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AN INTEGRATED STRUCTURAL ANALYSIS ON SEISMIC OF A PALEO MOUND DEVELOPMENT (WOOLSEY MOUND, NORTHERN GULF OF MEXICO)

by

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DEDICATION

To God, family and friends for their support and love throughout this journey and life, thus far.

ACKNOWLEDGEMENTS

First and foremost, thanks to 1) adviser, Dr. James Knapp for your guidance, support and critical insights towards understanding the complex earth; 2) committee members Dr. James Kellogg and Dr. Camelia Knapp, for your continued support and shared experiences, both through course and field works; 3) the Tectonics & Geophysics (Exploration) Lab(s), TG(E)L, along with Jaehoon Choe, Stephanie Bradley, and other faculty/staff of EOS, for your encouragement and support; 4) the Institute of International Education (IIE) and ExxonMobil (Esso) for their academic, cultural and financial support through the Esso Angolan Scholars Program, and 5) BOEM, GOM–HRC, Kingdom IHS and EOS Dept., for data provision and software usage. Thank you.

ABSTRACT

Woolsey Mound is ~1 km diameter thermogenic gas hydrate and cold seep (GHCS) complex system. It is located at ~900 m water depth in the Mississippi Canyon Lease Block 118 (MC–118) on the upper continental slope of the northern Gulf of Mexico (GOM). Due to its complex geology, widespread hydrate seepage activity and presence of benthic habitat, the mound serves as a permanent research site for a multidisciplinary seafloor observatory, thus providing insights into the dynamics of shallow fluid expulsion, their spatial and time variations and possible geological forcing mechanisms.

This study utilizes a set of high resolution 2D autonomous underwater vehicle (AUV) borne chirp seismic data acquired at MC–118, and it provides a unique basis for a twofold detailed structural characterization of an interpreted paleo mound development (PMD). The profiler gives ~50 m of subbottom penetration with ~0.1 m of vertical resolution. First, isochore analysis of deeper stratigraphy suggests 1) uniform sedimentation prior to and post PMD with strata variance of ~0.5-1 m, and 2) uneven sediment distribution during PMD activity, showing a localized growth strata or differential subsidence of ~5-6 m, as well as truncation and onlapping synkinematic geometry. In addition, integration with modern chronostratigraphic results further indicates that PMD is correlative to relative sea level highstands, of mid-Late Pleistocene. Second, PMD appears to have occurred during quiescent tectonic

environment as evidenced by a constant offset of ~1-2 m throughout stratigraphy, along major faults. These data may substantiate that Woolsey Mound cold seeps are ‘episodic’, and that sea level fluctuation or tectonic governance alone may not be critical geological triggers of seepage development.

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LIST OF ABBREVIATIONS

AUV	Autonomous Underwater Vehicle
GHCS	Gas Hydrate Cold Seep
GHSZ	Gas Hydrate Stability Zone
GOM	Gulf of Mexico
HFS	High Frequency Scattering
HRA	High Resistivity Anomaly
JPC	Jumbo Piston Cores
kya	Thousands of Years Ago
kyr	Thousands of Years
m	Meters
m/s	Meters per Second
MC–118	Mississippi Canyon Lease Block 118
MDAC	Methane Derived Authigenic Carbonates
N–S	North – South
PMD	Paleo Mound Development
SR	Sedimentation Rates
W–E	West – East
~	About/Approximately

INTRODUCTION

Gas hydrates, mostly methane, can form in high pressure and low temperature environments within relatively shallow oceanic fine grained sediment pores. They are often stable at the base of the gas hydrate stability zone (GHSZ), and influenced by temperature, pressure, pore-water salinity and hydrocarbon gas composition (Sloan and Koh, 2008). Cold seeps are zones whereby thermogenic gas hydrates when destabilized associate/dissociate and escape the deeper subsurface, via faults or smalls fractures, eventually outcropping the seafloor and reaching the atmosphere (Fisher et al., 2007; Bangs et al., 2013; Simonetti et al., 2013; Macelloni et al., 2012, 2013).

Methane seepage has been observed in marine environments worldwide (Mazurenko and Soloviev et al., 2003; Judd and Hovland, 2007). Some studies have proposed their occurrence to favor during sea level lowstands, as a result of hydrostatic depressurization, causing dissociation and rapid release of gas hydrates (Tong et al., 2013); both during sea level lowstands and highstands, using U/Th dating on methane derived authigenic carbonates as a proxy to seepage onset (Bayon et al., 2008; Feng et al., 2010); and as a result of (salt) tectonism, which can be a function of sea level fluctuation, sediment supply, sedimentation rates and distribution patterns (Roberts and Carney, 1997).

Gas hydrate cold seep system dynamics are better understood on a shorter term (within years to thousands) rather than on a longer term timeframe (within thousands to millions of years). Characterizing their mechanisms can provide critical insights into how these geological features activate, and their role on affecting benthic habitat, climate change and global economics (Ingram et al., 2010, 2013; Simonetti et al., 2013. Such correlations can be key in predicting where, when, and under what conditions methane seepage may or might have developed.

CHAPTER I

AN INTEGRATED STRUCTURAL ANALYSIS ON SEISMIC OF A PALEO MOUND DEVELOPMENT (WOOLSEY MOUND, MC–118, NORTHERN GULF OF MEXICO)

I.I GOM REGIONAL BACKGROUND

The Gulf of Mexico (GOM) is a hydrocarbon prolific basin dominated by salt tectonics (Fisher et al., 2007), with over 21,000 cold seep sites (Shedd, 2012; Bosewell et al., 2012). Understanding its complex geodynamic setting can shed light into the geological forces that cause methane seepage, which provides nutrients to a thriving fauna and chemosynthetic community.

In the northern GOM, the allochthonous Louann salt body (~4000 m thickness) has over time influenced the structure, stability and geometry of the subsurface, in particular along the continental slope. The continued differential loading between overlying sediments and underlying salt has created its current geologic framework, widely characterized by folding with varying relief, faults, marginal sub-basins and other deformational patterns (Dribus et al., 2008; Macelloni et al., 2012; Salazar et al., 2013).

I.I.I WOOLSEY MOUND GEOLOGIC SETTING

Woolsey Mound is ~1 km diameter thermogenic gas hydrate and cold seep (GHCS) complex system. It is located ~900 m water depth in the Mississippi Canyon Lease Block 118 (MC–118), on the upper continental slope of the northern Gulf of

Mexico, GOM (Figure 1.1). Similar to the rest of the GOM, Woolsey Mound has a complex geology, whereby salt movement have created an intricate network of faults (Figure 1.2) and placed strong controls on sediment accumulation patterns, location of mini basins, hydrate system, and other associated geological structures (Ingram et al., 2010; Macelloni et al., 2012).

Due to widespread hydrate seepage, presence of chemosynthetic fauna and authigenic carbonates, the mound serves as a permanent research site for a multidisciplinary seafloor observatory, thus providing insights into the dynamics of shallow fluid expulsion from deep sourced reservoirs, their spatial and time variations, and possible geological forcing mechanisms (Sassen et al., 2006; Lutken et al., 2011; Simonetti et al., 2013).

Previous studies have suggested that Woolsey Mound is a shallow ‘episodic’ gas hydrate and cold seep system. Episodic in that mound activity or events of transient gas release appear linked to an on and off switch, influenced by geological features and relative timing. The mound’s modern distribution pattern seems to vary both spatially and temporally, evidenced by high-frequency scattering (HFS) energy, and acoustic wipeout (Sassen et al. 2006, Macelloni et al. 2012, 2013). Most recently, Xu and Dunbar (2015) used direct-current resistivity (DCR) data to describe and ground truth the presence of shallow gas hydrates in the near bottom deep marine environment (Figure 1.5, right). These hydrates seem to be associated with intermediate to high resistivity anomalies (HRA), and to vary both laterally and in depth.

Using a set of 2D AUV-borne chirp seismic data, along with an integrated approach and analysis, this study provides a basis for a twofold detailed structural characterization of an interpreted paleo mound development (PMD), most likely of mid-Late Pleistocene. PMD appears correlative to sea level highstands during quiescent tectonism.

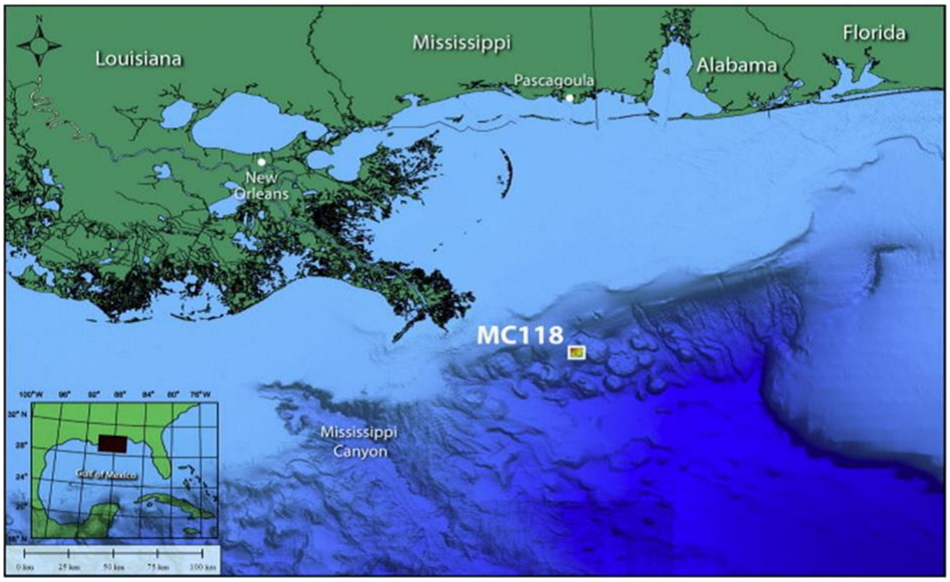


Figure 1.1 Location map of Woolsey Mound, MC–118 on the upper continental slope of the Northern Gulf of Mexico (Simonetti et al., 2013).

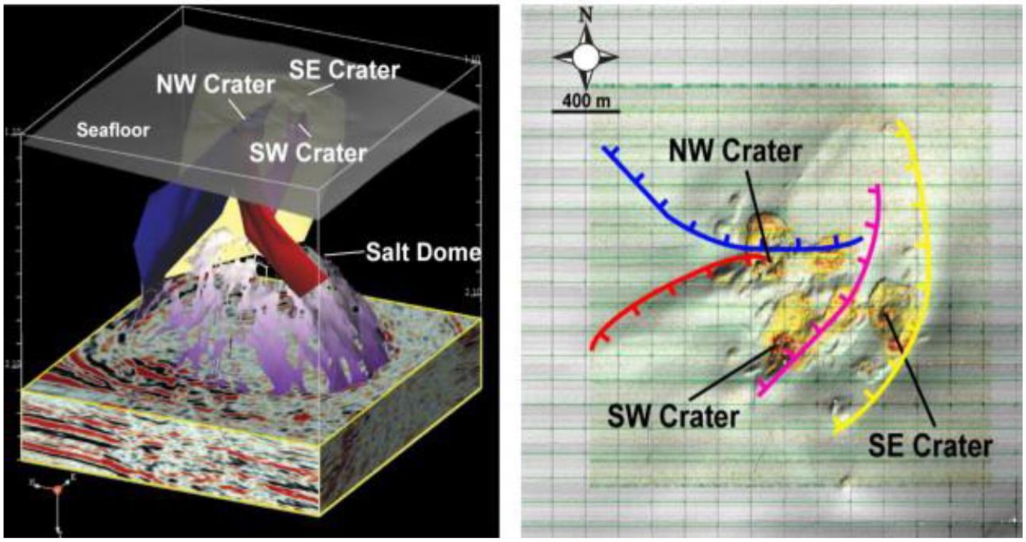


Figure 1.2 **left:** Salt dome identified at ~300 m b.s.f., craters and correlative master faults (upward migration pathways for rising hydrocarbons into the seafloor); **right:** Woolsey Mound cold seep sites and their spatial relation to master faults (Knapp, 2010; Macelloni et al., 2012).

I.II RESEARCH QUESTIONS

While modern cold seeps on Woolsey Mound are well documented and understood (Ingram et al., 2010, 2013; Simonetti et al., 2013; Robinson, 2014), the geological and time variant mechanisms that could trigger past cold seeps or paleo mound development (PMDs) remain at large. Looking at deeper strata on chirp data:

1) Does evidence exist for a paleo mound development? If so, when does paleo mound activity likely occur? What correlation may exist between past seepage activity and sea level fluctuation?

2) Under what tectonic setting might the observed paleo mound be active?

I.III DATA AND METHODOLOGY

I.III.I AUV-BORNE CHIRP SEISMIC REFLECTION DATA

We utilize 25 W-E and 2 N-S high resolution chirp seismic reflection data, acquired at MC–118, spaced ~200 m and ~4500 m respectively (Figure 1.5, left). The subbottom profiler provides ~50 m of penetration below seafloor with a vertical resolution of ~0.1 m. Parameters for the AUV sonar include a modulated frequency of 2-10 kHz, ~300 ms recorded length, ~63 µs sampling interval, and an average p-wave velocity estimate of 1500 m/s for time-depth conversion and subsurface relationship. Further chirp acquisition details, processing and integration with jumbo piston sediment cores (JPCs), related lithological, biostratigraphic, chronostratigraphic and radiometric boundaries are widely addressed in the following studies (Sassen et al., 2006; Sleeper et al., 2006; Macelloni et al., 2012, 2013; Simonetti et al., 2013; Robinson, 2014).

I.III.II SOURCES OF UNCERTAINTY

By using a constant time-depth profile conversion of ~1500 m/s, inaccuracies in the relative true thicknesses of ~0.3 m could be introduced thus affecting horizon picking at depths and isochore analysis. (Robinson, 2014). The single fold nature of acquisition, and the lack of velocity data for the types of sediments present could also help misrepresent the actual velocity of the sediments, as well as affect core data collection possibly due to sediment cores not being located directly on the seismic line, inclination of cores, and mismatch between depth to target sediments in the profile versus sediment core sampling. These errors might be minimized however, considering that Woolsey Mound's very shallow sediments, which are fine grained hemipelagic mud, often falling out of suspension and draping along the continental shelf. As these hemipelagic sediments are deposited slowly on GOM's slope, they accumulate too rapidly to react with sea water, and thereby can help reduce greater velocity contrasts and other effects.

I.IV GEOLOGICAL AND GEOPHYSICAL EVIDENCE OF PALEO MOUND DEVELOPMENT (PMD)

Geological observations of past GHCS onset and development rely on the presence of buried carbonate hard grounds, pockmarks, craters, gas venting and chimney observed at paleo seafloor with high paleo bathymetric relief (Figure 1.3, 1.4). The Holocene characterization proposes that modern mound development (from initiation to termination) is associated with changes in sedimentation patterns and stratigraphic thinning during mound activity, when compared to a more uniform stratigraphy pre-dating mound onset. Moreover, through oxygen isotope analysis of the upper section of sediment cores, modern activity appears time correlative to the most recent sea level transgression (Robinson 2014).

Based off this analysis, we observed similar and consistent patterns in the deeper stratigraphy with differential subsidence possibly associated with shallow buried methane derived authigenic carbonates (MDACs), proxy for past methane activity.

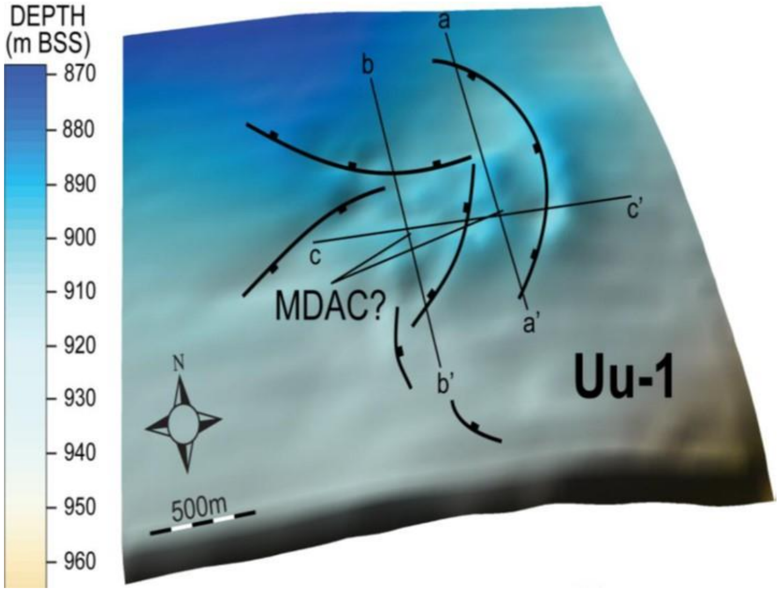


Figure 1.3 Paleo bathymetry, showing shallow buried carbonate mound. High relief of the paleo seafloor occurs in areas with presence of MDACs (Simonetti, 2013).

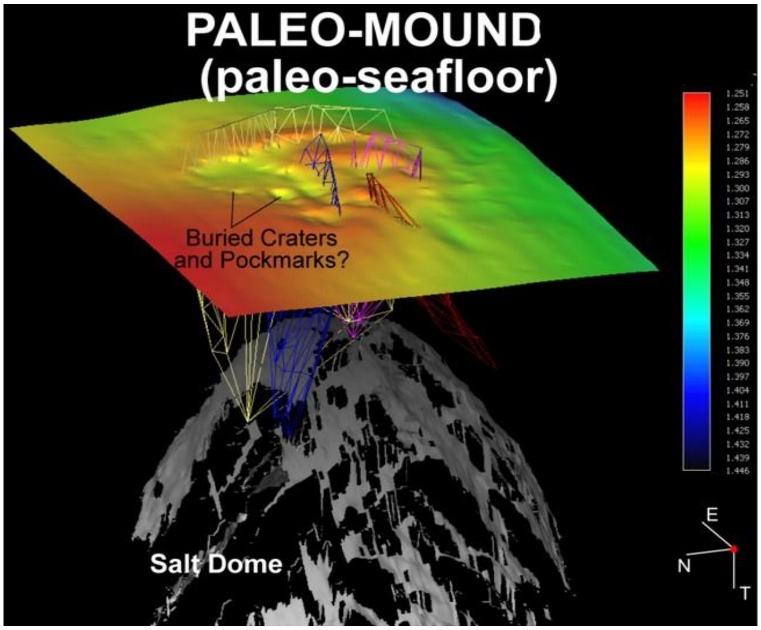


Figure 1.4 Paleo seafloor showing buried craters and pockmarks (Simonetti, 2013).

Geophysical evidences of paleo mound development (PMD) are mainly inferred from seismic anomalies such as seismic attenuation, hydrate chimney, acoustic wipeout, high frequency scattering (HFS), and high resistivity anomalies (HRA), varying both spatially and temporally, Figure 1.6, 1.7 (Simonetti et al., 2013; Xu and Dunbar, 2015). Overall, structural and stratigraphic features at Woolsey Mound cold seeps include faulting, folding, bathymetric uplift, and variable sedimentation deposition rates (Ingram et al., 2010, 2013).

By using chirp profiles and subsequent mapping of deeper horizons, we constructed isochore maps for sedimentation analysis. Chirp data shows much localized sedimentation uniformity prior to and post PMD in areas away from paleo mound activity, but an uneven sediment distribution or growth strata in areas enclosing PMD structure, with truncation and onlapping geometry of stratigraphy. The PMD is denoted by a synkinematic sequence (SKS), exhibiting pronounced lateral variations in thickness, interpreted to result from variable sedimentation during paleo mound onset, and likely induced by salt withdrawal, uplift and/or mobilization in response to increased differential loading. The SKS is enclosed by two angular unconformities: the lower unconformity (Lu-1), and the upper unconformity (Uu-1), where Lu-1 is a base lapping surface separating underlying sub parallel reflectors from overlying onlapping ones, and Uu-1 is a truncation/draping surface separating the onlapping package from the overlying sub parallel reflectors (Figure 1.8) (Simonetti, 2013).

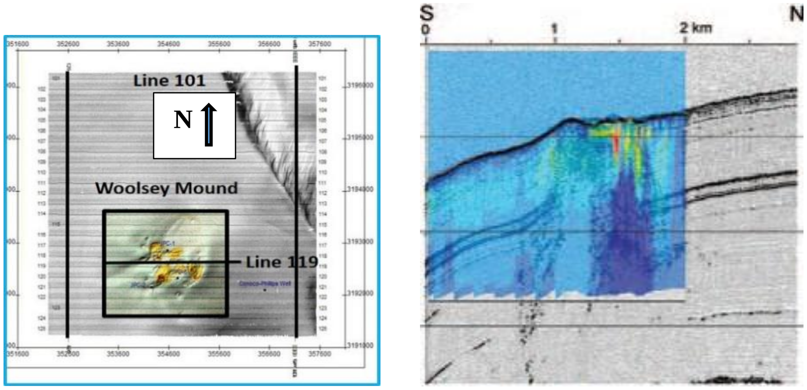


Figure 1.5 **left:** Woolsey Mound base map with line locations; **right:** SSDR line 27, (Xu and Dunbar, 2015) showing average energy attribute overlaid by the inverted resistivity model (approximate location near eastern most N-S line on chirp survey).

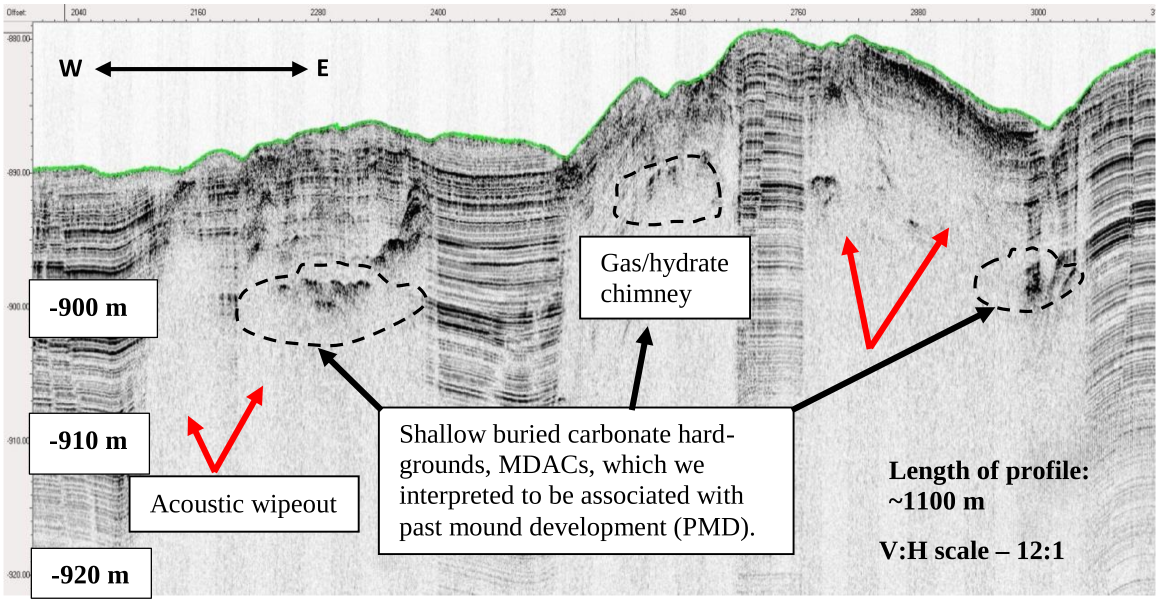


Figure 1.6 West – East profile view of seismic section 119 (a) crossing anomalies inferred to be shallow buried carbonate/gas hydrate grounds associated with PMDs.

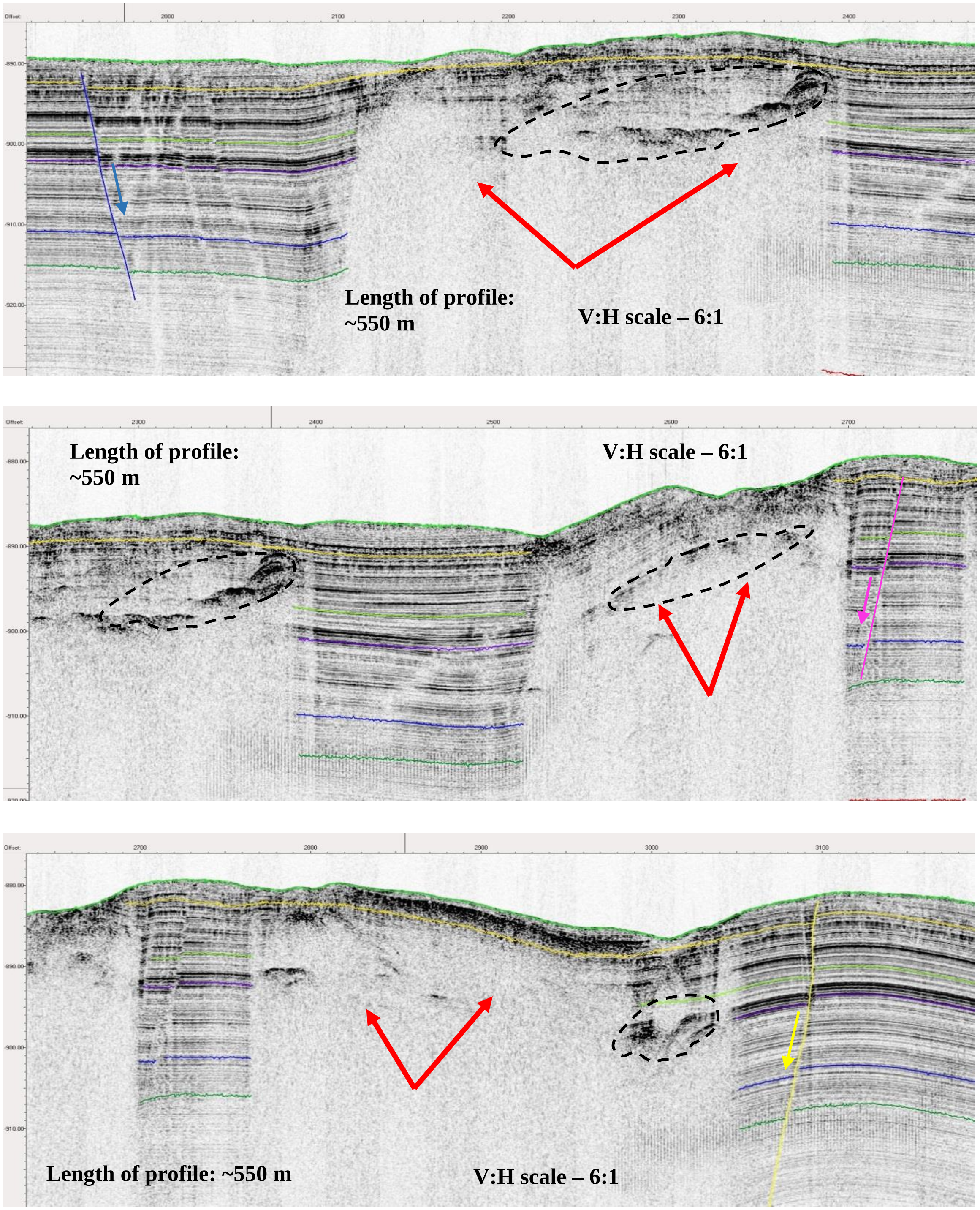


Figure 1.7 Seismic Section 119 (b) **top:** Left of PMD structure – spatially associated with location of buried carbonate hard grounds, and blue master fault; **middle:** Center of PMD structure, and pink fault; and **bottom:** Right of PMD and spatial correlation to yellow major fault.

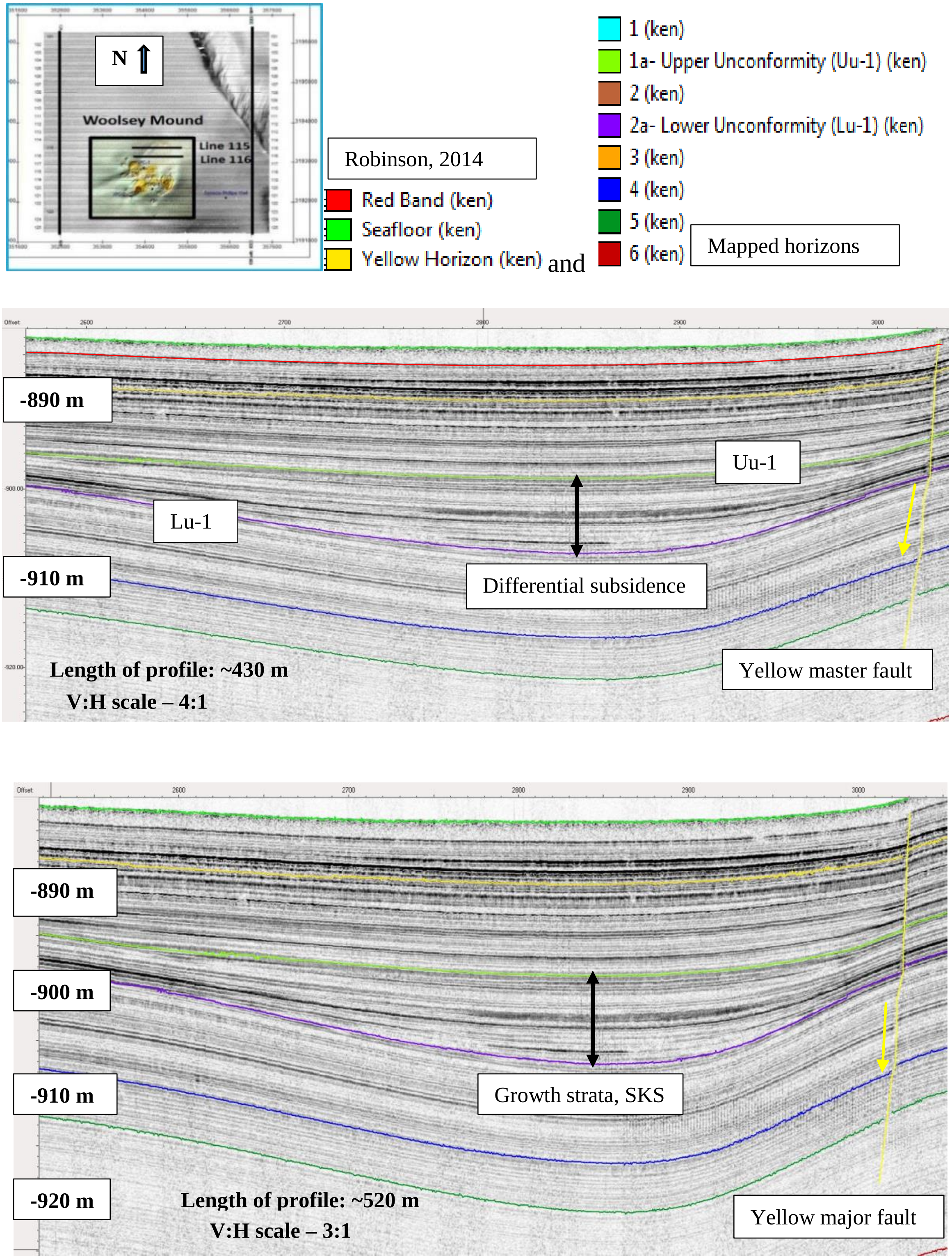


Figure 1.8 **top:** Location map and legend of mapped horizons; **middle:** W–E profile 116, showing much localized differential subsidence of ~5.5 m, and ~1.5 m of constant offset throughout stratigraphy against the yellow fault; **bottom:** Section 118, showing strata growth of ~4.5 m, and a uniform offset of ~1 m, also against the yellow fault.

I.V ISOCHORE MAPS ANALYSIS (DEPTH)

Isochore maps of deeper stratigraphy show 1) uniform or quiescent sedimentation prior to and post PMD, including from end of PMD to the yellow horizon, with strata variance of ~0.5-1 m, 2) uneven sediment distribution during PMD activity, with localized growth strata or differential subsidence of ~5-6 m, with truncation, onlapping synkinematic geometry and stratigraphic thinning away from mound (Figure 1.9).

These results support that Woolsey Mound cold seeps are ‘episodic’, seeming to have a geological process (or combination of various) controlling the on and off switch, from past to modern seepage occurrences. These episodes of methane seepage seem to occur rather very rapidly, following long periods of inactivity. In addition, they may substantiate that hydrates association/dissociation and thus seepage activity, while correlated to sea level fluctuations or tectonic governance, they alone appear to be not as critical or causal geological triggers of seepage onset, development and termination. The dynamics of how these geological features activate and their timing can provide significant insights on predicting their conditioning and their long term global effects.

Integrating these results with modern chronostratigraphic data can further help constrain the age of the paleo mound activity. To a first degree, PMD appears correlative to a relative and punctuated sea level highstand, of mid-Late Pleistocene, ~61 ± 3 kya.

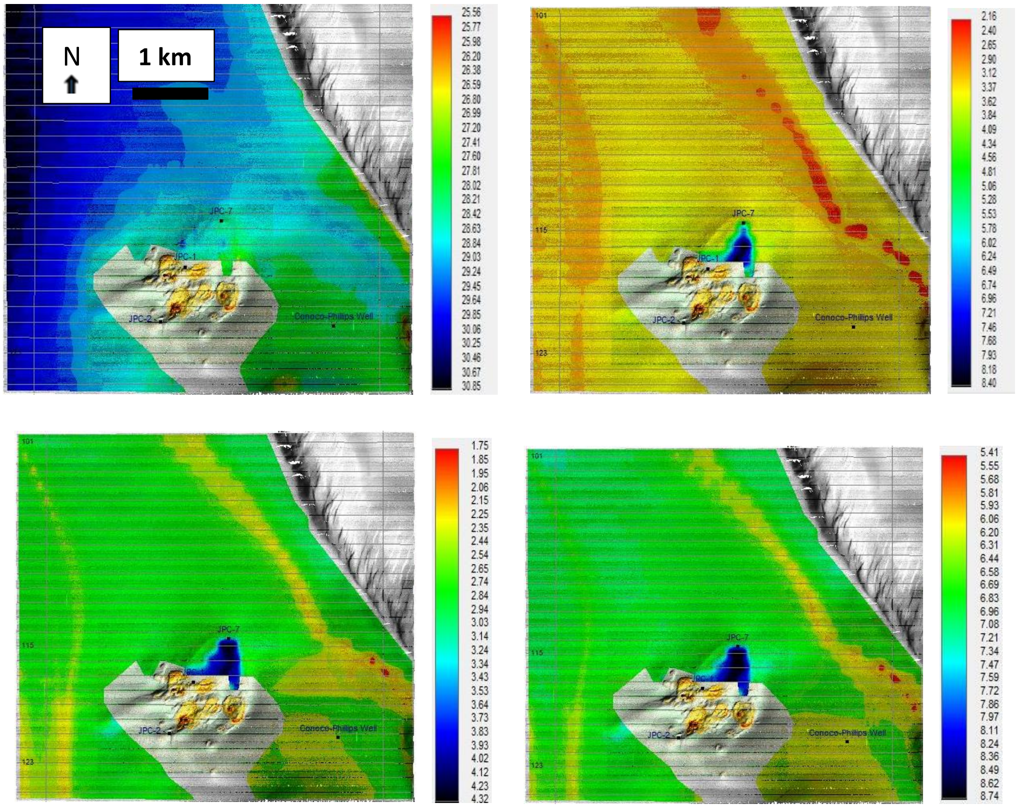


Figure 1.9 With exception of the NE corner of MC–118, North – South isochore maps (true vertical thickness) for deeper stratigraphy (at ~1045 m depth i.e., from late Pleistocene to ~19ka) between horizons show **(top left)**, a variance of ~1 m between horizons h6 to h2a (Uu-1), **(top right)** growth in strata of ~5.5 m between h2a to h1a (Lu-1 and Uu-1 respectively), **(bottom left)** a differential subsidence of ~1.5 m for h1a to h1 horizons, and **(bottom right)** a variance of ~1 m for h1a to the yellow horizon.

I.VI PALEO MOUND DEVELOPMENT CHRONOSTRATIGRAPHIC CORRELATION: INTEGRATION WITH "YELLOW HORIZON's" DATED AGE

To better estimate the timing associated with the PMD superstructure, we extrapolate results from the modern mound characterization. The modern mound seepage onset and termination is temporally constrained to have occurred in the Holocene (Robinson, 2014), after the Last Glacial Maximum and deposition of the "red band" (~14 kya, Figure 1.8), (Ingram et al., 2010) and lasting ~8-4 kya, during most recent sea-level highstand (Robinson, 2014). Moreover, oxygen isotope and radiometric dating constrains the age of a mapped yellow horizon, a post PMD depositional surface, to ~19 kya (Figure 1.10, top), (Robinson, 2014).

Based off this established chronostratigraphic relation, along with known sediment, benthic fauna distribution maps (appendix A), and reasonable estimates on sedimentation rates (SRs) within the mound, between highstands and lowstands, we could best estimate the age of PMD. In reference to the PMD structure, looking at rates of differential subsidence, most activity appears much localized and spatially close to master faults. For example, profile 115, in northern most area of activity, has a maximum subsidence of ~4 m and no faulting activity, while profile 116 sees ~5.5 m in growth strata, with faulting expression (Figure 1.10).

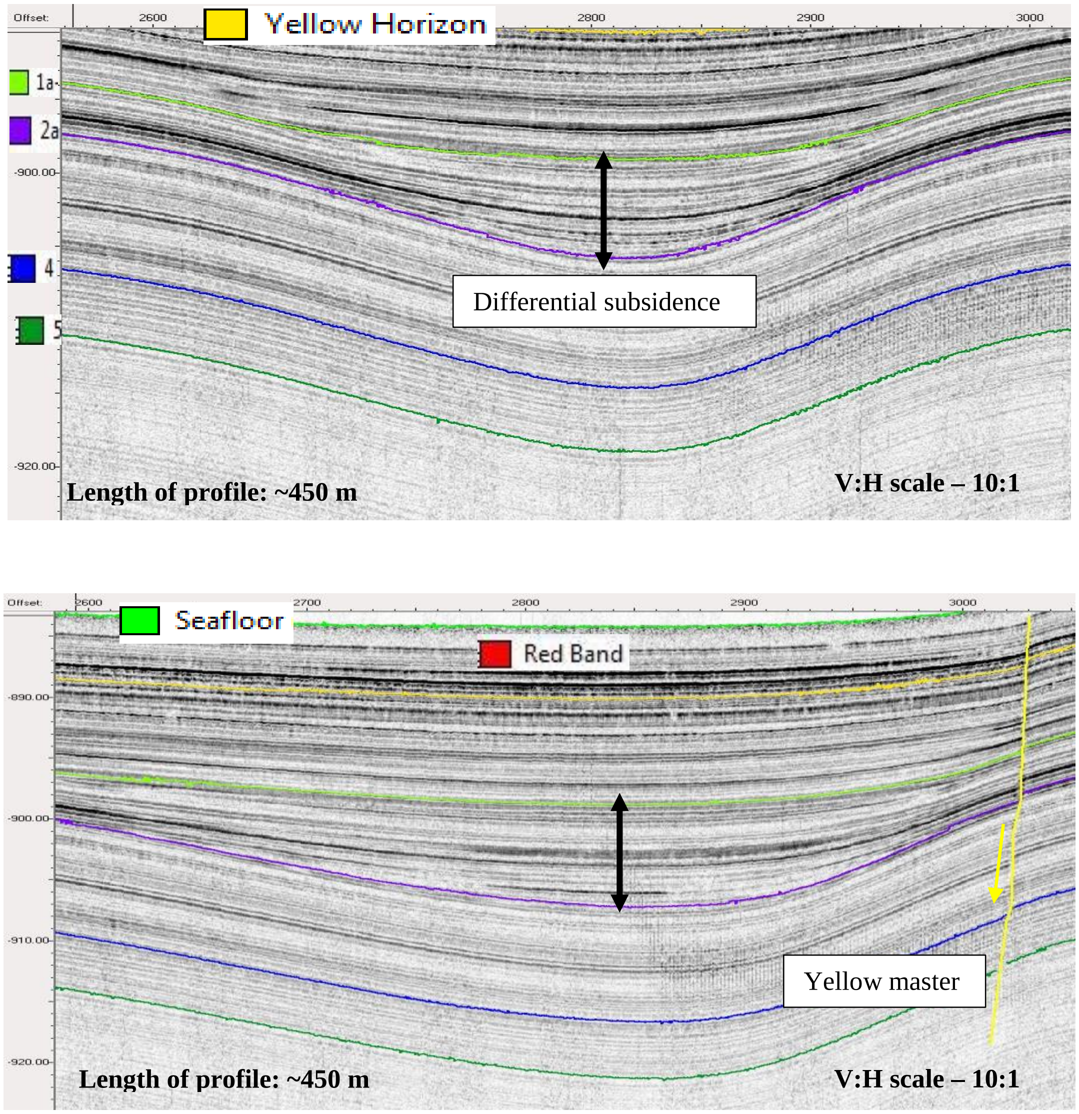


Figure 1.10 **top** Seismic line 115 with ~4 m in subsidence during PMD; **bottom** Profile 116 showing onset and termination of PMD with a differential growth of~5.5 m, as well as quiescent faulting with uniform offset of stratigraphy along it (yellow fault).

However, determining and validating appropriate SRs across the mound extent is difficult due to structural complexities, and GOM's high spatial and temporal variability in sedimentation deposition rates, often of ~25-50 cm/kyr (Bredehoeft and Hanshaw, 1968; Vendeville and Jackson, 1993; Ingram et al., 2010, 2013), derived from shallow gravity core dating, anomalous fluid pressures in sedimentary sequences, as well as overall slope distribution patterns resulting from varying salt deformation styles. Through modern mound's description and the age constraint associated to known stratigraphic units (yellow horizon, ~19 kya and "red band", ~14 kya), post-dating PMD and pre-dating modern activity, we can better derive SRs values prior to recent transgression, and thus better constraint age associated to PMD.

The average depth estimate from the 'yellow horizon' to the lower unconformity horizon (Lu-1) is ~15 ± 0.1 m (using correlational polygon), allowing us to correlate depth-time with relative certainty. Considering above range of SRs, in extreme cases assuming constant SRs of ~25 cm/kyr or ~50 cm/kyr, yields ~60 kyr, and ~30 kyr, with ~1-2 kyr in error. This would suggest that PMD structure was active no earlier than 79 ± 3 kya (upper PMD age bound) and no later than ~49 ± 3 kya (lower PMD age limit).

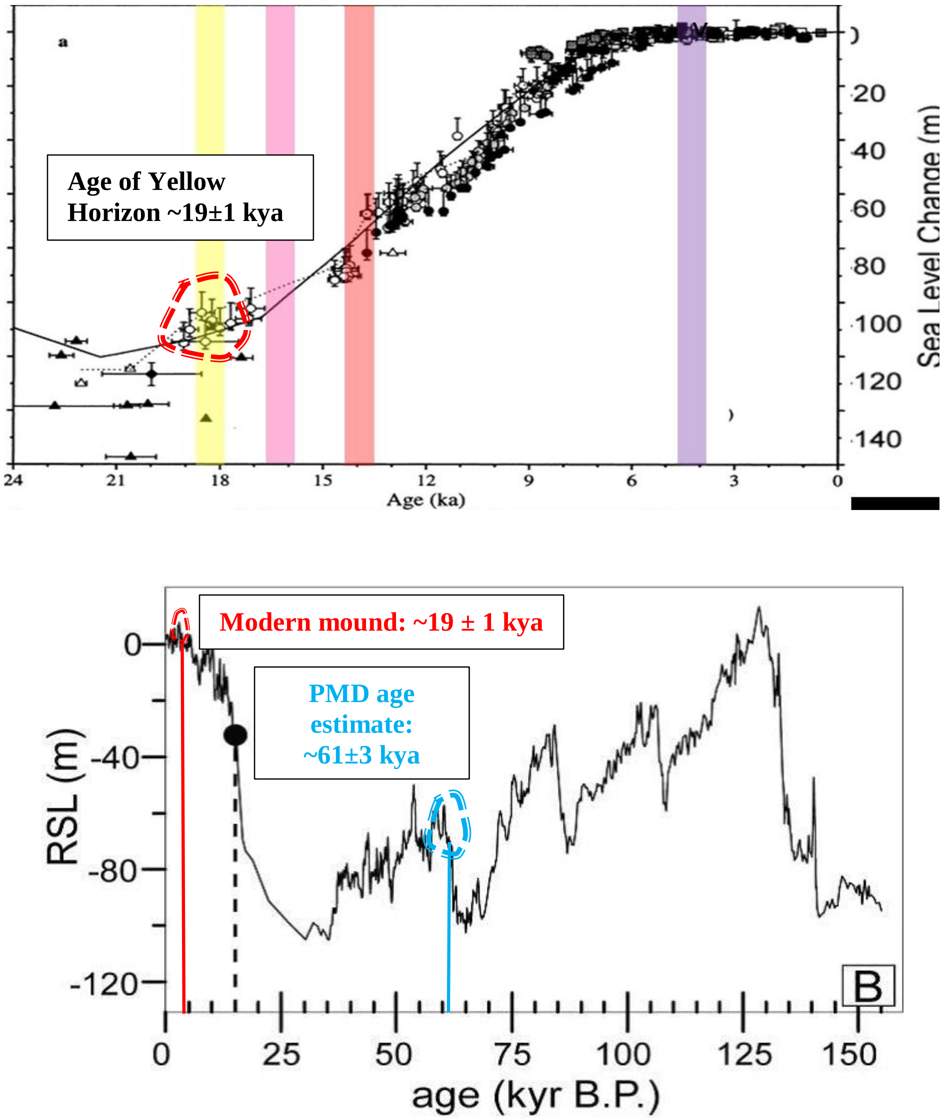
In addition, we measured the depth from yellow horizon to the "red band" to be ~2 ± 0.1 m, spanning ~5 kyr. This gives an SR of ~40 cm/kyr. This SR value seems reasonable, given that any time prior to deposition of 'yellow horizon' into the "red band" the mound system is way into the lowstands, with little variance on depositional rates assuming high sediment supply and variability into the lowstands, due to lowering of sea-level and decreased hydrostatic pressure.

Furthermore, the sediment thickness between Uu-1 and the yellow horizon is relatively uniform (Figure 1.9, bottom right), with ~1 m subsidence compared to an average of ~1.5 m growth resulting in uniform sedimentation from yellow horizon to the red band. This suggests relative quiescent stage before deposition of yellow horizon, but relative lower sedimentation rate, likely influenced by the frequency of changing sea level, from intermediate to punctuated stages.

To a first order, accounting for regional factors, relative deglacial sea level rise during Late Pleistocene to Holocene, and uniform sedimentation post-PMD structure (see isochore maps), we have further constrained SRs values to an average of ~35 ± 5 cm/kyr prior to deposition of the yellow horizon, with thick growth sequence along highest subsidence zones and stratigraphic thinning away from it. This ensures that any sediment variability during lowstands fall within the upper and lower bounds. Since the thickness from yellow horizon to Lu-1 is ~15 ± 0.1 m, assuming SRs of ~30 cm/kyr and ~40 cm/kyr, gives a length of ~50 kyr and ~38 kyr. This yields ~69 kyr and ~57 kyr, again within ~1-2 kyr error, from base of yellow horizon to top of Lu-1, providing another bound for the PMD occurrence. To a mean rate, an SR of ~35 cm/kyr yields ~42 ± 3 kyr. This would indicate that paleo mound activity occurred ~61 ± 3 kya, in the mid-Late Pleistocene. Based on a global sea level curve, PMD seems correlative to a very rapid transgression, during relative sea level highstand (Figure 1.11).

These age bounds should be regarded with cautious, however. Some errors associated with the PMD age estimate were derived using basic rules for uncertainty calculations. The absolute uncertainty for the yellow horizon’s age is ~19 ± 1 kya (Figure 1.10, top). The absolute/relative error in the measured depth to Lu-1, from yellow horizon, is ~15 ± 0.1 m (or 15 m ± 0.7 %), which yields ~42 ± 2 kya (or 42 kya ± 4.8 %).

Hence, ~(19 ± 1) kya + ~(42 ± 2) kya, gives PMD estimate of ~(61 ± 3) kya.



Age of Yellow Horizon ~19±1 kya

Modern mound: ~19 ± 1 kya

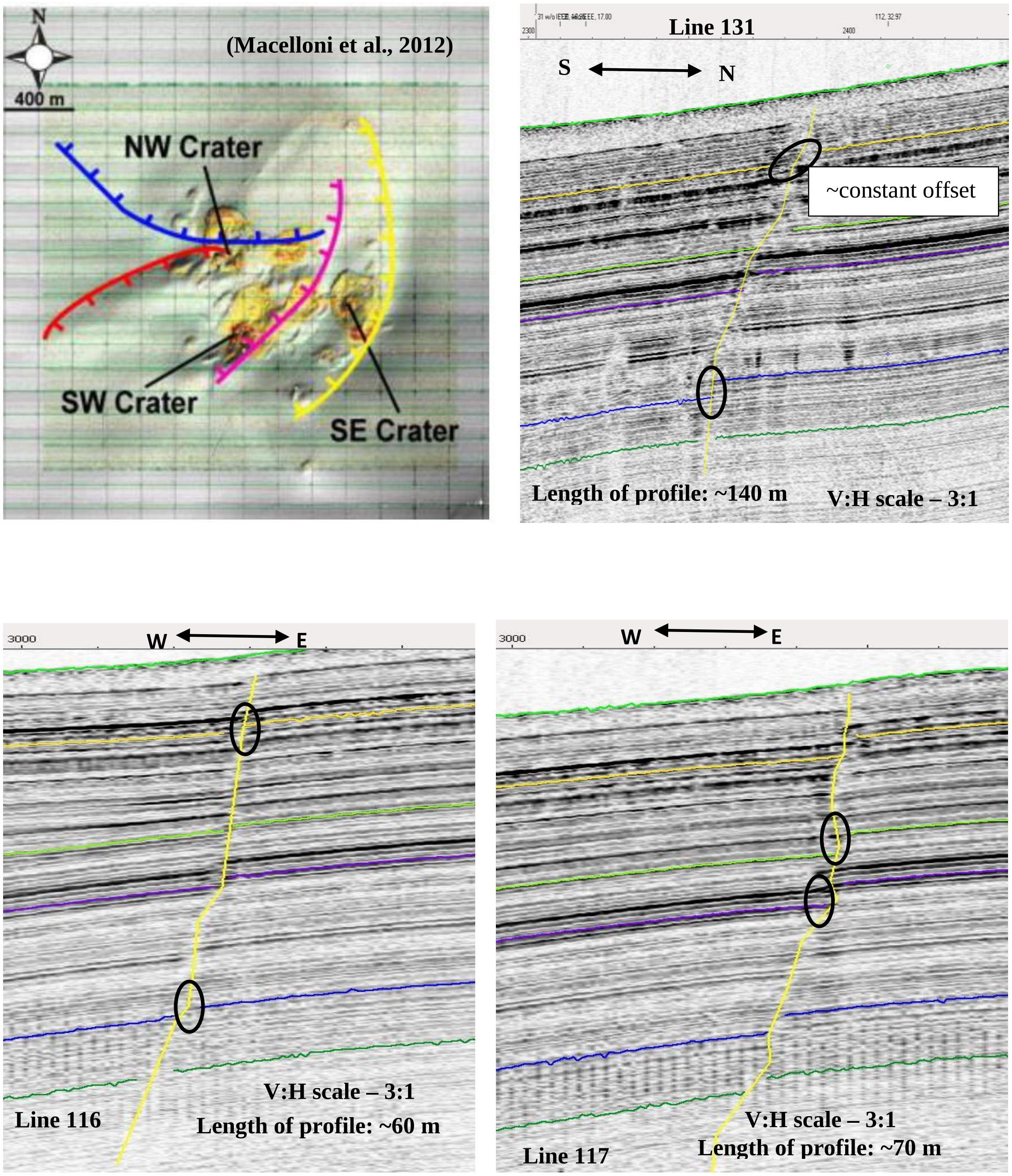
PMD age estimate: ~61±3 kya

Figure 1.11 **top:** Sequence of geologic events at Woolsey Mound in relation to sea level (modified after Fleming et al. 1998). The age of the yellow horizon is based off radiocarbon dating and expected sedimentation from Ingram et al. 2010 (Robinson, 2014) **bottom:** Relative sea-level curve (RSL) of depth b.s.f versus age in kyr before present (BP). The construction of Woolsey Mound, in particular the developments of its paleo mound system could be correlated to a relative sea level highstands, amid a series of lowstands. (Adapted from Rohling et al., 2009).

I.VII EVIDENCE FOR QUIESCENT TECTONISM DURING PALEO MOUND DEVELOPMENT

Woolsey Mound cold seeps are thought to occur primarily via faults, which provide upward conduits for rising thermogenic gas hydrates. This requires some hydraulic connectivity that allows free gas availability and escape (Simonetti et al., 2013), as well as other dissociation processes such as changes in bottom temperature, anomalous pressure, water salinity, sea level fluctuation and salt tectonics that affect the shallow subsurface (Macelloni et al., 2012; Simonetti et al., 2013; Robinson, 2014). These faults can also act as seals or hydrate reservoirs, provided no recent movement. If sealing faults, they would accumulate gas/hydrocarbons in the subsurface, releasing them during active seepage, as a result of pressure release up fault. This leaves contentious the ultimate relationship or the effect of active tectonism (faulting activity) and the PMD structure, given their spatial constrains.

The spatial distribution of these hydrate mounds on seismic are associated with the location of master faults, craters and zones of high frequency scattering (HFS) (Simonetti et al., 2013). Paleo mound development (PMD) appears to have occurred during a quiescent tectonic environment. There's enough syn-kinematic evidence suggesting a constant or uniform offset of ~0.5-2 m throughout deeper stratigraphy until recent fault escarpments with seafloor, along major faults i.e., blue, pink and yellow faults, despite variance/growth strata associated to PMD occur in close proximity to those faults. The yellow fault, possibly and older flux system for example, is the third largest route for rising hydrocarbons and with medium displacement compared to the blue and pink ones. These latter faults are associated with recent movement and activity, and act as secondary migration pathways, (Figure 1.12 – 1.14) (Knapp, 2010, Macelloni, et al., 2012). The faults have general NW–SE trend, seemingly consistent with NW trend of salt mobilization.



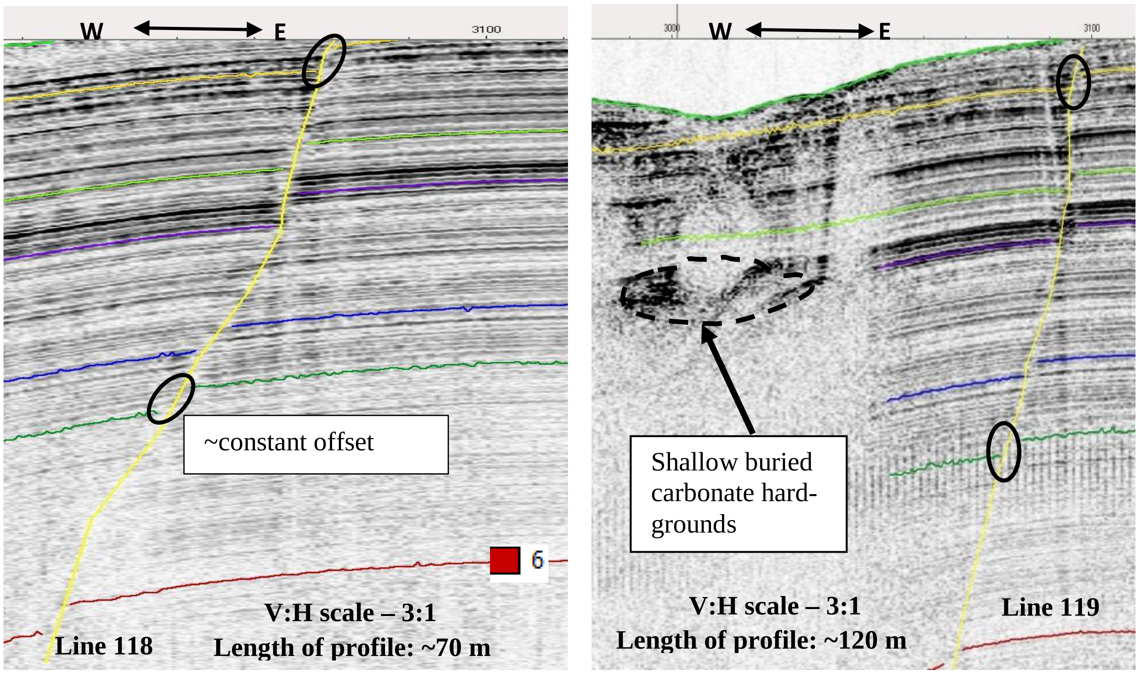


Figure 1.12 Yellow Major Fault Displacement, with ~1-2 m constant offset.

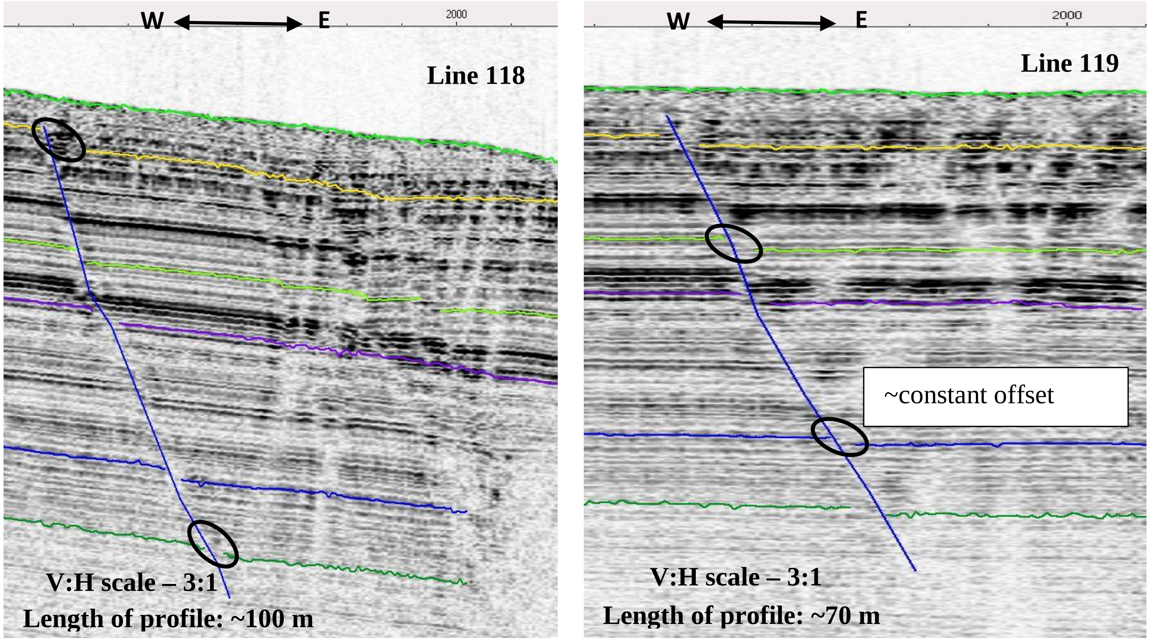


Figure 1.13 Blue Master Fault Displacement, with ~0.5-1 m uniform offset along stratigraphy.

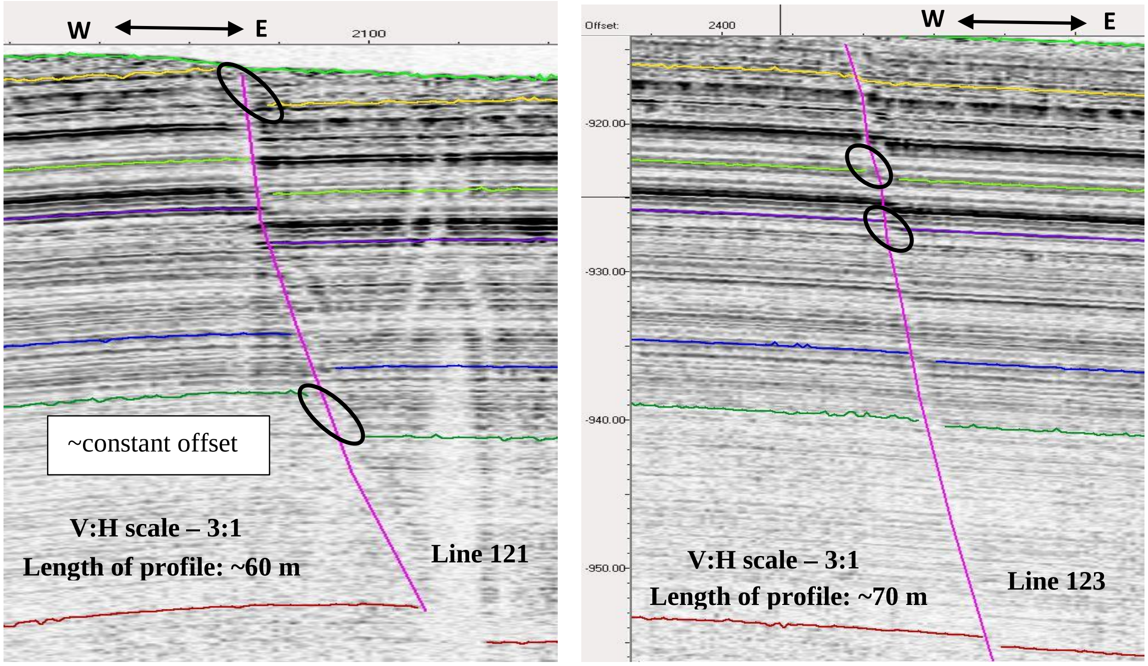


Figure 1.14 Pink Major Fault Displacement, with ~2-3 m constant offset throughout stratigraphy.

I.VIII SALT TECTONICS AND POSSIBLE INFLUENCE ON WOOLSEY MOUND'S COLD SEEPS HYDRATE FLUX SYSTEM

With respect to this study, and given modern results, the fact that PMD activity likely occurred during relative sea level highstands, in a tectonically quiescent environment is important to establish that Woolsey mound activities, both modern and past ones, may not be governed solely by sea level fluctuations or active tectonics. While correlative to sea level highstands, there lacks a causal relationship, leaving to discussion the true geological forcing trigger(s) of methane seepage. The analysis of this data and results would fall short without a basic salt tectonics understanding and approach, and its overall forcing effect on mound development, both past and modern.

The Gulf of Mexico as a petroleum basin is inextricably tied to the hierarchic complexities arisen from salt deformation styles, from allochthonous withdrawal and extension to diapirism (Salazar et al., 2013). Under deformation, though very slow, salt is mechanically stable when compressed during burial or withdrawal. These, in addition to other physical forces such as gravitational loading (lateral salt flow towards thinner or less-dense overburden) and displacement loading (often horizontal and driven by tectonic force) result in complex and asymetrical continental slope with varying stratigraphic and structural architectures). Moreover, like Woolsey's shallower structures, vertically and horizontally connected GOM's salt bodies appear trending in the NW–SE direction, likely indicating withdrawal and movement direction (Dribus et al., 2008).

In terms of the mound dynamics, since salt tectonics is a function of sea level and sediment inputs (Robert and Carney, 1997), as it evolves, it creates intrabasins and mini-basins, (passive) diapirs, canopies, squeezed structures and forms, within shallow accommodation zones, without necessarily faulting. Sometimes, these result from rapid deposition and accumulation, particularly with abundant and readily available sediment supply. Therefore, while directly not causing PMD structure to activate, sea level fluctuation or tectonic governance may be influenced by salt movement locally due to the interdependency between sediment loading, sea-level changing and faulting on the slope, or PMD structure likely forced by minor salt adjustments and increased pressure up faults. An evidence of local withdrawal can be seen across the mound in NE corner of MC–118, with a major salt slump feature and numerous shallow fractures, mimicking the mound's core structure.

As a result, with continued yet slow movement, salt tectonism can effect pore-water salinity, fractured porosities or other pressure instabilities, driving hydrates destabilization and thus methane seepage. Understanding the relationship of gas hydrate mounds, and their spatial and temporal variations in relation to the lateral and depth extent of salt presence in the subsurface, or where we see evidences of seismic energy scattering and high resistivity anomalies, can help discriminate more precisely these mound occurrences, both modern and most importantly past ones, at greater depths.

I.IX RESULTS AND DISCUSSION

This study reveals interesting results regarding Woolsey's observed paleo mound development (PMD) and activity. Isochore analysis of deeper stratigraphy shows uniform sedimentation prior to and post PMD with strata variance of ~0.5-1 m, and uneven sediment distribution pattern during PMD activity, with a localized differential subsidence of ~5-6 m and onlapping syn-kinematic geometry. Depth analysis and integration with modern chronostratigraphic results further indicates that PMD correlates to relative sea level highstand, during mid-Late Pleistocene (~61 ± 3 kya). In addition, PMD appears to have occurred during a quiescent tectonic environment as evidenced by a constant offset of ~0.5-2 m throughout stratigraphy, along major crestal faults.

If correct, these structural data and results substantiate that Woolsey Mound cold seeps are episodic, and that they occur irrespective of sea level fluctuation or tectonic governance. These findings are supported by their previously documented modern occurrence, and now, of an interpreted past mound development. Though 2D, fault slip analysis along stratigraphy in close proximity to PMD structure demonstrates uniform offset along master faults, throughout imaged stratigraphy. The constant offset is observed to have occurred prior to, during and post paleo mound activity, including during modern activity, evidenced by tectonic termination, and deposition of draping unconformity ~4 kya (Robinson, 2014). This attests for PMD activity in a quiescent tectonic setting, and ground truths Woolsey's seepage episodic nature. Though correlated to sea level fluctuation, there appears to be no causal or one-to-one relationship between PMD and changing sea level.

Similar to modern mound results, episode of past methane seepage appears to have occurred in a relative sea level highstands, during punctuated transgression and periods of high pressure environment. The interdependency between rising sea level, sedimentation and salt adjustment/movement as result of differential loading could be attributed as providing the framework for past seepage activity.

In relation to major faults, results show that PMD activity may not correlate to active faulting, further constraining that these crestal faults and other mini fractures could have acted as hydrate reservoirs, at least until very recently, upon tectonic termination. Fault activity and growth fault down dip structures appear to follow periods of slow yet punctuated movement, as evidenced by uniform and constant offset along stratigraphy.

I.X CONCLUSION

This study presents the first evidence for a Woolsey's paleo mound development (PMD), likely active during a punctuated and relative sea level highstand in the mid-Late Pleistocene, approximately 61 ± 3 kya. PMD structure appears to have occurred within an inactive or quiescent tectonic setting, as evidenced by an observed uniform constant stratigraphic offset of ~0.5-2 m along major faults. These results suggest that substantial subsurface methane fluxes may be triggered independently from active faulting or eustatic fluctuations. Therefore, sea level fluctuation or tectonic governance alone may not be too critical of geological causes of seepage development. It appears that salt withdrawal, movement or adjustment control the overall tectonic architecture of the mound system, at least in the longer term, though lacking evidence in the upper resolution of the chirp survey. In the short term, methane seepage occurs most likely at the frequency of sea level change, and hydrates stabilization/destabilization.

Confined to its physical nature, the evolution of salt structures in response to differential loading can over time be attributed as a primordial cause for overall mound development (both past and modern), as well as active tectonics, particularly during periods of high vertical or lateral movement, and periods of slow but punctuated motion, as salt eventually comes to a relative relaxation.

These influences help destabilize the slope, and create accommodation space for sediments to fill in, generating growth strata. Methane seepage while occurring even without active faulting (tectonic), can be linked to relative sea level highstands and salt movement. This supports that depressurization of gas hydrates as a result of sea level lowstands may not have been the trigger for Woolsey Mound's past seepage onset or paleo mound development (PMD).

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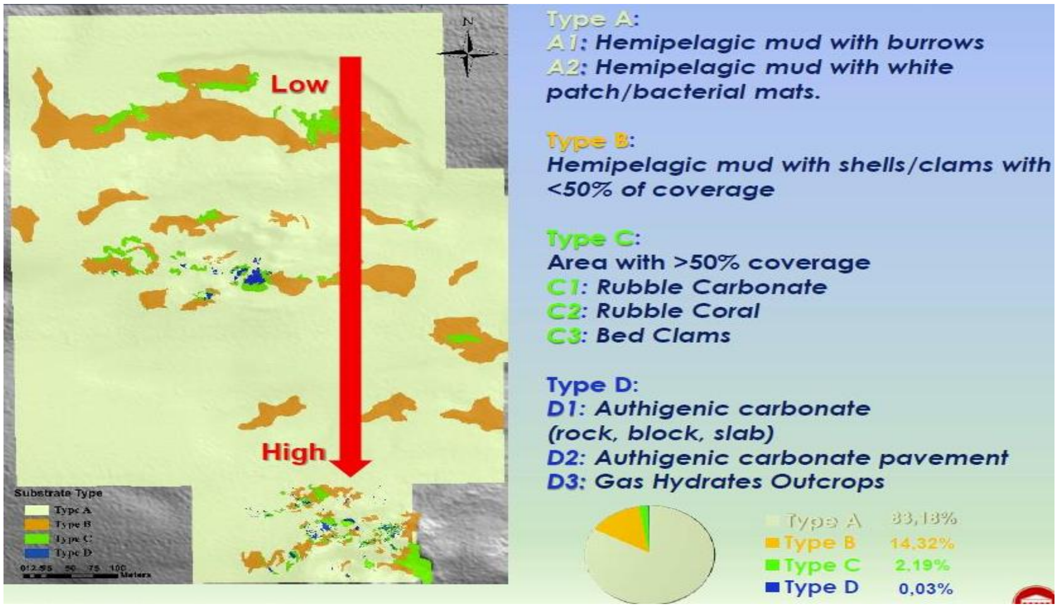
APPENDIX A SUPPLEMENTARY DATA



Type A:
A1: Hemipelagic mud with burrows
A2: Hemipelagic mud with white patch/bacterial mats.

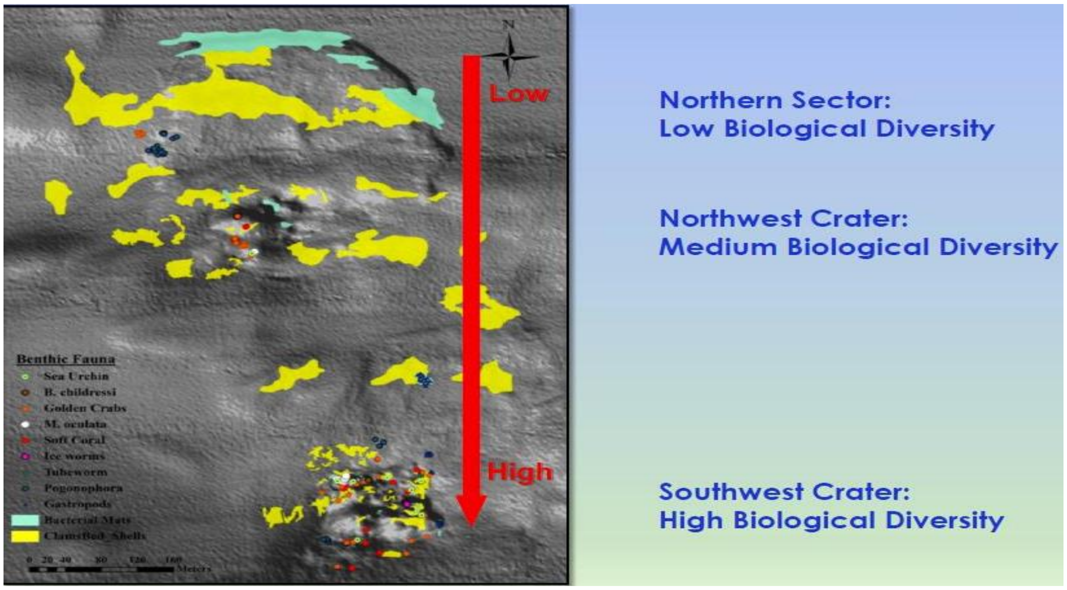
Type B:
Hemipelagic mud with shells/clams with <50% of coverage

Type C:
Area with >50% coverage
C1: Rubble Carbonate
C2: Rubble Coral
C3: Bed Clams

Type D:
D1: Authigenic carbonate (rock, block, slab)
D2: Authigenic carbonate pavement
D3: Gas Hydrates Outcrops

Type A	83,18%
Type B	14,32%
Type C	2,19%
Type D	0,03%

Figure A.1 Sediment Distribution Map Over Woolsey Mound, MMRI, GOM–HRC 2011



Northern Sector:
Low Biological Diversity

Northwest Crater:
Medium Biological Diversity

Southwest Crater:
High Biological Diversity

Figure A.2 Benthic Fauna Map Over Woolsey Mound, MMRI, GOM–HRC 2011

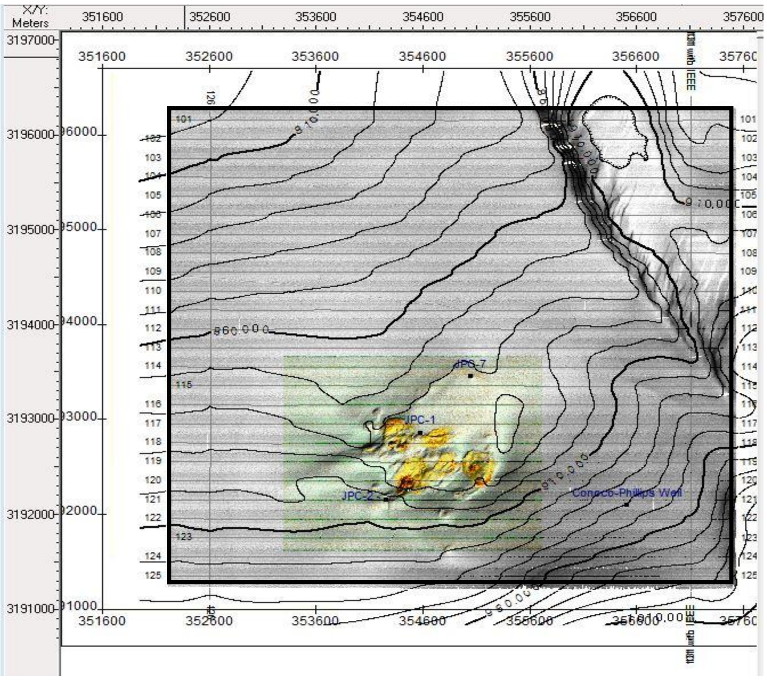


Figure A.3 Seafloor Bathymetric Map Over Woolsey Mound

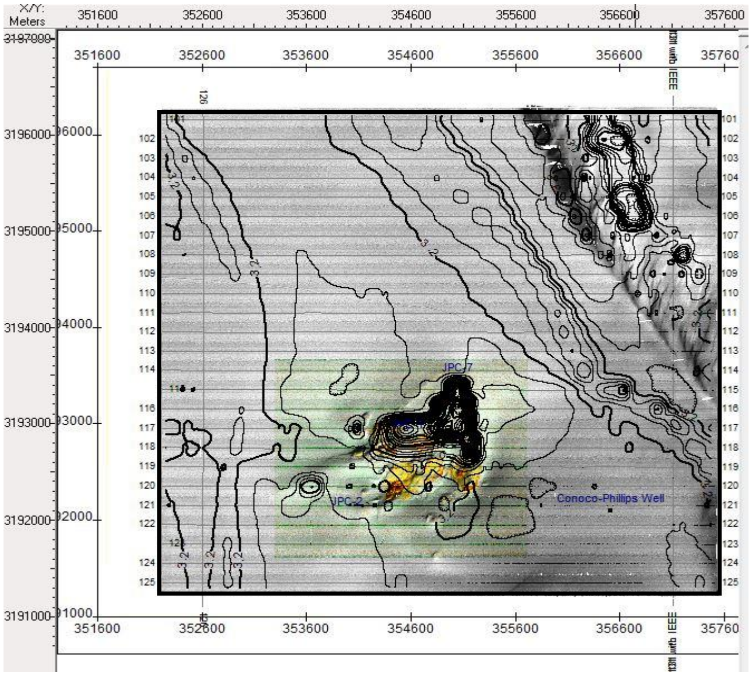


Figure A.4 Isochore horizon grid contours between H2a (Lu-1) to H1a (Uu-1) i..e., Lower unconformity-1 to Upper unconformity-1