Seismic Characterization of a Gas Hydrate System in the Gulf of Mexico Using High-Resolution Wide-Aperture Data

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Summary

Gas hydrates were discovered in a mud diapir in the leased block Mississippi Canyon 798, Gulf of Mexico, through piston coring. Subsequently, a seismic experiment was carried out to investigate the dynamics behind the hydrate formation. During the experiment high-resolution multi-channel seismic reflection data using a 24 channel streamer and wide-aperture data using six ocean bottom seismometers were collected along five lines. High Reflectivity Zones (HRZs) are present in the reflection data along all lines. A wedge shaped feature is also present adjacent to the HRZs on some lines. To better constrain the interpretation of the reflection data, the traveltimes from the multi-channel and wide-aperture datasets were jointly inverted to estimate a P-wave velocity model along each line. A minimum-parameter/minimum-structure modeling approach yielded geologically simple models and a comparison of the models at their intersection points shows they are consistent to within ±10 m/s in velocity and ±20 m in depth. In the final P-wave velocity models, the HRZs are associated with a lowering of velocity. The simultaneous presence of high reflectivity and lowered velocity is attributed to the presence of free gas. Surface topography and studies from nearby areas suggest ongoing deformation in the region due to the movement of salt bodies. The faulting and fracturing due to salt movement may serve as conduits for gas from deeper sources which gets
trapped and creates the HRZs. Two geological scenarios are proposed to explain the presence of the wedge adjacent to the HRZs. First, the wedge-shaped feature is interpreted as the levee of a channel complex whose axis serves as a reservoir for free gas. In this case, hydrates would not be expected to exist, except close to the HRZs, and we wouldn't expect to be able to identify the hydrate-gas interface in the seismic data. Second, the top the wedge-shaped feature is a bottom simulating reflector (BSR) and the reflection strength and shape of the BSR is due to the concentration of free gas and salinity decreasing laterally away from the HRZs; gas hydrates may be present throughout the study area, giving rise to BSRs where the concentration of free gas is adequate.

Introduction

Gas hydrates are naturally occurring solids comprised of water molecules that form a rigid lattice of cages around gas molecules of low molecular weight. Although other gases form hydrate, such as CO₂ and H₂S, methane is the most common gas, estimated to make up more than 99% of naturally occurring hydrates (Kenvolden 2000). Gas hydrates have been of interest to the geoscience community for over thirty years due to their potentially significant role in climatic change, the carbon cycle, seafloor stability, and as an energy resource.

Gulf of Mexico gas hydrate discoveries can be traced to 1984 (Brooks et al. 1984). Hydrate discoveries in the Gulf of Mexico have commonly been made by the analysis of high-resolution shallow seismic datasets collected by the industry to determine the seabed and near subsurface conditions before deploying offshore facilities (Antoine 1975; Sieck & Self 1977; Prior & Coleman 1981).

Neurater & Bryant (1989) analyzed a seismic dataset from the leased block Mississippi Canyon 798 (Fig. 1) (hereafter referred to as MC798) and found evidence for the presence of gas
hydrates in a small topographic mound in the SE region of the block. The mound seemed to be
acoustically amorphous in an otherwise generally well-stratified region. It has 10 m of relief, stands
beneath a water depth of 810 meters and has a radius of 275 m. A 10 m piston core taken at the crest
of the mound revealed that the mound was a mud diapir. The recovered core had approximately 5 m
of greenish-gray to black silty clay with white ice-like chunks of gas hydrates disseminated in the
matrix (Neurater & Bryant 1989).

In 1998, the U.S. Geological Survey, the University of Mississippi, and the Department of
Energy jointly conducted a high-resolution seismic survey in MC798 to understand the properties of
hydrate-bearing sediments in the block. High-resolution multi-channel seismic (MCS) reflection and
ocean bottom seismometer (OBS) data were acquired around the mud diapir along five lines, each
approximately 10 km long (Fig. 1).

In this paper, two-dimensional (2-D) P-wave velocity models have been developed along the
five shot lines for the shallow subsurface using the Zelt & Smith (1992) traveltime inversion
algorithm; hereafter referred to as ZS92. The velocity models have been obtained by inverting the
wide-angle and the near-vertical datasets simultaneously. Geologic interpretations of the velocity
models have been made to explain the key features in the models and the seismic data.

Background: Gas Hydrates and the Gulf of Mexico

The Gulf of Mexico is increasingly being identified as a focused-methane-flux environment where
faults supply gas to localized zones within the gas hydrate stability zone (GHSZ) as opposed to an
environment where gas is present throughout the GHSZ in quantities enough to sustain a hydrate-gas
system (reference needed from Ingo). The northern deep-water slope of the Gulf of Mexico consists
largely of mini basins formed by salt withdrawal separated by ridges above the crests of sub-surface salt structures (e.g. Nelson 1991). Above these ridges and along the flanks of salt domes, extensive faulting occurs, providing numerous deeply rooted fluid migration paths. Vent sites, such as mud diapirs and volcanoes, are ubiquitous where these faults intercept the seafloor (e.g. Neurauter & Roberts 1994). Gas hydrates have been observed frequently as outcrops or in shallow sediment cores in the vicinity of vent sites (Neurauter & Bryant 1989; MacDonald et al. 1994).

Gas hydrates and free gas affect the elastic properties of the host sediment in ways that are seismically detectable. They have historically been inferred on the basis of the presence of high amplitude reversed polarity events on seismic reflection records that mark the base of the GHSZ, known as bottom simulating reflectors (BSRs) (e.g. Shipley et al. 1979; Holbrook et al. 1996). The depth of the base of the GHSZ depends mainly on the geothermal gradient, salinity and P-T conditions of the subsurface. Gas hydrate systems in the focused-methane-flux environment generally seem to lack the conventional ways in which BSRs are thought to manifest themselves in seismic data (Bangs et al. 1993; MacKay et al. 1994; Holbrook et al. 1996). One reason may be that in petroleum generating areas like the gulf, where other gas hydrate forming gases leak up from great depths through fault systems, the base of the GHSZ is significantly perturbed (Paull et al. 2000).

**Seismic Experiment and Data**

In 1998, the U.S. Geological Survey, the University of Mississippi and the Department of Energy jointly conducted a high-resolution seismic survey using the R/V Tommy Munro in MC798 (Dillon et al. 1999). High-resolution MCS and OBS data were acquired along five lines (two north-south, two east-west and one northwest-southeast), each approximately 10 km long (Fig. 1). A 575/575cm³
generator/injector (GI) airgun source with a dominant frequency of ~120 Hz was used. The shot spacing was ~28 m. The MCS shot logger recorded the data with an accuracy of 0.01s.

Multi-Channel-Seismic Reflection Data

The MCS data were acquired using a 24-channel streamer with a near trace offset of 40 m. The streamer was 240 m long with a 10 m group interval and three hydrophones per group. The near trace from each MCS shot is collectively termed the single-channel-seismic (SCS) data. For display purposes in this paper the SCS data have been used because they are less susceptible to processing artifacts and they show the relevant structural features.

As shown in Figures 2a through 6a, three events E1, E2 and E3, were distinct and coherent enough to be identifiable on all lines. The first of these events (E1) marks the base of an acoustically transparent layer, possibly a pelagic Holocene drape of silty clays (Neurauter & Bryant 1989). This layer is referred to as L1. The second and third reflection events (E2 and E3) are from the base of sedimentary packages L2 and L3. The lithology of L2 and L3 are not known due to the absence of well logs or core samples. Some coherent events were also identified locally (feature R) but their continuity becomes obscure at various depths. The diapir manifests itself as chaotic reflections (feature C) on the lines passing near it. Thick chaotic seismic sequences show up as high reflectivity zones beneath E2 at different locations (feature Z). The lowermost event (E3) seems to dome up beneath the diapir.

For better resolution of the reflection events, the MCS data from all the shot lines were converted into six-fold common-midpoint (CMP) stacks with a trace spacing of 14.5 m using conventional CMP processing techniques (P. Hart, personal communication 2001).

Ocean Bottom Seismometer Data
The wide-angle OBS data were collected at the same time as the MCS data using the same source and six OBSs deployed around the mud diapir 1.5 km apart along the lines (Fig. 1). Each of the OBSs collected four component data: three displacement components using 4.5 Hz geophones and one pressure component. The sampling interval was 1.434 ms. The maximum offset for which picks could be made was typically about 4.5 km. Only the inline components of the OBS data recorded by the hydrophone and vertical geophone (z-component) have been used in the 2-D modeling in this paper.

Due to clipped amplitudes and low-frequency high-amplitude noise, the peak frequency of the hydrophone data is relatively low, ~20 Hz (Fig. 7a). The z-component data have a dominant frequency of 40-60 Hz. Due to a lack of strong coupling between the ocean bottom and the OBSs, the z-component data show a lot of ringing (Fig. 7b). Unresolved timing problems with the OBS data necessitated its correction by assuming the direct (water wave) arrival has a constant water velocity of 1.49 km/s (reference?)

Data Picking
A simple method was developed to identify and pick events consistently across the MCS/SCS and OBS data. The portion of the SCS data lying between two OBSs was inserted between the positive offset half of one and the negative offset half of the other hydrophone data such that the direct arrivals on both the datasets coincided. In this process, the subsequent reflection events near zero offset align automatically (Fig. 8). Events E1-E3 were identified and were picked on the SCS data across each line and on the OBS data to about 3 km offset. Beyond 3 km offset, the OBS phases were difficult to identify due to weak signal and waveform changes, and were picked in a bootstrap method using the predicted times from preliminary velocity models (described in the next section).

Modeling Methodology
The traveltime $t$ between a source and receiver along a ray path is given in discrete form as $t = \sum_{i=1}^{n} \frac{l_i}{v_i}$, where $l_i$ and $v_i$ are the path length and velocity of the $i^{th}$ ray segment, respectively. The unknown model parameter is velocity, but since the ray path is dependent on velocity, both the velocity and ray path must be treated as unknowns, making the inverse problem nonlinear (Zelt 1999). To solve the inverse problem, the ZS92 algorithm requires a starting velocity model of the subsurface. The velocity field in a ZS92 model is described by two types of model parameters: velocity nodes and boundary nodes, the latter specifying the depth of interface points between layers. Rays are traced through the starting model and traveltimes are predicted. Predicted traveltimes are compared with the observed traveltimes picked from the seismograms and their difference is used to update the starting model. The updated model serves as the starting model for the next iteration, and the process is repeated until the updated model predicts traveltimes that agree with the observed traveltimes to a degree determined by the assigned pick uncertainties (Zelt 1999).

The MCS and OBS picks were jointly inverted to maximize model constraint and ensure model consistency with both datasets. After common reflection events were identified in both datasets (Fig. 8), the picks from the MCS data were used to construct a pseudo 1-D P-wave velocity model using reasonable velocity values for shallow marine sediments (reference Ingo?). This “1-D” starting model has a constant velocity within each layer, but the layer boundaries have the lateral structure required by the shape of the events in time in the MCS data. Using different sets of velocity values for the layers by trial and error, traveltimes to 3 km offset were computed at all OBS positions. The velocity functions obtained independently at each OBS position that best predicted the traveltimes were found to be close enough to be replaced by a common velocity function for all starting models (1.5, 1.6, 1.7 and 1.8 km/s in layers L1, L2, L3 and L4, respectively). The closeness of the velocity functions below the OBSs suggests the absence of strong lateral velocity variations in the region.
The “1-D” starting model was parameterized using one velocity node placed below each OBS in all layers and more nodes were added only if required by the data. There are no vertical velocity gradients with the layers because there is insufficient refracted ray coverage to constrain gradients. Using the starting model, reflection and refraction times from the base of L1, L2 and L3 were predicted. The predicted times were compared to the OBS data and used as a rough guide to pick events to greater offset and refine a few earlier picks that were largely inconsistent with the initial predictions. The new set of picks was used to update the model and this in turn was used as a guide to slightly refine the model and a few picks in the next cycle. A few cycles like this were repeated until picks had been made at all possible receiver locations and a reasonable 2-D model for each line had been estimated that could be used as the starting model for traveltime inversion using the ZS92 algorithm. Final models were sought that had the following characteristics (Zelt 1999):

1. A minimum number of velocity and depth nodes to predict the observed traveltimes to within their associated uncertainties.
2. Allow rays to be traced to the maximum possible number of observation points.
3. Contains only those features that are required by the data, as opposed to merely being consistent with the data, to avoid over-interpretation.

The determination of pick uncertainties used during the traveltime inversion was based on a combination of the magnitude of the pick refinements required by the initial models, and the dominant frequency of the seismic data. Uncertainties of 6 ms for the OBS data and 4 ms for the MCS data were used. Using the principles of travel time reciprocity, the OBSs were treated as shots and the original shot locations near the sea-surface were treated as receivers for modeling purposes. Lines 1, 4 and 5 have two OBSs, and lines 2 and 3 have three OBSs (Table 1).
As opposed to a conventional “layer stripping” approach for modeling using the ZS92 algorithm, all phases and all model parameters were inverted simultaneously in a "whole model" approach (Zelt 1999); this was possible because the starting models were carefully constructed as described above.

**Modeling Results**

Final models that provide an acceptable fit to the data (Table 2) for all lines were obtained in a single iteration using the ZS92 algorithm. One iteration is not typical for the inversion of wide-aperture traveltime data using this algorithm. However, in this study it occurred because:

1. The starting models were carefully constructed, providing good initial fits to the data.
2. Lateral velocity gradients in the region are not strong.
3. The models consist of relatively few model parameters.
4. In the joint inversion, strong constraints are applied to both the boundary nodes (mainly through the MCS data) and the velocity nodes (mainly through the OBS data) simultaneously.

Line 1 has a NW-SE orientation (Fig. 1). The SCS data show a high-reflectivity zone (HRZ) below OBS D within L3 (Fig. 2a). Two extra velocity nodes at model positions 4.5 and 10.0 km in L2 and L3 were required to fit the data. Overall, there is a lateral lowering of velocity from 1.70 km/s at both ends of the model to 1.66 km/s below OBS D in L3 (Fig. 2b). The model also shows a lowering in velocity from 1.61 km/s from the ends to 1.59 km/s below OBS D and B in L2.

Line 2 is the eastern line with a N-S orientation (Fig. 1). The SCS data show a HRZ between OBSs D and F in L3 (Fig. 3a). The model contains a lowering in velocity from 1.70 km/s below OBS E in the north to 1.67 km/s below OBS F to 1.66 km/s below OBS D in the south in L3 (Fig. 3b). The model shows a similar behavior in L2 where the velocity drops from 1.64 km/s to 1.60 km/s to 1.59 km/s below OBSs E, F and D, respectively.
Line 3 is the western line with a N-S orientation (Fig. 1). The SCS data show a HRZ below OBS B in L3 (Fig. 4a). Two extra velocity nodes were required at model positions 2.0 and 8.0 km in both L2 and L3 in order to fit the data. The model shows a gentle lowering of velocity from 1.70 km/s below OBS A to 1.69 km/s below OBS B in L3 (Fig. 4b). The model also shows a similar behavior in L2 where the velocity decreases from 1.64 km/s below OBS A to 1.60 km/s below OBSs B and C.

Line 4 is the southern line with an E-W orientation (Fig. 1). The SCS data show the presence of a HRZ below OBS D in L3 (Fig. 5a). Two extra velocity nodes were required at model positions 3.0 and 6.0 km in L2 and L3 in order to fit the data. The model shows a gradual decrease in velocity from 1.71 km/s from the western end of the line to 1.66 km/s below OBS D in L3 (Fig. 5b). There is a sharp decrease in velocity eastwards to 1.57 km/s. This is the strongest lateral velocity gradient in the study area, and indicates a rapid change in sediment properties or composition. L2 on the other hand shows a slight increase in velocity from 1.58 km/s below OBS D to 1.59 km/s further east. L2 shows a gradual decrease in velocity from 1.65 km/s at the west end of the model to 1.58 km/s below OBS D.

Line 5 is the northern line with an E-W orientation (Fig. 1). The SCS data show a HRZ in the model between OBSs F and B in L3 (Fig. 6a). Two extra velocity nodes were required at model positions 4.0 and 7.5 km both in L2 and L3 in order to fit the data. The model shows a gradual lowering of velocity from both ends towards OBS F in L2 and L3 (Fig. 6b). In L3, the velocity decreases from 1.71 km/s in the west to 1.69 km/s in the east, dropping to 1.67 km/s in between. In L2, the velocity decreases from 1.61 km/s at both ends to 1.59 km/s below OBS F.

In line 4, the reflection phase from the base of L3 could not be confidently identified at the far offsets to the east (Fig. 9a). Therefore, Line 4 was modeled again using 78 extra picks along the reflected phase. In the new model (Fig. 9b), the value of the velocity node at 6.0 km in L3 goes down to 1.48 km/s suggesting the presence of a low-velocity zone (LVZ) in this region. As the study area is a speculated hydrate-gas system where the presence of hydrates has been confirmed by shallow coring, it would not be unexpected if LVZs were part of the final models (Domenico 1977).
velocity within the LVZ suggests the presence of free gas. Though the extent of the LVZ in the
alternate model coincides with the extent of the HRZ in the SCS data, and its presence seems to be
required by the data, the velocity within the LVZ is especially uncertain because (1) the LVZ is
controlled mainly by a single OBS, (2) the extra picks responsible for the LVZ may correspond to
another arrival, such as a diffraction, and (3) Lines 1 and 2 that pass nearby this region do not support
the presence of such a low velocity value. This model is therefore not a part of the regional
interpretation.

Data Fit
Figure 10 shows the comparison of the observed and predicted traveltimes for the wide-angle and
near-vertical datasets. The data misfit is assessed using the normalized form of the misfit parameter,
\( \chi^2 \) (Bevington 1969; Zelt 1999). Assuming the errors in the observed picks are uncorrelated and
Gaussian in nature, a value of \( \chi^2 \) equal to 1 indicates that the observed data have been fit to within
their assigned uncertainties. In this paper, \( \chi^2 \) values for individual phases (reflections from L1, L2
and L3, and refractions) and each dataset (wide-angle and near-vertical) were monitored so that each
would be as close to unity as possible, and as a result the overall \( \chi^2 \) is less than 1 for each line, with
values ranging from 0.61-0.99 (Table 2).

Model Assessment
The simplest form of model assessment is provided by the raypath coverage within the final models.
Figure 11 shows the corresponding raypaths for individual phases: wide-angle and near-vertical
reflections from L1, L2 and L3, and refractions from the base of L1. Note that only refractions form
the base of L1 (the Holocene drape) were identified in the data, so that unlike most wide-angle
datasets, the majority of constraint on the velocity model comes from reflected raypaths, both wide-
angle and near-vertical.
In order to check the consistency of the results obtained by the inversion along all five lines, 1-D velocity-depth profiles at the line intersection points have been compared (Fig. 12). This corresponds to the location of OBSs B, C, D and F (Fig. 1). Since the modeling of the five lines was done independently, the relatively good consistency of the profiles suggests that the velocity and the depth node values in the final models may have errors of ±10 m/s and ±20 m, respectively. These relatively small errors are at least one order of magnitude smaller than those estimated for typical crustal-scale wide-angle data (Zelt 1999), and are indicative of the high-resolution nature of these data.

The estimated lateral velocity variations in the region are subtle (Figs 2-6). To test this, the modeling of Line 2 was re-done with only one velocity node in each layer to check for inversion artifacts and to see if lateral velocity variations are required by the data. It was not possible to obtain a final overall $\chi^2$ value of close to one (Table 3). In addition to the consistency of the models at their intersection points, this confirms that lateral velocity variations are required by the data.

**Discussion**

It is well known that salt tectonics in the Gulf of Mexico causes intense fracturing and faulting. The surface topography in the study area is in part a result of the deformation due to active salt domes in the region. Though faults and fractures have not been modeled in this paper, it is likely, as in the case of MC853 (Sassen *et al.* 2001), that gas present in the study area has a deeper source and comes up through these types of conduits. *(Ingo can support it through his interpretations of the GDBS line where he can actually see the salt body?).*
The contour map of velocity within L2 shows a systematic decrease in velocity towards the diapir location (Fig. 13a). The lowest velocity of 1.57 km/s occurs near OBS D along Line 4 directly adjacent to the diapir location. This zone, hereafter referred to as LVZ2, has a thickness in L2 of ~120 m. It is likely that LVZ2 has the maximum concentration of free gas in L2. The contour map of the base of L2 shows an increase in elevation towards the diapir (Fig. 13b). The contour map of velocity within L3 shows a velocity distribution of 1.66–1.72 km/s throughout the region except in the southeast where the presence of a LVZ is indicated (Fig. 14a). This zone, hereafter referred to as LVZ3, has a velocity of ~1.56 km/s and occurs east of OBS D along Line 4. The thickness of L3 at LVZ3 is ~200 m. The contour map of the base of L3 shows a increase in elevation below LVZ3 (Fig. 14b). The ray coverage associated with LVZ3 is not as good as that associated with LVZ2.

Understanding the nature of the reflections labeled F from the top of the wedge-shaped features labeled W in Figures 2a, 5a and 6a is crucial to the interpretation. Event F generally has a negative polarity and it disappears before it intersects with E2; best illustrated on Line 1 (Fig. 2a). Two possible interpretations of the reflections from the top of the wedge-shaped feature combined with the locations of the HRZs (labeled Z in Figures 2-6) are suggested.

In the first interpretation, the wedge-shaped feature is a levee of a channel complex (Fig. 15), not to be confused with the Mississippi River complex. This is a typical case of a channel deposit in which the channel axis is sandier and gives rise to HRZs and the overbank deposits are shalier and have the shape of a wedge (reference?). Due to the deposits in the levee being shaly, reflections from its top have a negative polarity. In this interpretation though, the sandy deposits along the channel axis would be expected to have a higher P-wave velocity than the surroundings. However, the fact that HRZs are associated with a lateral lowering of velocity suggests that free gas is present along the axis complex. The reflectivity along these zones are further enhanced due to the presence of free gas,
as in the case of the Blake Ridge (Holbrook et al. 1996). Therefore the sandy deposits along the axis of the channel complex may be acting as a potential reservoir for free gas. The levee eventually thins below seismic resolution and disappears on the records. Free gas from the channel complex migrates upwards through faults and fractures (interpreted on Line 1 and Line 5 in Figure 15) to features like the mud diapir where it comes within the GHSZ and forms hydrates.

As an alternate interpretation, the reflections from the top of the wedge-shaped feature is a BSR, i.e., it marks the gas hydrate–free gas contact. The stability diagram-(Fig. 16a), constructed with a reasonable bottom water temperature (8°C) and range of geotherms (25–40 °C/km) for this area (Sassen et al., 2001), estimates the depth of the base of the gas hydrate stability zone close to the top of the wedge and supports this interpretation. The shape and the nature of reflectivity of event F can be explained by assuming that the concentration of gas decreases laterally away from the HRZs. Due to a decrease in the gas concentration, the strength of the BSR decreases away from the HRZs. The BSR eventually disappears when the gas concentrations are so low that the hydrates and free gas are no longer in contact (Fig. 16b). Again, assuming that HRZs containing free gas are sitting close to the top of salt, the BSR deepens away from the HRZ because the salinity of the water decreases away from the salt dome. This explains the shape of F in Figures 2a, 5a and 6a.

Conclusions

A joint inversion of the wide-angle and near-vertical travelt ime data made the P-wave velocity modeling effective and simple. The minimum-parameter /minimum-structure modeling approach allowed inclusion of prior knowledge, helped in tracing rays to a maximum number of observations points, and prevented the model from being over-interpreted by keeping it geologically simple. The fit to the data along each line was obtained within a single iteration because the starting models were carefully constructed. The final models of all lines predicted all the identified phases in the observed data. The final overall $\chi^2$ errors for each of the five lines were less than unity because the $\chi^2$ values of
the individual wide-angle and the near-vertical phases were monitored during modeling to get each of them as close to unity as possible. Comparing 1-D velocity profiles at the intersections of the lines showed that the final models of all lines are consistent to within ±10 m/s in velocity and ±20 m in depth.

The lowering of velocity in the HRZs was attributed to the presence of free gas. It was speculated that the gas has a deeper source and its migration to the shallower subsurface is related to the ongoing deformation due to the movement of proximal salt bodies. Two possible geological scenarios were proposed. According to the first scenario, the wedge shaped feature is identified as the levee and HRZs were identified as the axis of a channel complex. The axis of the channel complex, which is sandier, acts like a reservoir sealed effectively on its sides and top. According to the second scenario, the top the wedge shaped feature is a BSR. The reflection strength and shape of the BSR is due to the concentration of the free gas and salinity decreasing laterally away from the HRZs.

According to the first scenario, the chance of gas being present anywhere else in the minibasin, apart from regions near the HRZs is low. As the sustenance of a hydrate system requires a constant and steady influx of free gas, it is possible that the hydrates may not exist anywhere else in the study area apart from the regions (like the mud diapir) that are close to the HRZs. In this case, the occurrence of a hydrate-gas interface that mimics the sea floor is not possible, and this is consistent with the seismic data presented here. According to the second scenario, it is possible that gas hydrates may be present throughout the study area and give rise to BSRs at places where the concentration of free gas is adequate.

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References


Dillon et al. 1999?


Neurauter & Roberts 1994?


Table 1. OBS Locations.

<table>
<thead>
<tr>
<th>Line</th>
<th>Shotpoints</th>
<th>OBS</th>
<th>Depth below sea level (m)</th>
<th>X position in the model (km)</th>
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Table 2. Inversion statistics.

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<th>Line</th>
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Table 3. Inversion statistics for Line 2 with constant layer fixed velocities.

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Figure 1. Study Area. (a) Location of the study area over the Mississippi Trough. Bathymetric contours in meters. (b) Experiment design in MC798. Seismic lines are black and labeled 1 through 5 at the beginning of each line. The positions of OBSs A, B, C, D, E and F are shown as black circles. The mud diapir is shown as a white circle. Seafloor bathymetry is contoured every 50 m and labeled every 100 m.
Figure 2. Comparison of SCS data and velocity model for Line 1. (a) SCS data from Line 1 post-stack time migrated with velocities obtained from the model in (b). (L1) is the Holocene drape. (L2) and (L3) are sedimentary packages for the purpose of modeling. Other labels are as follows: (E1) reflection from base of L1, (E2) reflection from base of L2, (E3) reflection from base of L3, (R) reflectors that are only locally continuous and coherent, (C) chaotic reflections below the diapir, (Z) HRZ below L2, (W) is a wedge-shaped feature, (F) is the reflection from the top of the wedge-shaped feature that has largely negative polarity. Also shown is the location of the diapir. Vertical exageration is approximately 7:1. (b) Final model for Line 1. P-wave velocities are shown in the model at the locations of the velocity nodes. Positions of OBSs B and D on the sea floor are shown as solid circles in (a) and (b).
Figure 3. Comparison of SCS data and velocity model for Line 2. (a) SCS data from Line 2 post-stack time migrated with velocities obtained from the model in (b). Symbols have same meaning as in Figure 2a. P-wave velocities are shown in the model at the locations of the velocity nodes. Positions of OBSs D, F and E on the sea floor are shown as solid circles in (a) and (b).
Figure 4. Comparison of SCS data and velocity model for Line 3. (a) SCS data from Line 3 post-stack time migrated with velocities obtained from the model in (b). Symbols have same meaning as in Figure 2a. Vertical exaggeration is approximately 6.5:1. (b) Final model for Line 3. P-wave velocities are shown in the model at the locations of the velocity nodes. Positions of OBSs A, B and C on the sea floor are shown as solid circles in (a) and (b).
Figure 5. Comparison of SCS data and velocity model for Line 4. (a) SCS data from Line 4 post-stack time migrated with velocities obtained from the model in (b). Symbols have same meaning as in Figure 2a. Vertical exaggeration is approximately 7:1. (b) Final model for Line 4. P-wave velocities are shown in the model at the location of the velocity nodes. Positions of OBSs C and D on the sea floor are shown as solid circles in (a) and (b).
Figure 6. Comparison of SCS data and velocity model for Line 5. (a) SCS data from Line 5 post-stack time migrated with velocities obtained from the model in (b). Symbols have same meaning as in Figure 2a. Vertical exaggeration is approximately 4:1. (b) Final model for Line 5. P-wave velocities are shown in the model at the location of the velocity nodes. Positions of OBSs F and B on the sea floor are shown as solid circles in (a) and (b).
Figure 7. OBS C data from Line 4. (a) Hydrophone channel data. (D) is the direct arrival, (E1), (E2) and (E3) are the reflections from the base of L1, L2 and L3, (rf) is the refraction from the base of L1, and (m) is the multiple of the direct arrival. The amplitudes of the direct arrivals are clipped to about 3km on either side. (b) Vertical component data. Symbols have same meaning as in (a). Plots made with a reducing velocity of 2 km/s.
Figure 8. Event identification along Line 3 using the SCS and OBS data. (a) SCS data inserted between OBS A and C hydrophone channels. (b) SCS data inserted between OBS A and B hydrophone channels. (c) SCS data inserted between OBS B and C hydrophone channels. Green, blue and red arrows indicate reflection events in the OBS data from the base of L1, L2 and L3, respectively. Corresponding events on SCS record labeled 1, 2, and 3, respectively.
Figure 9. Alternate model of Line 4. (a) OBS D hydrophone channel data showing the picks that constrain the LVZ in Line 4. Extra picks that were responsible for lowering velocity from 1.57 km/s to 1.48 km/s in the LVZ are bounded by a solid box. Plot is made with a reducing velocity of 1.75 km/s. (b) P-wave velocities are shown in the model at the location of the velocity nodes. Also shown are the locations of inline OBSs C and D in solid circles.
Figure 10. Traveltime Comparisons. (a) Comparison of the observed and predicted wide-angle traveltimes for the final model of each line. (b) Comparison of the observed and predicted near-vertical traveltimes for the final model of each line. Colored symbols are the observed traveltimes with their vertical length proportional to the associated pick uncertainty; color code is same as in Figure 8. The predicted traveltimes are plotted as black lines in (a) and as black dots in (b). Plots in (a) are made with a reducing velocity of 2 km/s. OBS locations are indicated and labeled in (a). Light blue arrivals in (b) are reflections from the seafloor that are not modeled as part of the traveltime inversion.
Figure 11. Ray diagrams for the (a) refraction from the base of L1, and the near-vertical and wide-angle reflections from the base of (b) L1, (c) L2, (d) L3. Layer boundaries are indicated as dashed lines. For clarity, every fifth wide-angle ray is shown.
Figure 12. One-dimensional velocity profiles from the line intersection points. The profiles from Line 1 are black, Line 2 are red, Line 3 are green, Line 4 are magenta and Line 5 are blue. Vertical axis in the plots is two-way reflection time.
Figure 13. (a) Contour plot of velocity in L2. (b) Contour plot of depth to the base of L2. Shot lines are numbered at their beginning. OBSs A through F are shown as black circles. The diapir is shown as a white circle. The location of LVZ2 is indicated by an open black circle.
Figure 14. (a) Contour plot of velocity in L3. (b) Contour plot of depth to the base of L3. Shot lines are numbered at their beginning. OBSs A through F are shown as black circles. The diapir is shown as a white circle. The location of LVZ3 is indicated by an open black ellipse.
Figure 15. (a) Interpretation on Line 1. (A) stands for the channel axis, (L) stands of levee complex. Rest of the symbols have the same meaning as in Figure 2. (b) Interpretation on Line 5. (A) stands for the channel axis, (L) stands of levee complex. Rest of the symbols have the same meaning as in Figure 2. F1 and F2 are faults.
Figure 16. (a) Estimation of depth of BSR. Stability of methane hydrate in seawater as defined by temperature and pressure in which pressure is expressed by water depth. The seawater equilibrium curve is plotted with data obtained from laboratory experiments (reference?). Variations of stability with variations in salinity are not taken into account in this diagram. The data on the equilibrium curve are shown as cross marks(?). Horizontal line at 800 m depth is the seafloor. Dashed lines are two geotherms calculated with a bottom water temperature of 8°C. The intersection points of the geotherms with the equilibrium curve is the expected depth of BSRs for 800 m water depth. According to this diagram the thickness of the GHSZ can vary anywhere from 50 to 150 m below the sea floor depending on the geotherms taken into consideration. The actual thickness in the study area can be more or less depending on the lateral variations of the bathymetry, geotherm, salinity and bottom water temperature (Sassen et al. 2001). (b) Schematic diagram of solubility curves and phase relationships. This diagram is relevant to understanding the presence of free gas and gas hydrates in the study area. O is the triple point. Dashed curves are the methane concentration. (1) Variation in methane concentration such that BSR is absent even though free gas and hydrate is present, and (2) variation of methane concentration such that the hydrates are in contact with free gas and BSR is formed at the contact. The strength of the BSR reduces as (2) moves towards left with decreasing methane concentration and disappears as soon as the concentration curve crosses the triple junction. After that point, the hydrates and free gas may be present but the BSR is absent. (1) explains the absence of BSR in the presence of hydrates and free gas, and (2) explains the presence of BSR.