JPC-6 (17 m recovery) core is located ~100 m to the southeast of the surface projection of the magenta fault (Fig. 2.3b) and intended to calibrate an acoustic wipeout anomaly detected on the CHIRP data (Fig. 2.7a). The wipeout anomaly was interpreted as a gas chimney along a synthetic fault of the magenta fault which likely represents an integral element of the main plumbing system. Hence, JPC-6 served to characterize the pore-fluid along the magenta fault, though indirectly. Also, there is no indication of the HFS for this site based on the SSDR data (Fig. 2.7b).

2.5.4 CORE JPC-7

The target of core JPC-7 (20 m recovery) was a seafloor pockmark associated with the northernmost tip of the yellow fault (Fig. 2.3b), which represents a third major route for rising thermogenic hydrocarbons (Knapp et al., 2010; Macelloni et al., 2012). The pockmark overlies a polarity-reversed negative amplitude bright spot referred to as a discontinuous BSR which indicates free gas beneath the BHSZ (Fig. 2.8). The pockmark was interpreted to be the result of recent fluid-flow episodes (Macelloni et al., 2012). Since pockmarks are generally produced by violent fluid and gas escape into the water
Figure 2.7 Core JPC-6. Core JPC-6 meant to calibrate an acoustic wipeout anomaly on the CHIRP data a) interpreted as a gas chimney proximal to the magenta fault and southwest crater (the acoustic wipeout underlying the southwest crater may also be produced by the lack of penetration due to authigenic carbonate crusts at the seafloor); b) a coinciding SSDR profile denoting the absence of high-frequency scattering (HFS) at this coring location.
column (Hovland and Judd, 1988; Løseth et al., 2001), Macelloni et al. (2012) speculated that the intermittent sealing mechanism for the underlying free gas could be represented by transitory gas hydrate formation along the yellow fault. The HFS is absent in this site.

Figure 2.8 Core JPC-7. East-west SSDR profile showing the location of JPC-7. The coring target was a minor seafloor pockmark proximal to the yellow fault and overlying a polarity-reversed negative amplitude bright spot referred to a discontinuous bottom simulating reflector (BSR) indicating the base of the hydrate stability zone (BHSZ). The high-frequency scattering anomaly (HFS) is absent for this site, whereas a negative amplitude bright spot that may represent a minor free gas accumulation occurs near the bottom of the core.

2.5.5 CORE JPC-2

JPC-2 (20 m recovery) was collected ~80 m to the northwest of the surface trace of the magenta fault (Fig. 2.3b). This coring location was chosen based on an up-lifted succession on the footwall of an antithetic fault of the magenta fault (Fig. 2.9a) with the
aim to obtain the oldest stratigraphic constraint with a 20 m core. The seismic expression of the sampled subsurface in this coring site does not show any particular anomaly that could be ascribed to the presence of either gas hydrate or free gas (Fig. 2.9a, b).

Figure 2.9 Core JPC-2. a) JPC-2 was chosen based on an up-lifted succession on the footwall of an antithetic fault of the magenta fault identified on the CHIRP data, with the aim of obtaining the oldest possible local stratigraphic constraint with a 20 m long core; b) a coinciding SSDR profile denotes the absence of the high-frequency scattering (HFS) for this coring site.
2.6 Coring Results

Once JPC-1 was retrieved on board, gas leakage from the piston corer (causing a distinct petroleum odor) was noticed by both the crew and the science party. Due to gas expansion, several meters of sediments were extruded from the top of the core. Also, minute grains of gas hydrate were noticed at the bottom of the core in the core catcher. Larger fracture-filling chunks and massive nodules of solid hydrate were identified from 3m above the bottom of the core down to the base during the core sectioning (Fig. 2.10a, b). While IR scans of the shallower sections did not reveal any thermal anomalies, the mean temperature of the three deepest sections of JPC-1 ranged from 14 to 15 °C. In spite of the longest residence time on-deck due to the science party’s attempts to sample the solid hydrate they contained, these sections exhibited the coldest temperatures of all sections recovered during the cruise (Fig. 2.10c). IR imaging of the bottom sections of JPC-1 allowed the identification of numerous “cold spots” anomalies whose temperature was on the order of 2-3 °C lower than the background (Fig. 2.10d). These sections also coincide with the HFS (Fig. 2.6b). In order to calibrate the IR anomalies and verify whether or not the cold spots were reflecting the occurrence of gas hydrate, this core section was split in half. Gas hydrates were found in fracture-filling nodules, chunks and blades in dark grey hemipelagic sediments (Fig. 2.10e).

On the other hand, gas hydrate was not retrieved in JPC-3, which consisted of a monotonous succession of undisturbed dark grey fine-grained sediments from the top to the bottom. Also, the mean temperature of the whole JPC-3 detected through IR surveys was about 19-20 °C and no cold spots were detected.
Figure 2.10 Infra-red imaging and coring results for JPC-1. a) fracture-filling gas hydrate chunk and b) a gas hydrate layer 2 × 10 cm cored near the bottom of JPC-1 recovered during the core sectioning; c) infra-red (IR) thermo-graphic profile related to the 1 m-long bottom section of JPC-1; d) IR scan of a segment of the bottommost section denoting prominent cold spot anomalies 2-3 °C colder than the core background; e) the same core segment was opened to calibrate the cold spot anomalies and it revealed gas hydrate occurring in fracture porosity within hemipelagic mud. Note: Since the core section was rotated during the core opening, the orientation of the picture does not reflect the polarity of the IR scan.
JPC-6 retrieved fine grained hemipelagic sediments as well. The core texture was slightly disturbed, though not as chaotic as in JPC-1. No hydrates were encountered during the sectioning and no cold spots were detected through IR scan (the mean temperatures throughout the core ranged around 19 °C). However, some “hot spots” anomalies about 3 °C warmer than the background were found from the middle towards the bottom of JPC-6 (Fig. 2.11a, b), indicating possible voids created by gas expansion. In fact, the core was extremely gassy and sediment extrusion caused by gas expansion occurred both during the core sectioning and several hours after all the sections were stored in the laboratory on-board (Fig. 2.11c).

JPC-7 consisted of an undisturbed succession of dark grey hemipelagic sediments throughout the core. Gas hydrates were not encountered during core sectioning and the IR surveys did not reveal any thermal anomalies. During the core sectioning, a core liner blow-out produced a 6 × 4 cm crack, though it is not clear whether the episode can be ascribed to the presence of gas or a preexisting fissure or weakness along the core liner.

Lastly, JPC-2 was characterized by a repetitive succession of fine-grained sediments and by the absence of both gas hydrate and free gas throughout the core. The coring results revealed the nature of the shallow gas hydrate system to be dominated by fracture porosity in fine-grained sediments.

The univocal correlation between gas hydrate and HFS suggests that this anomaly may be indicative of hydrate occurrence within fracture porosity. The acoustic blanking on the CHIRP data instead seems to correlate well with the presence of free gas within the theoretical HSZ, as confirmed with the recovery of JPC-6. Finally, the absence of gas hydrate in JPC-7 has demonstrated once again that a BSR may not be a reliable
A standalone predictor for gas hydrates occurrence. A BSR anomaly could simply be produced by a small percentage of underlying free gas without implying necessarily the presence of gas hydrate above it (Kleinberg, 2006).

Figure 2.11 Infra-red imaging and coring results for JPC-6. a) Infra-red (IR) scan of a middle section of JPC-6 showing a hot spot anomaly ascribable to the presence of a void created by gas expansion and b) thermo-graphic profile related to the same 1 m long section showing the spike in temperature; c) core extrusion due to gas expansion feature, indicative of the high gas content found in JPC-6.
2.7 DISCUSSION

2.7.1 SPATIAL DISTRIBUTION OF GAS HYDRATES DETECTED FROM THE SSDR DATA

The HFS may resemble high-frequency noise. However, it does not occur consistently throughout the SSDR dataset. Also, the instrumental contributions of high-frequency noise were selectively removed with the EMD technique (Macelloni et al., 2011). Based on the results from core JPC-1, it is proposed that the HFS may indicate heterogeneous accumulations of gas hydrate within fractured fine-grained sediments. Such occurrence would contradict several previous studies in which gas hydrate-bearing sediments have been associated with a reduction of the acoustic impedance or “amplitude blanking” on seismic data (Lee and Dillon, 2001; Dvorkin and Uden, 2004). However, this dissimilarity may be in part due to the significantly higher dominant frequency of the SSDR data compared to the frequencies used in other studies, and partly to different lithology and hydrate saturation values. Macelloni et al. (2011) successfully calibrated the HFS with the recovery of solid hydrates in a gravity core suggesting that there may be a causal relationship in addition to a correlation between the two. Although there is not a robust acoustic model to confirm this evidence, the cause-effect relationship between gas hydrate occurrence and the HFS is supported by the following empirical observations:

1) The exclusive occurrence of gas hydrates at the base of JPC-1 consistent with the HFS and the absence of hydrates in the other four cores where the scattering anomaly is absent;

2) The HFS is spatially associated with the master faults (thermogenic gas conduits) whereas it appears to be absent in areas removed from them (Fig. 2.12). Such observation is consistent with our hypothesis that if shallow
coarse-grained sediments are absent thermogenic gas hydrate would likely accumulate in fracture porosity proximal to the master faults. This hypothesis was tested and corroborated with cores JPC-1 and JPC-3. Woolsey Mound is primarily a thermogenic gas hydrate system and the shallow subsurface must be in hydraulic connection with deeper hydrocarbon sources to guarantee the availability of gas required to form gas hydrates. Such a hydraulic continuity is predominantly provided by the master faults. Figure 2.12a shows a polarity-reversal negative amplitude bright spot indicating a potential antiformal gas trap at ~200 m b.s.f., where the reservoir is represented by permeable turbidite deposits sealed by low permeability hemipelagic mud (Macelloni et al., 2012). In absence of faults that connect this hydrocarbon source to the shallow subsurface, the upward migration of thermogenic gas into the HSZ is very unlikely. As a result, even though the thermo-baric field in the upper sedimentary column may be favorable, the lack of thermogenic gas precludes hydrates formation. Therefore, it is speculated that the absence of the HFS in the overlying uniform stratigraphy reflects the absence of gas hydrates. An opposite scenario is depicted in Figure 2.12b, where the HFS surrounds the blue and magenta faults. Here the bright spot indicating the source of thermogenic gas of the same stratigraphic horizon as in Figure 2.12a is missing, suggesting that gas might have migrated upwards into the HSZ. In fact, major hydrocarbon leakage features occur at the seafloor in close association with the blue and magenta master faults (Fig. 2.3b). Also, gas migration footprints along the faults (i.e. gas chimneys) are interpretable on
seismic data (Fig. 2.12b). This strongly suggests that in this area the master faults provide the hydraulic continuity for thermogenic gas to migrate towards the shallow HSZ, where gas hydrate can form and accumulate unlike the case in Figure 2.12a. Hence, the occurrence of the HFS around the blue and magenta master faults may be symptomatic of gas hydrate accumulation. Such observation has been confirmed from coring JPC-1 and it will likely be tested again in the future to confirm or controvert the one-to-one correlation;

3) Finally, the HFS is not distributed homogeneously along the master faults, but it rather seems to be restricted in areas along them characterized by fluid-flow anomalies and associated with prominent hydrocarbon seepage features at the seabed. In fact, even though the master faults are tectonically active structures (Fig. 2.13b) which potentially allow deeper reservoirs to communicate with the shallow gas hydrate system and the seafloor, hydrocarbon migration is only focused in specific areas along them. An example is shown in Figure 2.13. Here the yellow master fault exhibits a pronounced HFS anomaly right underneath the southeast crater (Fig. 2.13a), which is a seafloor complex produced by escape of hydrocarbon into the water column. On the other hand, the HFS is absent in an area about 300 m North from the southeast crater where the yellow master fault still intersects the seafloor but no hydrocarbon seepage anomalies occur at the surface (Fig. 2.13b). In other words, the HFS and precise locations intersected by migration of thermogenic gas along the master faults are spatially correlated across Woolsey Mound.
All the above observations corroborate our hypothesis that the discontinuous occurrence of the HFS along the master faults may reflect the heterogeneous accumulation of gas hydrate in fracture porosity. Therefore, at Woolsey Mound shallow gas hydrates occur in areas along the faults where transit of thermogenic gases takes place and where the physical and chemical requisites for hydrates to form and accumulate are favorable.

2.7.2 Gas Hydrate Accumulation Model

The main concept that emerges from coring results and seismic analysis of the SSDR data is that the HFS likely reflects heterogeneous accumulation of gas hydrate in areas where transit of thermogenic gases takes place.

Another key observation made in the core descriptions is the absence of coarse-grained sediments in the shallow subsurface, suggesting that thermogenic gas hydrate can only form and accumulate significantly where secondary porosity occurs. The secondary porosity (Fig. 2.10d), is provided by an irregular network of interconnected fractures associated with/derived from the master faults. Though the fractured fabric can host gas hydrate, it also provides permeability routes along which thermogenic gases transit towards the shallow subsurface. The dual nature of the master faults being both gas hydrate reservoirs and hydrocarbon conduits, implies an ephemeral gas hydrate stability field (GHSF). As a matter of fact, the GHSF is mainly controlled by temperature, pressure, pore-water salinity and availability of hydrocarbon gases.

In cold seep areas like Woolsey Mound, particularly along the master faults where local advection of heat and the transit of thermogenic hydrocarbons and brines occur more or less repeatedly, these parameters may be subject to radical changes through time.
Figure 2.12 Spatial correlation between master faults and high-frequency scattering. a) Amplitude envelope of a SSDR profile removed from the master faults. The absence of the high-frequency scattering (HFS) in the shallow subsurface is interpreted as the absence of thermogenic gas hydrate; b) amplitude envelope of a SSDR section across the master faults showing the location of core JPC-1. Here the HFS surrounding the blue (white for display purposes) and magenta master faults is interpreted to be produced by gas hydrate (GH) occurrence in fracture porosity, as confirmed in core JPC-1. The areas enclosed in the HFS characterized by higher reflection strength may also represent massive concentrations of hydrates or buried authigenic carbonates.
Figure 2.13 Uneven distribution of the high-frequency scattering along the master faults. a) Amplitude envelope of a SSDR transect crossing the southeast (SE) crater. The shallow high-frequency scattering (HFS) is interpreted to be an expression of gas hydrate (GH) accumulations in fracture porosity. Hydrates appear to occur in this area of the yellow master fault where migration of thermogenic gas occurred. This is suggested by the presence of hydrocarbon seepage features at the seafloor (Fig. 2.3b); b) amplitude envelope of a SSDR profile in an area where, although the yellow fault is active (seafloor offset visible on the CHIRP data close-up), the absence of hydrocarbon seepage features at the seafloor suggests that transit of thermogenic gas does not take place at this site. Hence, the absence of HFS could be correlated with the absence of thermogenic gas hydrate, unlike the subsurface of the northwest (NW) crater.
While the availability of gas is required to form hydrates, migration processes may promote transitory destabilization of gas hydrates along the faults. Also, these processes may drive the upward shift of the BHSZ, depending on the intensity and composition of the flux of hydrocarbons migrating through the system.

A simplified way to describe a scenario that accounts for the dynamics and mechanisms leading to gas hydrate formation, accumulation and destabilization at Woolsey Mound is illustrated in Figure 2.14. Thermogenic gases rise along the master faults from deep reservoirs located at the flanks of the underlying salt dome (Knapp et al., 2010; Macelloni et al., 2012). During the ascent, hydrocarbons partly accumulate laterally in shallower cap-rock reservoirs where favorable trapping conditions are met and partly continue migrating towards the shallow subsurface in restricted areas along master faults. In absence of shallow, highly permeable sediments, lateral migration is unlikely and gases would be forced to migrate farther up along the faults and eventually enter the water-column. However, at a depth range 150 m b.s.f. the parameters controlling the GHSF may be optimal, as shown in Figure 2.4. Therefore, gas hydrates may form in fractures along the master faults, in a volume extending from the seafloor down to the BHSZ. The formation and accumulation of hydrates decreases the hydraulic continuity along the faults as plugs of hydrate form, preventing further passage of free gas migrating upwards. Since it cannot migrate laterally, free gas continues accumulating in fractures in the vicinity of the faults at the BHSZ, building up pressure. When the stress exerted by the free gas exceeds both the mechanical strength of the overlying fracture-filling hydrates and the hydrostatic pressure, the free gas invades the overlying clathrate structures. This process triggers the destabilization of gas hydrate and promotes
venting of hydrocarbon gases at the seafloor until gas hydrates begin forming again once the dynamic equilibrium of the early stage is reestablished. And so forth.

The time scale at which these processes occur either episodically or periodically may be primarily a function of the rate at which hydrocarbons are migrating into the system. However, such phenomena are still poorly understood and merit continuous monitoring for clarification. Bangs et al. (2011) proposed a similar scenario for South Hydrate Ridge (Offshore Oregon) to occur within a time frame of 15 years, based on time-lapse seismic monitoring.

Although our model is derived from Woolsey Mound, it may be valid for thermogenic hydrate systems in fractured fine-grained sediments worldwide. The dynamics of the hydrate system at Woolsey Mound may be comparable to the ones proposed by Daigle and Dugan (2010) for both Hydrate Ridge (Offshore Oregon) and Keathley Canyon Block 151 (Gulf of Mexico). However, due to the diversity of fluid-flux regimes at Woolsey Mound (Macelloni et al., 2013), one model may not be representative of the entire mound. In fact, some areas of the mound appear to be characterized by long-term moderate flux of hydrocarbon (inferred from the presence of authigenic carbonates – Lutken et al., 2011). This suggests that thermogenic gas may bypass directly the HSZ with a mechanism similar to the one described by Liu and Flemings (2006) or Milkov et al. (2004). On the other hand, some areas of the mound show evidences of episodic fluid-flow (i.e. pockmarks, craters), suggesting that hydrocarbons may be temporarily retained in gas hydrates and abruptly released in the water column, as illustrated in Figure 2.14.
Figure 2.14 Gas hydrate accumulation model. A schematic cartoon showing the inferred mechanisms governing gas hydrates formation, accumulation and destabilization at the JPC-1 location. a) At time zero ($T_0$) gas hydrates are stable along the blue fault and clog thermogenic gas migrating upwards along the fault at the base of the hydrate stability zone (BHSZ); b) at $T_1$ more free gas accumulates at the BHSZ building up pressure as it cannot migrate laterally due to the absence of high permeability sediments; c) at $T_2$ when the upwards pressure exerted by the free gas exceeds both the mechanical strength of the overlying clathrate and the hydrostatic pressure, thermogenic gas breaks through the overlying fracture-filling hydrates promoting dissociation and seafloor venting; d) gas hydrate begins forming again once the dynamic equilibrium of $T_0$ is reestablished.
Finally, since the fluid-flux dynamics differ for each master fault and even along one single fault, the parameters controlling the GHSF at Woolsey Mound can be extremely variable through time and space. This would translate in a highly heterogeneous extent and depth of the BHSZ across the Mound.
CHAPTER 3

TEMPORAL CHARACTERIZATION: THE LONG-TERM DYNAMICS

3.1 BACKGROUND ON THE LONG-TERM DYNAMICS DRIVING METHANE HYDRATE DISSOCIATION AND SEEPAGE IN COLD SEEP-HYDRATE SYSTEMS

The long-term dynamics (thousands to millions of years) driving methane seepage in CSHSs cannot be monitored directly. However, evidences of seepage activity in the past may be inferred indirectly from the occurrence of methane-derived authigenic carbonate (MDAC) in the stratigraphic record (Teichert et al., 2003; Kutterolf et al., 2008; Watanabe et al., 2008; Kiel, 2009; Mazumdar et al., 2009; Feng et al., 2010; Crémière et al., 2012). Nevertheless, what turns on and off the seepage “switch” on long time scales is today still contentious.

Two main processes are generally regarded as a plausible forcing mechanism: eustatism and tectonics. Many studies proposed that recurring methane seepage is primarily favored during sea-level lowstands (Teichert et al., 2003; Kutterolf et al., 2008; Watanabe et al., 2008; Kiel, 2009; Feng et al., 2010; Tong et al., 2013; Bertoni et al., 2013). This trend would be caused essentially by a lower hydrostatic pressure which destabilizes gas hydrates and activates the release of subsurface methane in seawaters. In the majority of cases, the authors noticed a correlation between lowstands and seepage activity by plotting radiometrically-derived ages of MDACs against the global sea-level curve. Whilst a correlation was found in many examples, causality may be debatable. In fact, numerous active cold seeps have been documented even during rising and high-
standing sea-level of the Pleistocene (Teichert et al., 2003; Kutterolf et al., 2008; Feng et al., 2010; Tong et al., 2013) and the present-day (e.g. the Gulf of Mexico, http://www.boem.gov/Oil-and-Gas-Energy-Program/Mapping-and-Data/Map-Gallery/Seismic-Water-Bottom-Anomalies-Map-Gallery.aspx). This absence of a one-to-one correlation between lowstands and seepage activity suggests that eustatism may not be a critical forcing mechanism.

To date, a tectonic drive for the long-term methane fluxes in CSHSs has only been postulated (Roberts and Carney 1997; Teichert et al., 2003; Kutterolf et al., 2008; Watanabe et al., 2008; Mazumdar et al., 2009; Feng et al., 2010; Tong et al., 2013). While a correlation between methane seepage and eustatism could be simply found by plotting radiometric ages of MDACs on the global sea-level curve, a cause-effect relationship between seepage and tectonics is more challenging to substantiate.

This study aimed to untangle the long-term forcing mechanisms driving methane hydrate dissociation and seepage in CSHSs. Three distinct evidences of episodic activation of a CSHS in the recent geologic past are here documented on high-resolution SSDR and CHIRP data (§2.4.1). Each seepage activation correlates univocally with stages of active tectonics and it appears to be unrelated to sea-level lowstand.

3.2 WOOLSEY MOUND AS A PROXY FOR THE UNDERSTANDING OF THE LONG-TERM DYNAMICS IN COLD SEEP-HYDRATE SYSTEMS

The study area is Woolsey Mound, an active CSHS located at ~900m water depth in the Mississippi Canyon lease block (MC118), northern Gulf of Mexico (Fig. 3.1A). Here, a network of faults generated by salt-tectonics intersects the seafloor (Fig. 3.1B). Faults provide permeability routes for vertical migration of thermogenic methane into the water column (Macelloni et al., 2012; Simonetti et al., 2013; Chapter 2). Massive
MDACs and gas hydrates (Fig. 3.1C), craters and pockmarks (Fig. 3.1B), hydrocarbon vents and chemosynthetic communities (Macelloni et al., 2013) occur where the faults intersect the seafloor. Also, subsurface gas hydrates are distributed in fracture-porosity along the fault network and seal thermogenic methane at the BHSZ (Simonetti et al., 2013; Chapter 2).

Figure 3.1 Geographic location and morpho-bathymetric appearance of Woolsey Mound. A) Geographic location of Woolsey Mound (image courtesy of Marco D’Emidio, MMRI – University of Mississippi); B) AUV-seafloor reflectivity map and location of the seismic profiles. The positive reflectivity anomalies are mainly produced by the presence of massive methane-derived authigenic carbonate (MDAC); C) ROV-imagery of the “Sleeping Dragon”, one of the largest gas hydrate (GH) outcrops documented in the Gulf of Mexico. Note the lateral variation in relief between hemipelagic mud (HM) and massive MDAC (image courtesy of Carol Lutken, MMRI – University of Mississippi).
These observations suggest a clear spatial correlation between methane fluxes and tectonic activity, or faulting. The prominent fault scarps at Woolsey Mound indicate that these structures are active today or have been active until recent times (Fig. 3.1B), suggesting that seepage and tectonics may be related even temporarily. However, in order to substantiate the hypothesis of a long-term temporal correlation between methane seepage and tectonic activity, our approach consisted of: 1) detecting eventual evidence of seepage in the past (i.e. buried MDAC); 2) if found, searching for geological evidence of tectonic activity.

3.3 DATA AND METHODOLOGY

The fine-scale analyses of this study depend on the high level of detail of the data. Two types of 2-D unconventional seismic data were used: 1) Surface-Source Deep-Receiver (SSDR) data (Figs. 3.2, 3.3), which provide hundreds of meters of subsurface penetration with a sub-meter resolution, and 2) AUV-borne chirp sub-bottom profiler data (Fig. 3.5), which provide ~50 m of subsurface penetration with about 0.1 m of vertical resolution (§2.4.1). A detailed description of the data was presented McGee (2000), Macelloni et al. (2011) and Macelloni et al. (2012). Both the SSDR and the CHIRP data were converted from two-way time to depth using a 1500 m/s P-wave velocity. This value was derived from stacking velocities extrapolated from proprietary conventional 3-D seismic data available for the site. The time-depth conversion was carried out aiming to tie radiometric ages derived from gravity cores (Ingram et al., 2010) to the shallow seismic stratigraphy.

In order to detect the occurrence of MDAC in the subsurface, basic reflection seismology concepts were adopted. In a depositional environment dominated by low-
reflectivity hemipelagic sediments (i.e. Gulf of Mexico slope), the presence of massive MDAC (Fig. 3.1C) may be inferred from positive anomalies on AUV-seafloor reflectivity data (Fig. 3.1B). These anomalies are an acoustic response to the higher reflectivity of MDAC with respect to surrounding hemipelagic sediments (Fig. 3.1B). Similarly, if massive isolated MDAC occur in the shallow subsurface, it should be detectable on seismic reflection data due to its higher acoustic impedance (Taylor et al., 2000) compared to surrounding unconsolidated sediments.

3.4 Observations

3.4.1 Evidences of Fossil Methane Seeps on High-Resolution Seismic Data

Figure 3.2 shows three SSDR transects across Woolsey Mound, each presenting subsurface high-reflectivity anomalies at the same chronostratigraphic surface. The seismic anomalies are isolated positive-amplitude bright spots (Fig. 3.2). These anomalies are comparable to the positive-reflectivity anomalies produced by massive MDAC observed on AUV-reflectivity data (Fig. 3.1B). Such anomalies are a seismic response to the subsurface presence of a medium that has a higher velocity and/or higher density with respect to the encasing medium. Referring to the Woolsey Mound seafloor as a present-day analog, these anomalies may be indicative of buried massive MDAC imbedded in unconsolidated sediments. This would be the first indirect evidence of an older seepage system activated in recent geologic times at this site.

A key observation is that the MDAC anomalies mark the top of a syn-kinematic sequence (SKS-1) that exhibits pronounced lateral variations in thickness (Fig. 3.2A, B). The SKS-1 is enclosed by two angular unconformities: the lower unconformity, a base-lapping surface separating underlying sub-parallel reflectors from overlying on-lapping
Figure 3.2 First evidence of ancient methane seepage and active tectonics on high-resolution seismic data. A) North-south SSDR profile showing an isolated positive-amplitude bright spot at the top of a syn-kinematic sequence (SKS-1) (the depth axis is in meters below sea surface). The anomaly is interpreted to be indicative of massive methane-derived authigenic carbonate (MDAC). The SKS-1 is bounded at the bottom by the lower unconformity Lu-1 (solid line) and at the top by the upper unconformity Uu-1 (dashed line); the arrows indicate the on-lapping geometry of the SKS-1 reflectors; B) north-south SSDR profile showing another MDAC anomaly at the same chronostratigraphic surface for a different location, where MDAC have been also documented at the seafloor. C) east-west SSDR profile crossing the anomalies observed.
reflectors (Lu-1, Fig. 3.2A); the upper unconformity, a truncation/draping surface separating underlying on-lapping reflectors from overlying sub-parallel reflectors (Uu-1, Fig. 3.2A). We interpret the SKS-1 to be resulting from sedimentation during uplift of a salt dome located at ~400 m below the sea floor (b.s.f.) (Macelloni et al., 2012; Simonetti et al., 2013; Chapter 2). The on-lapping geometry of the SKS-1 reflectors on Lu-1 suggests that the deposition of the Lu-1 precedes the onset of a tectonic pulse induced by salt uplift, while Uu-1 marks the end of it. Similar seismic facies have been already documented in the Gulf of Mexico (Prather et al., 1998a). Further evidences of tectonic activity during the time from Lu-1 to Uu-1 are inferred from growth strata against the faults (Fig. 3.2B, C).

The second evidence of an active seepage system occurs deeper in the stratigraphy (Fig. 3.3A, B). Similarly to SKS-1, isolated positive-amplitude bright spots mark the top of another distinct SKS (SKS-2) bounded at bottom and top by the lower and upper unconformities (Lu-2 and Uu-2) (Fig. 3.3A, B). These high-reflectivity anomalies may likewise be indicative of buried MDAC imbedded in poorly-consolidated sediments. The Uu-2 also shows pronounced sub-circular depressions which may be buried pockmarks (Fig. 3.3A), namely fossil evidences of episodic and abrupt gas release in the water column (Hovland and Judd 1988). We interpret the SKS-2 to have the same geological genesis of the SKS-1.

3.4.2 FOSSIL METHANE SEEPS VERSUS WOOLSEY MOUND

Referring to the present-day seafloor, it is likely that both the upper unconformities are ancient analogs of Woolsey Mound, or cold seep-authigenic carbonate mounds. The morphological expression of the paleo-seafloor of both Uu-1 and Uu-2 (Fig.
Figure 3.3 Second evidence of ancient methane seepage and active tectonics on high-resolution seismic data. A) East-west SSDR profile showing the syn-kinematic sequences SKS-1 and SKS-2 (the depth axis is in meters below sea surface). SKS-2 is bounded by the lower unconformity Lu-2 (solid line) and the upper unconformity Uu-2 (dashed line). Uu-2 is characterized by lateral changes in acoustic impedance contrasts (isolated positive bright spots) and sub-circular depressions. The bright spot anomalies are interpreted to be produced by massive methane-derived authigenic carbonate (MDAC) embedded in hemipelagic mud, and the sub-circular depressions as buried pockmarks (PK); B) east-west SSDR profile showing the reflectors of the SKS-2 on-lapping on Lu-2 and being truncated by Uu-2.
Figure 3.4 Paleo-bathymetric reliefs of the two upper unconformities. The two upper unconformities Uu-1 and Uu-2 were picked on 30 E-W and 30 N-S SSDR profiles with 100 m line-spacing and subsequently interpolated in 3-D via flex gridding. High relief of the two paleo-seafloors occurs in areas where the presence of methane-derived authigenic carbonate (MDAC) was inferred from seismic data; low-relief circular depressions are instead interpreted as buried pockmarks (PK). Uu-1 and Uu-2 are interpreted as paleo-cold seeps, or paleo-carbonate mounds. (The depth axis is in meters below sea surface).
3.4) is strikingly similar to the one of the modern mound (Fig. 3.1B). The two paleo-bathymetries in Figure 3.4 show high-relief areas in proximity of the MDAC anomalies observed on seismic data, which may be an equivalent of the present-day massive MDAC shown in Figure 3.1C. Also, the buried pockmarks (Fig. 3.4) are comparable in size to the ones observed at the seafloor today (Fig. 3.1B). Both the buried pockmarks and MDCAs anomalies are distributed along the same fault network that intersects the seafloor (Figs. 3.4, 3.1B). This suggests that in the past, during active tectonics, methane may have been mobilized along the same faults that today supply methane at Woolsey Mound.

3.5 DISCUSSION

3.5.1 TIMING OF EPISODIC SEEPAGE ACTIVATION AT WOOLSEY MOUND

Age constraints from deep (> 10 m) cores are not available. However, the approximate duration of the two active tectonic stages has been estimated from the thickness of the SKSs. Removed from growth strata the SKS-2 is ~10 m thick whereas SKS-1 is ~5 m. Using the average sedimentation rate of 20 cm per thousand years (0.2 m/kyr) (Ingram et al., 2010), the length would be ~50kyr for SKS-2 and ~25kyr for SKS-1. We speculate that during these two time windows, subsurface fluxes of methane and seafloor venting were promoted and amplified, culminating with the formation of Uu-2 and Uu-1 which we interpret as authigenic carbonate mounds (Fig. 3.4). However, sedimentation rates at Woolsey Mound are highly variable both in time and space (Ingram et al., 2010); therefore these age information should be regarded cautiously.

Without robust age constraints for Lu-1 and Lu-2, it can still be argued that the two fossil seepage systems may have been activated during sea-level lowstands. However, key findings related to the present-day seepage system at Woolsey Mound
suggest that seepage activation may be significantly younger than the last lowstand, hence not directly related to it.

As for the present day seepage system, a lower unconformity (Lu-0) marks the bottom of the syn-kinematic sequence SKS-0 (Fig. 3.5A). Lu-0 has the same geologic significance of Lu-1 and Lu-2, marking the onset of salt uplift and of the youngest tectonic stage. In fact, the stratigraphy overlying Lu-0 (seafloor included) is on-lapping and pinching-out on Lu-0 (Fig. 3.5A), suggesting that the deposition of Lu-0 precedes the uplift. Furthermore, the sediments thickness between Uu-1 and Lu-0 is relatively uniform (Fig. 3.5A), which suggests a relative quiescent stage before Lu-0. The key point is that the depth b.s.f. of the Lu-0 is consistent with the depth of the biostratigraphic boundary Y1/Y2 (~15kyr) detected on shallow gravity cores collected at Woolsey Mound (Ingram et al., 2010). Therefore salt-uplift and faulting, which we interpret to be the cause for both the present-day mound edifice and cold seep activation, initiated some time post-15kyl, when the sea-level was not at its lowest stand (Fig. 3.5B). We speculate that salt-uplift and faulting were triggered after an increased sedimentary loading of the slope during the last lowstand. It is likely that tectonic uplift and faulting are still ongoing; if not, the present-day seafloor would represent the upper unconformity Uu-0 and it would be progressively draped by hemipelagic sediments.

The post-15kyr onset for methane seepage at Woolsey Mound is consistent with other areas in the Gulf of Mexico where the timing of seepage activity has been inferred from U-Th dating of seafloor MDACs (12.4kyr at Atwater Valley lease block 340, 12kyr at Alaminos Canyon lease block 645 – from Feng et al., 2010).
3.5.2 Tectonic Controls on the Long-Term Fluxes of Methane in Cold Seep-Hydrate Systems

Relatively inactive tectonics (or quiescence) resulting in uniform stratigraphy, characterizes the time before Lu-2, between Uu-2 and Lu-1 and finally between Uu-1 and Lu-0 (Figs. 3.3, 3.5A). A crucial observation is that there are no seismic anomalies indicative of an older seepage system (e.g. MDCAs, pockmarks) within the uniform stratigraphy (Fig. 3.3). Contrarily, those anomalies occur exclusively in close relation with the SKSs (Figs. 3.2, 2.3, 2.5). This suggests that methane seepage may be irrelevant during quiescence and that considerable subsurface fluxes of methane are triggered primarily during stages of tectonic activity. If methane fluxes were significant even during quiescence, eventual authigenic carbonate mounds should be detectable within the uniform stratigraphy through the high-resolution seismic imaging adopted here.

From a physical standpoint, we agree that a lower hydrostatic pressure during lowstand may promote hydrate destabilization and the release of overpressure thermogenic methane trapped at the BHSZ. Yet, as emerged in Figure 3.5, it appears that methane seepage and lowstand are not directly related. If significant methane fluxes were systematically triggered during lowstand, there should be more than three evidences of methane seepage in the stratigraphy down to Lu-2. In fact, the depth of Lu-2 is ~85 m b.s.f. Using the average sedimentation rate of 0.2 m/kyr (Ingram et al., 2010), the Lu-2 would be ~425kyr before present (B.P.). Since there are four major lowstands from 425kyr B.P. to the present-day, we would expect to observe four evidences of methane seepage down to Lu-2. Instead only three evidences are detectable and each one correlates univocally with active tectonics. Also, the youngest evidence (Woolsey Mound) seems to post-date significantly the last lowstand. These observations suggest
that eustatism may not be the main forcing mechanism for long-term seepage activation in at Woolsey Mound.

Figure 3.5 Third (modern) evidence of methane seepage in relation to relative sea-level variations. **A)** AUV-Chirp profile showing the pinch-out and on-lapping geometry of the syn-kinematic sequence SKS-0 strata on the lower unconformity (Lu-0), which is ~15kyr in age (the depth axis is in meters below sea surface); **B)** the age of Lu-0 plotted on the relative sea-level curve (RSL) suggests that the construction of Woolsey Mound and therefore the developments of the modern seepage system may not be directly related to the last lowstand (RSL curve from Rohling et al., 2009).
The univocal correlation between MDAC and SKSs suggests that substantial methane fluxes in CSHSs may be triggered primarily during episodes of active faulting. We propose the following conceptual model to explain the intermittent seepage mechanism at Woolsey Mound:

1) relatively stable hydrates and limited or null methane seepage characterize the quiescent sedimentation before Lu-2;

2) salt uplift begins right after the deposition of Lu-2 and deep-sourced methane is mobilized as a consequence of salt adjustment at depth (Roberts and Carney 1997);

3) thermogenic methane migrates upwards along the faults and reaches the hydrate stability zone;

4) methane hydrates are repeatedly destabilized during the deposition of the SKS-2, as vigorous fluxes of methane are facilitated during active faulting (Fischer et al., 2013);

5) the abundance of methane through the system promotes the development of a cold seep system where chemosynthetic biota thrive;

6) MDAC precipitates at the seafloor as a result of microbial degradation of long-lasting fluxes methane (Crémière et al., 2012);

7) subsurface methane fluxes dwindle and cease once the salt dome is at the buoyancy equilibrium with surrounding sediments and faults become inactive;

8) the deposition of the Uu-2 marks the end of both active faulting and methane seepage at the seafloor;
9) MDAC are progressively draped by hemipelagic sediments and methane hydrates return to a relatively more stable regime until the deposition of Lu-1;  
10) then, back to stage 1) and so forth for SKS-1 and SKS-0.

This model may substantiate the speculations of a tectonic forcing for long-term seepage activation in CSHSs around the world. Active faulting was hypothesized to trigger long-term seepage off-shore Nicaragua and Costa Rica through episodic increases in subduction rates (Kutterolf et al., 2008), in the Bay of Bengal through activation of shale diapirism (Mazumdar et al., 2009) and in the Gulf of Mexico through activation salt diapirism (Roberts and Carney 1997; Feng et. al., 2010).
CHAPTER 4

TEMPORAL CHARACTERIZATION: THE SHORT-TERM DYNAMICS

4.1 BACKGROUND ON THE SHORT-TERM DYNAMICS DRIVING METHANE HYDRATE DISSOCIATION AND SEEPAGE IN COLD SEEP-HYDRATE SYSTEMS

Short-term (days to years) hydrates dissociation and methane venting in CSHSs may be triggered by any process that perturbs the GHSF. Variations in pressure associated with tides, ocean swell, storm surges, bottom current velocities, and biologic pumping (Teichert et al., 2005), may be considered as potential drivers. Short-term destabilization may be also driven by the release of overpressure thermogenic gas trapped at the BHSZ (Bangs et al., 2011; Simonetti et al., 2013; Chapter 2). Also, a recent study reported about earthquakes being a potential trigger for significant submarine hydrocarbon seepage on short time-scales (Fischer et al., 2013).

Despite the limited accessibility of the hostile deep waters, the short-term variations in fluid flow in CSHSs can be observed experimentally and monitored (Vardaro et al., 2005; Riedel, 2007; Bangs et al., 2011; Crutchley et al., 2013).

4.2 TIME-LAPSE SEISMIC MONITORING (4-D SEISMIC IMAGING) AT WOOLSEY MOUND

One way to detect the short-term dynamics in CSHSs is via repeating seismic surveys through time, a technique known as time-lapse seismic monitoring. Time-lapse seismic monitoring, or 4-D seismic imaging, consists mainly in conducting repeated 3-D seismic surveys on a same area through time (the time elapsed is the 4th dimension).
4-D seismic analyses allow detecting differences in subsurface amplitude anomalies which may be resulting from variations in pore-fluid contents (this study) and/or pressure through time (Fig. 4.1).

Figure 4.1 Time-lapse seismic images of a CO₂ plume. a) N–S inline through the 1994 dataset prior to injection and through the 1999 and 2001 datasets. Enhanced amplitude display with red/yellow denoting a negative reflection coefficient; b) maps of integrated absolute reflection amplitudes calculated in a two-way travel time (TWTT) window from 0.84 to 1.08 seconds. Blue, low reflectivity; red, high reflectivity. Black disc denotes injection point. C denotes the main chimney. (from Chadwick et al., 2005).
Time-lapse seismic monitoring is conventionally adopted in the petroleum industry to monitor reservoir depletion during hydrocarbon production (Watts et al., 1996; Lumley, 2001; Tura et al., 2005; Fomel and Jin, 2009), as well as reservoir injection during CO₂ sequestration (Chadwick et al., 2005; Lumley, 2010).

While conventional 4-D seismic is routinely applied in the Industry, the approach appears to be more challenging in areas where hydrocarbon leaks naturally from the subsurface (i.e. in CSHSs). In controlled hydrocarbon production (or CO₂ sequestration) the location where the pore-fluid saturation will change through time is known (i.e. the reservoir). This allows isolating the reservoir that is being depleted (or injected) from the surrounding areas, where the pore-fluid content is not expected to be change dramatically during the time elapsed. The identification of areas where changes through time are not expected to occur is a crucial step required to perform an accurate and reliable 4-D processing sequence (see §4.4).

In CSHSs, hydrocarbons leak uncontrollably and the subsurface location from which hydrocarbons are being depleted is unknown. Also, the magnitude of the subsurface changes in amplitude through time is not predictable as the volume of hydrocarbons mobilized is uncertain.

Despite these technical challenges, Riedel (2007) inferred significant hydrocarbon venting episodes to take place within a 5-year time scale at Bulls-eye Vent, a CSHS offshore Vancouver Island, adopting time-lapse seismic monitoring. Similarly, Bangs et al. (2011) predicted substantial methane seepage to occur on 15-year time interval at South Hydrate Ridge, another CSHS offshore Oregon.
However, the short-term recurrence of methane hydrate dissociation and seepage in CSHSs is poorly constrained. Massive hydrate dissociation and seepage may take place even at shorter time-scales without being recorded, if seismic data are not acquired at proper time intervals. Therefore, the acquisition of multiple datasets through time is required to constantly monitor these complex settings. The importance of a continuous monitoring is comparable to the benefit of a higher sample rate in digital seismic acquisition: it is desirable for a faithful reproduction of a transient time function and to preserve the frequency content without distortions (i.e. aliasing).

The third part of this study aimed to detect the short-term dynamics at Woolsey Mound. A time-lapse seismic monitoring has been conducted to verify whether methane hydrate dissociation and seepage in CSHSs may occur within time-scales even shorter than those documented by Riedel (2007) and Bangs et al. (2011). Also, the goal was to detect the short-term forcing mechanisms for recurring methane hydrate dissociation and seepage. Two sets of standard 3-D seismic data acquired 3 years apart were used to perform the 4-D seismic analyses. To date, this study is the first documentation of a 1) time-lapse seismic monitoring of a CSHS in the Gulf of Mexico waters and 2) time-lapse seismic monitoring of a CSHS within a 3-year time scale.

4.3 3-D Standard Seismic Data

Two sets of post-stack standard 3-D seismic data were analyzed for the time-lapse seismic monitoring at Woolsey Mound:

1. TGS data, acquired in 1999-2000 (henceforth referred as 2000 data);
The original acquisition and processing parameters of the two datasets will not be presented in detail in this study due to proprietary reasons.

4.4 4-D PROCESSING SEQUENCE

The time-lapse seismic monitoring of at Woolsey Mound has been carried out using the CGG Hampson Russell software (Pro-4D module). The most important feature of time-lapse seismic monitoring is the opportunity to compare seismic images as a function of elapsed time. However, small artifacts in amplitude, phase and time of imaged seismic events could obscure real signatures of sub-surface temporal changes. Hence, careful attention to data processing issues is needed to ensure that images obtained at one time are validly comparable to subsequent images (Lumley, 1995b). The intent of 4-D seismic processing is to attenuate the 4-D “noise” caused by changes in acquisition parameters or environmental conditions, and to emphasize the 4-D signature caused by subsurface changes in fluid (this study), pressure and stress.

A standard seismic processing technique in time-lapse seismic monitoring is known as cross-equalization (Eastwood et al., 1998; Harris and Henry, 1998; Naess, 2006; Gan et al., 2004; Riedel, 2007). Essentially, the cross-equalization allows the user to perform a time-lapse seismic monitoring by removing differences in terms of sample rate, survey geometry, time, phase, amplitude (gain), and frequency. The main purpose of the cross-equalization is to reduce differences in areas where changes through time have not occurred and optimize differences in areas where changes have occurred (Riedel, 2007).

As mentioned in §4.2, in CSHSs the identification in advance of areas of the subsurface where the pore-fluid content is going to change through time is challenging.
However, these areas can be inferred directly where seafloor methane vents occur (although if the flux of methane is constant, subsurface changes may not be detectable even though the gas is still transiting into the system). Also, these areas can be inferred almost directly from their seafloor appearance. For example, seafloor pockmarks and craters are generally resulting from episodic and abrupt hydrocarbon release into the water column (Hovland and Judd, 1988; Løseth et al., 2001). Therefore, below these areas changes in pore-fluid through time are more likely to occur than in areas characterized by smooth seafloor.

The approach adopted here was to consider Woolsey Mound (subsurface and areal extension) as a potential location where changes in pore-fluid content through time are expected to occur. Woolsey Mound was hence defined as the “dynamic window” (Fig. 4.2), which may be considered the equivalent of a target reservoir in conventional 4-D seismic imaging. A “static window” was instead identified and chosen removed from the mound, where the absence seafloor vents and pockmarks suggests that subsurface changes in pore-fluids are less likely to occur in short time-scales (Fig. 4.2). The depth of the subsurface window analyzed is ~0.3 seconds two-way travel time (TWTT) b.s.f. (~250 m b.s.f.). This depth range, as emerged in Figures 2.12 and 2.13, is sufficient to image the HSZ and monitor the hydrate dynamics at Woolsey Mound. Before applying the 4-D seismic processing sequence, the 2000 dataset was set as “base” (or reference) and the 2003 dataset as “monitor”. Then, the 4-D processing sequence consisted in re-processing the 2003 data aiming to match the 2000 data and minimize their instrumental differences. This allowed us to highlight differences in subsurface amplitude anomalies that could have been indicative of real changes in pore-fluid saturation through time.
Figure 4.2 Location of the dynamic window (Woolsey Mound) and the static window designed for the 4-D processing sequence. The seafloor at Woolsey Mound suggest that this is an area where subsurface changes in the pore-fluid content through time are likely to occur; whereas significant variations through time are not expected to take place within the static window within a 3-year time scale.

Once the static window was designed for the calculation of the 4-D processing parameters, the cross-equalization consisted in:
• re-sampling;
• 3D geometry re-binning;
• cross-correlation time shifting and phase matching;
• shaping filter;
• amplitude balancing (gain cross-normalization).

4.4.1 RE-SAMPLING

The Nyquist frequency \( (F_N) \) of the 2000 data was 125 Hz (Fig. 4.3a), whereas the \( F_N \) of the 2003 data was 250 Hz (Fig. 4.3b). Since \( F_N \) is \( \frac{1}{2} \) of the sampling rate \( (\Delta_t) \) (Sheriff and Geldart, 1995), the \( \Delta_t \) was 4 milliseconds for the 2000 data and 2 milliseconds for the 2003. As the standard 4-D processing sequence requires that the two datasets must have the same \( \Delta_t \), the 2003 data were down-sampled from 2 to 4 milliseconds to match the 2000 data. After re-sampling, the \( F_N \) of the 2003 data was 125 Hz and the \( \Delta_t \) was 4 milliseconds, namely the same as for the 2000 data (Fig. 4.3c).

4.4.2 3-D GEOMETRY RE-BINNING

Once the data were re-sampled, the next step of the 4-D processing sequence consisted in the re-binning of the 2003 survey using the geometry of the 2000 data as reference. The Inline orientation of the 2000 data was north-south (0° azimuth), whereas the Inline orientation of the 2003 data was northwest-southeast (315° azimuth) (Fig. 4.4a, b). In addition, the Inline-spacing of the 2000 data was 20 m versus 12.5 m of the 2003 data. Also the 2000 data covered only the area of MC118 lease block (4.8 × 4.8 km); whereas the survey area of the 2003 data was 1.6 km wider than MC118 on each side (8 × 8 km) (Fig. 4.4b). Furthermore, the record length of the 2000 data was 3 seconds TWTT, whereas the record length of the 2003 data was 10 seconds TWTT.
Figure 4.3 Survey spectra and Nyquist Frequency of the 3-D used for the time-lapse seismic monitoring. a) original 2000 data, b) original 2003 data and c) re-sampled 2003 data.
As all these differences needed to be removed, the 2003 data were re-binned through interpolation with a 25 m Inline spacing to match the 0° azimuth 2000 survey geometry (Fig. 4.4c). Also, the record length of the 2003 data was reduced to 3 seconds TWTT.

![Figure 4.4 Survey geometry of the 3-D used for the time-lapse seismic monitoring.](image)

In order to make sure that the 3-D geometry re-binning did not introduce any geometry error to the data, two horizontal slices were extrapolated from the original 2003 data and the 2003 re-binned data at the same depth (1.250 seconds TWTT, ~100 m b.s.f.) and compared (Fig. 4.5). The comparison between the two amplitude slices does not seem to show any appreciable difference, suggesting that no major structural artifacts were introduced with the 3-D re-binning step.
Figure 4.5 Quality check of the 3-D re-binning geometry. 1.250 seconds two-way travel time (TWTT) time-slices extrapolated from the original 2003 data and the re-binned 2003 data. Since there appear not be any significant difference in subsurface structures, no structural artifacts were introduced during the re-binning processing step.

4.4.3 CROSS-CORRELATION TIME SHIFTING AND PHASE MATCHING

The mean time-shift between the 2000 and the 2003 re-binned data was about 3.5 milliseconds (Fig. 4.6a), and the mean cross-correlation was about 86% and (Fig. 4.6b).

Even though this discrepancy may be considered negligible because it is lower than the sampling rate (§4.4.1), the 2003 data were still corrected for the shift in order to match the 2000 data and minimize the acquisition/processing differences. As for the cross-correlation time shift, the seafloor of the 2000 data was chosen as a picked event for the static shift, with a 20 milliseconds sliding window length and a maximum 3 milliseconds time-shift to be adjusted (which is the maximum time-shift observed between the 2000 and the 2003 data – Fig. 4.6a). Then, the filter for the phase matching calibration was
designed in the static window. This step was carried out with a global average, choosing again the 2000 data seafloor as picked event and a 100 milliseconds window length.

Figure 4.6 Comparison between the original 2000 and the 2003 re-binned data. a) Cross-correlation time shift between the 2000 and the re-binned 2003 data. The mean time shift was 3.5 milliseconds (ms) with a standard deviation of 1; b) trace by trace cross-correlation between the 2000 and the re-binned 2003 data. The mean correlation was 86% with a 0.05 standard deviation. Note the high correlation in the static window (where subsurface changes through time are not expected) and the low correlation at Woolsey Mound (where pore-fluid contents are likely to change through time).

4.4.4 SHAPING FILTER

The next step in the processing sequence was the designation of a shaping filter to transform the 2003 data and match them with the 2000 data for a specific horizon. The idea behind this step is to reproduce a section out of the 2003 data that was as close as possible to the 2000 data acquisition parameters (source wave-form and frequency content), but which preserved any real changes present in the sub-surface (Riedel 2007). The static window was again used as a reference zone where no changes were expected to have occurred between the two surveys. The 1000-1500 seconds TWTT window was
chosen to define the shaping filter, with a filter length of 81 milliseconds and an additive noise level of 0.001. A global average was chosen as a shaping processing mode, with a full matching as a global shaping option.

4.4.5 AMPLITUDE BALANCING

The 2000 and the 2003 data were acquired with different gain settings (Fig. 4.7a, b). Before proceeding with the amplitude differencing, the final step of the 4-D processing sequence consisted in the removal of the gain differences between the 2003 and balanced 2000 data through a gain cross-normalization. A 0.5 seconds TWTT window designed in the static window was used to define the RMS amplitudes. A single global scalar was used for all traces to adjust the 2003 data. The 2003 gain-adjusted data, which are the final product of the whole 4-D seismic processing sequence, are shown in Figure 4.7c.

![Figure 4.7](image)

Figure 4.7 Gain comparisons between the original 2000, the original 2003 and the 4-D processed 2003 data. **a)** 2000 data, **b)** original 2003 data and **c)** 2003 post-4-D processing. Note the overall improvement in c) compared to b).
4.5 QUANTITATIVE AMPLITUDE DIFFERENCING

As this 4-D seismic monitoring aimed to detect subsurface changes in pore-fluid through time, a new 3-D seismic volume was created by subtracting the amplitudes of the 2003 post-4-D data from the 2000 data. The resulting dataset, henceforth referred as the “difference volume”, shows the differences in seismic amplitudes anomalies between the 2000 and 2003 data. As the instrumental (acquisition and processing) differences were minimized during the 4-D processing sequence, these residual amplitudes are likely to reflect temporal variations in the pore-fluid content in the subsurface.

4.6 SESMIC ATTRIBUTES CALCULATION: THE COHERENCY CUBE

The IHS Kingdom Suite software was used to compute the coherency seismic attribute (Rock Solid Attributes module). The geometrical attribute “coherence” (Taner 2000; Chopra 2002) represents the trace-to-trace similarity and provides distinct images of salt bodies, faults, buried channels, etc. (Fig. 4.8). The coherence (or similarity) is calculated over a specific frequency range and window size and it identifies the overall similarity of a trace with its nearest neighbors. Because of their higher vertical resolution ($\Delta t=2$ milliseconds, §4.4.1), in this study the similarity was calculated on the original 2003 data. The attribute was computed for a 12-80 Hz frequency range, with a window length of 20 milliseconds and incorporating the nearest 5 neighbor traces.

The coherency attribute was used primarily with the aim to image in detail the fault network in the subsurface and compare it with the amplitude differences. The rationale behind this approach was that changes in the pore-fluid contents through time are more likely to occur in higher permeability areas, such as faults (fracture-porosity).
Figure 4.8 Subsurface structures imaged through the coherence seismic attribute. 1.908 seconds two-way travel time (TWTT) coherency (or similarity) slice extrapolated from the original 2003 data (note the greater survey area with respect to MC118). Low-coherence features (e.g. faults, salt domes, channels, etc.) stand out on the coherence cube.
4.7 Evaluation of the 4-D Seismic Imaging Results

The wavelet and the amplitude spectrum of the 2003 post 4-D data are similar to those of the original 2000 data (Fig. 4.9a, b). The mean time-shift between the 2000 and

![Waveform and frequency spectrum](image)

Figure 4.9 a) Waveform and b) frequency spectrum of the original 2000, the original 2003 and the 4-D processed 2003 data. Both the wavelets and the frequency spectra were extrapolated from the 1.0-1.5 seconds two-way travel time (TWTT) window analyzed throughout the survey areas.
the 2003 data after the 4-D processing was 0.6 milliseconds (Fig. 4.10a), compared to 3.5 milliseconds before the 4-D processing (Fig. 4.6a). The mean cross-correlation after the 4-D processing was 92% (Fig. 4.10b), compared to 86% before the 4-D processing (Fig. 4.6b).

Figure 4.10 Comparison between the original 2000 and the 4-D processed 2003 data. a) Cross-correlation time shift between the 2000 and the 2003 post-4-D data. The mean time shift was 0.6 milliseconds (ms) with a standard deviation of 1.3; b) trace by trace cross-correlation between the 2000 and the 2003 post-4-D data. The mean correlation was 92% with a 0.04 standard deviation. Note again the high correlation in the static window (where subsurface changes through time are not expected) and the low correlation at Woolsey Mound (where pore-fluid contents are likely to change through time).

These observations suggest that the cross-equalization has significantly minimized the instrumental differences between the 2000 and the 2003 data, which was the purpose of the 4-D processing sequence. The residual differences that persisted between the 2000 and the 2003 post-4-D data (Fig. 4.10b) are mainly found within the dynamic window (Woolsey Mound), where the subsurface pore-fluid contents are
expected to change through time. This suggests that the residual differences may be attributed to real subsurface variations in the pore-fluid content between 2000 and 2003.

In order to test this hypothesis, the next step consisted in analyzing the subsurface distribution of the 4-D anomalies. The rationale behind this step was that if the spatial distribution of the residual amplitudes was random, these differences could have still been attributed to 4-D noise. If the residual amplitudes were instead distributed systematically along higher permeability areas, then they may have likely reflected real changes in the pore-fluid content through time.

Two time-slices were extrapolated from the difference volume at 1.360 and 1.380 seconds TWTT (Fig. 4.11a, b). According to Figures 2.12 and 2.13, these depths should be near the depth range for the BHSZ. The two amplitude slices highlighted the residual differences that were not removed during the 4-D seismic processing sequence and which may have been indicative of real temporal changes in pore-fluids. Figure 4.11a and 4.11b show that significant subsurface changes in amplitude anomalies occurred within a 3-year time scale at Woolsey Mound.

Subsequently, two coherence (or similarity) time-slices (Fig. 4.11c, d) were extrapolated at the same depths as the previous (1.360 and 1.380 seconds TWTT) from the coherency volume (§4.6). The two coherence slices highlighted the presence of the following geological discontinuities in the subsurface at Woolsey Mound:

1. faults (Fig. 4.11c, d);
2. channels (Fig. 4.11c, d);
3. turbidite lobes (Fig. 4.11d), perhaps related to lowstand slope-fan deposits.
Figure 4.11 4-D seismic imaging and seismic attribute analysis. a) 1.360 seconds two-way travel time (TWTT) and b) 1.380 seconds TWTT time-slices extrapolated from the difference volume. The residual amplitude differences highlight the 4-D anomalies between 2000 and 2003; c) 1.360 seconds TWTT and d) 1.380 seconds TWTT time-slices extrapolated from the coherence cube. This seismic attribute highlighted the presence in the subsurface of faults (see Fig. 2.3b for the color code of the faults), channels and turbidite lobes.
All these geological features are generally characterized by having a relatively high permeability, due to fracture-porosity in faults (Fig. 2.10c, §2.7.2) and sand-prone deposits in both buried channel and turbidite lobe deposits.

Therefore, if the 4-D anomalies seen in Figure 4.11a and 4.11b were spatially associated with any of these geological features, they may have realistically reflected variations in the pore-fluid content through time.

Aiming to substantiate this hypothesis, both the residual amplitude slices were overlaid in transparency on their equivalent coherence slices (Fig. 4.12a, b). The comparison between residual amplitudes and subsurface structures shows that the 4-D anomalies are not just randomly distributed in the subsurface. They rather seem to follow closely the trend of the major faults (Figs. 4.11c, 4.12a) and appear to be enclosed within channel and turbidite-fan deposits (Figs. 4.11d, 4.12b).

The spatial correlation between these relatively high-permeability structures and the 4-D anomalies would substantiate the hypothesis that the 4-D anomalies may indicate variations in the pore-fluid content between 2000 and 2003 in the subsurface Woolsey Mound.

In further support of this hypothesis, the locations of seafloor methane seeps observed in 2011 during the NOAA Okeanos Explorer Gas Plume Cruise (Shedd 2011) seem to be consistent with areas interested by the 4-D anomalies (Fig. 4.12a, b). Interestingly, the two easternmost methane seeps documented in 2011 were not known to be active in 2006 basing on Remotely Operated Vehicle (ROV) survey imageries. These seeps are located in the south-east crater complex (Fig. 2.3b), which was considered to be dormant (Lutken et al., 2011), and they are spatially distributed along the yellow fault
(Figs. 2.3b, 4.11c, d). Therefore, the activation of these two methane seeps in 2011 may have been a consequence of underlying changes in pore-fluid in fracture porosity, perhaps ongoing since 2000-2003 basing on the 4-D anomalies. This suggests again an extreme dynamism for the short-term hydrate dissociation and methane seepage at Woolsey Mound.

Figure 4.12 Comparison between 4-D anomalies and subsurface structures. a) Transparent overlay of the residual amplitudes on the coherence time slices extrapolated at 1.360 seconds TWTT. Note how the 4-D anomalies are spatially distributed along the major faults and confined in buried channel deposits identified in Figure 4.11c; b) Transparent overlay of the residual amplitudes on the coherence time slices extrapolated at 1.380 seconds TWTT. Note how the 4-D anomalies are spatially distributed along the major faults and confined within a major turbidite lobe identified in Figure 4.11d. The location of core JPC-1 and transect A-A’ refer to the seismic profiles in Figure 4.13. The red circle represents the location of core JPC-1 w, The green circles represent the location of seafloor methane seeps observed in 2011 (data courtesy of Marco D’Emidio, MMRI – University of Mississippi).
4.8 Proposed Model for the Short-Term Dynamics Driving Methane Hydrate Dissociation and Seepage

In order to detect the hydrate dissociation and seepage dynamics at Woolsey Mound, a subsurface location where the occurrence of gas hydrates was confirmed through coring (Fig. 2.10) was investigated. This location also showed changes in the pore-fluid content through time were inferred from 4-D anomalies (Fig. 4.12a, b). Figure 4.13a and 4.13b show two coinciding north-south seismic transects from the 2000 and 2003 post-4-D data. The profiles intersect the location of core JPC-1, where gas hydrates were recovered in the shallow subsurface in 2011 (§2.6, Fig. 2.10). The 2000 data show a prominent negative-amplitude polarity-reversal bright spot (Fig. 4.13a), which is a common direct hydrocarbon indicator (DHI) for the presence of gas in the pore-space. According to Figures 2.12, 2.13 and 2.14, this seismic anomaly may represent a large thermogenic methane accumulation at the BHSZ. A key observation is that the anomaly appears to be absent on the 2003 post 4-D data (Fig. 4.13b), suggesting the following scenario:

1. in 2000 thermogenic methane was being clogged at the BHSZ by overlying gas hydrates in fracture porosity;
2. thermogenic methane continued to migrate upwards from deep hydrocarbon reservoirs and to accumulate as free gas at the BHSZ;
3. at some time between 2000 and 2003 the methane accumulations at the BHSZ reached an overpressure regime and triggered overlying hydrate dissociation via hydraulic fracturing, followed by seafloor methane venting (Fig. 4.13c).
Figure 4.13 Proposed model for the short term-dynamics. Two coinciding seismic profiles of the a) 2000 data and b) 2003 post 4-D data (the location is shown in Fig. 4.12); c) 4-D cartoon showing the model proposed for the short-term dynamics driving methane hydrate dissociation and seepage in cold seep-hydrate systems.
If this scenario is realistic, significant amount of methane may have been abruptly released into the water column at some time between 2000 and 2003, with the same mechanism as the one speculated in Figure 2.14. Hydraulic fracturing triggered by overpressure gases and fluids accumulations at the BHSZ (Daigle and Dugan, 2010) may be the primary cause for hydrate destabilization and seafloor venting in a 3-year time scale.

As mentioned in §3.2, the prominent fault scarps at the seafloor indicate that these major faults may be active today or have been active until recent times. In other words, the syn-kinematic sequence mentioned in §3.5.1 (SKS-0) may be still ongoing. If so, this study suggests that during active faulting gas hydrates may be frequently destabilized on short time-scales. Finally, the gas hydrate stability through time may depend primarily on the amount and vigor of the hydrocarbon flux supplied from deep sources through the system via faults.
CHAPTER 5

CONCLUSIONS

The first part of this research documents a successful attempt to integrate cost-effective unconventional seismic surveys with jumbo piston cores to determine the spatial distribution of gas hydrate in hostile deep-water settings. To date, in-place methane hydrate resource assessments have been evaluated for many reservoir categories (i.e. arctic sandstones, marine sandstones, and marine shale). Yet, two classes of hydrate-bearing sediments are poorly understood and difficult to assess: fractured muds and seafloor hydrate mounds. These two categories are typically found in cold seep-hydrate systems (CSHSs). The main technical issues related to the spatial characterization of CSHSs stem from the general lack of seismic data capable of imaging them in sufficient detail. The occurrence of gas hydrates in restricted geometries (i.e. fractures, veins, etc.), requires optimal seismic resolution in order to provide an interpretable image. Integration of five jumbo piston cores with high-resolution Surface Source-Deep Receiver (SSDR) and AUV-CHIRP seismic reflection data at Woolsey Mound provides the first documentation of the subsurface distribution of gas hydrates at this CSHS in the deep-water Gulf of Mexico. Gas hydrates occurred in fracture porosity in fine-grained sediments and were encountered only in one core, which was specifically selected to ground-truth a high-frequency scattering (HFS) anomaly on the SSDR data. The HFS is systematically distributed along the areas of the faults intersected by migration of thermogenic hydrocarbon and where the physical and chemical requisites for gas hydrate
to accumulate are favorable. These observations suggest that the HFS anomaly may be a seismic signature for heterogeneous hydrate accumulations in fracture porosity. Therefore, the SSDR data may be perspective for mapping hydrates in hostile deep-water settings such as CSHSs. Also, the fractured fabric of the subsurface hydrate reservoir implies that hydraulic continuity for upward-migrating gases and fluids along the faults exists and it can be clogged by local and transitory gas hydrates accumulation. This dual nature of the faults being both hydrocarbon conduits and hydrate reservoirs suggests the presence of a highly dynamic and laterally heterogeneous gas hydrates stability field throughout the mound.

The second part of the study then aimed to characterize the long-term dynamics that drive methane hydrate dissociation and seepage in CSHSs. Analyses of high-resolution SSDR and AUV-CHIRP seismic data at Woolsey Mound suggest the presence of three distinct methane seepage systems episodically activated in the recent geologic past. Methane-derived authigenic carbonate (MDAC) anomalies were identified on seismic records and each anomaly correlates univocally with stages of active tectonics. This suggests that substantial subsurface methane fluxes may be triggered primarily during episodes of active faulting. A long-term tectonic forcing had been previously proposed to regulate the seepage activity in many CSHSs around the world. However, in all these examples a tectonic trigger has only been postulated. This work supports all these studies providing the first documentation for a univocal correlation between evidences of long-term methane seepage and active tectonics. Also, this study suggests that CSHSs may operate independently from eustatic fluctuations, opening the question
on what is the real long-term role of eustatism in hydrate dissociation and methane seepage through geologic time.

For the third part of the research, the goal was to detect the short-term dynamics driving methane hydrate dissociation and seepage in CSHSs. Quantitative time-lapse seismic monitoring conducted at Woolsey Mound showed that this CSHS may have experienced significant variations in the subsurface pore-fluid contents on a 3-year time scale. This suggests that on short-time scales gas hydrate may dissociate frequently in CSHSs, releasing considerable volumes of methane to the oceans. Also, methane hydrate destabilization and seepage appear to be triggered primarily by episodic migration of overpressure thermogenic methane through the system. Therefore, the stability of gas hydrates through time in CSHSs may be primarily depending on the amount and vigor of the flux of hydrocarbons supplied from deep sources through the system via faults. Finally, the time-lapse seismic monitoring conducted at Woolsey Mound provided useful insights for the understanding of short-term recurrence of methane seepage in CSHSs. However, the collection of only two datasets within a 3-year time-window may not be sufficient to detect the real frequency at which gas hydrates dissociate and methane is released in the water column. These processes may occur on a time-frame even shorter than 3 years. Therefore, CSHSs deserve a more continuous monitoring through time in order to better constrain their short-term dynamics (i.e. transience versus periodicity).
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